Self-supervised Auxiliary Learning with Meta-paths for Heterogeneous Graphs

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Abstract
Graph neural networks have shown superior performance in a wide range of applications providing a powerful representation of graph-structured data. Recent works show that the representation can be further improved by auxiliary tasks. However, the auxiliary tasks for heterogeneous graphs, which contain rich semantic information with various types of nodes and edges, have less explored in the literature. In this paper, to learn graph neural networks on heterogeneous graphs we propose a novel self-supervised auxiliary learning method using meta-paths, which are composite relations of multiple edge types. Our proposed method is learning to learn a primary task by predicting meta-paths as auxiliary tasks. This can be viewed as a type of meta-learning. The proposed method can identify an effective combination of auxiliary tasks and automatically balance them to improve the primary task. Our methods can be applied to any graph neural networks in a plug-in manner without manual labeling or additional data. The experiments demonstrate that the proposed method consistently improves the performance of link prediction and node classification on heterogeneous graphs.

1 Introduction
Graph neural networks \cite{1,2,3} have been proven effective to learn representations for various tasks such as node classification \cite{4}, link prediction \cite{5,6}, and graph classification \cite{7,8}. The powerful representation yields state-of-the-art performance in a variety of applications including social network analysis \cite{9,4,10}, citation network analysis \cite{11,12}, visual understanding \cite{13,14,15}, recommender systems \cite{16,18}, physics \cite{19,20}, and drug discovery \cite{21,22}. Despite the wide operating range of graph neural networks, employing auxiliary (pre-text) tasks has been less explored for further improving graph representation learning.

Pre-training with an auxiliary task is a common technique for deep neural networks. Indeed, it is the de facto standard step in natural language processing and computer vision to learn a powerful backbone networks such as BERT \cite{23} and ResNet \cite{24} leveraging large datasets such as BooksCorpus \cite{25}, English Wikipedia, and ImageNet \cite{26}. The models trained on the auxiliary task are often beneficial for the primary (target) task of interest. Despite the success of pre-training, few approaches have been generalized to graph-structured data due to their fundamental challenges. First, graph structure (e.g., the number of nodes/edges, and diameter) and its meaning can significantly differ between domains. So the model trained on an auxiliary task can harm generalization on the primary task, i.e., negative transfer \cite{27}. Also, many graph neural networks are transductive approaches. This often makes transfer learning between datasets inherently infeasible. So, pre-training on the target dataset has been proposed using auxiliary tasks: graph kernel \cite{28}, graph reconstruction \cite{29}, and attribute masking \cite{21}. These assume that the auxiliary tasks for pre-training are carefully selected with substantial domain knowledge and expertise in graph characteristics to assist the primary task.
Since most graph neural networks operate on homogeneous graphs, which have a single type of nodes and edges, the previous pre-training/auxiliary tasks are not specifically designed for heterogeneous graphs, which have multiple types of nodes and edges. Heterogeneous graphs commonly occur in real-world applications, for instance, a music dataset has multiple types of nodes (e.g., user, song, artist) and multiple types of relations (e.g., user-artist, song-film, song-instrument).

In this paper, we proposed a framework to train a graph neural networks with automatically selected auxiliary self-supervised tasks which assist the target task without additional data and labels. Our approach first generates meta-paths from heterogeneous graphs without manual labeling and train a model with meta-path prediction to assist the primary task such as link prediction and node classification. This can be formulated as a meta-learning problem. Furthermore, our method can be adopted to existing GNNs in a plug-in manner, enhancing the model performance.

Our contribution is threefold: (i) We propose a self-supervised learning method on a heterogeneous graph via meta-path prediction without additional data. (ii) Our framework automatically selects meta-paths (auxiliary tasks) to assist the primary task via meta-learning. (iii) We develop Hint Network that helps the learner network to benefit from challenging auxiliary tasks. To the best of our knowledge, this is the first auxiliary task with meta-paths specifically designed for leveraging heterogeneous graph structure. Our experiment shows that meta-path prediction improves the representational power and the gain can be further improved to explicitly optimize the auxiliary tasks for the primary task via meta-learning and the Hint Network, built on various state-of-the-art GNNs.

2 Related Work

Graph Neural Networks have provided promising results for various tasks [16, 18, 30, 32]. Bruna et al. [33] proposed a neural network that performs convolution on the graph domain using Fourier basis from spectral graph theory. In contrast, non-spectral (spatial) approaches have been developed [12, 11, 4, 34]. Inspired by self-supervised learning [35-38] and pre-training [23, 39] in computer vision and natural language processing, pre-training for GNNs has been recently proposed [21, 28]. Recent works [34, 40] show promising results that transfer learning can be successful on graphs but they require additional manually labeled data. To avoid the need for manual labeling, self-supervised learning on the target domain such as graph kernel [28], graph reconstruction [29], and attribute masking [21] has been proposed. The auxiliary tasks should be manually chosen with domain knowledge and they are not optimized for the primary task.

Auxiliary Learning is a learning strategy to employ auxiliary tasks to assist the primary task. It is similar to multi-task learning, but auxiliary learning cares only the performance of the primary task. A number of auxiliary learning methods are proposed in a wide range of tasks [41-43]. AC-GAN [44] proposed an auxiliary classifier for generative models. Recently, Meta-Auxiliary Learning [45] proposes an elegant solution to generate new auxiliary tasks by collapsing existing classes. However, it cannot be applicable to some tasks such as link prediction which has only one positive class. Our approach generates meta-paths on heterogeneous graphs to make new labels and trains models to predict meta-paths as auxiliary tasks.

Meta-learning aims learning to learn models efficiently and effectively, and generalizes the learning strategy to new tasks. Meta-learning includes black-box methods to approximate gradients without any information about models [46], optimization-based methods to learn an optimal initialization for adapting new tasks [47-50], learning loss functions [48, 51] and metric-learning or non-parametric methods for few-shot learning [52-54]. In contrast to classical learning algorithms that generalize across samples, meta-learning generalizes across tasks. In this paper, we use meta-learning to learn a concept across tasks and transfer the knowledge from auxiliary tasks to the primary task.

3 Method

The goal of our framework is to learn with multiple auxiliary tasks to improve the performance of the primary task. In this work, we demonstrate our framework with math-path predictions as auxiliary tasks. But our framework could be extended to include other auxiliary tasks. The meta-paths capture diverse and meaningful relations between nodes on heterogeneous graphs [55]. However, learning with auxiliary tasks has multiple challenges: identifying useful auxiliary tasks, balancing the auxiliary tasks with the primary task, and converting challenging auxiliary tasks into solvable (and relevant)
tasks. To address the challenges, we propose SELf-supervised Auxiliary Learning (SELAR). Our framework consists of two main components: 1) learning weight functions to softly select auxiliary tasks and balance them with the primary task via meta-learning, and 2) learning Hint Networks to convert challenging auxiliary tasks into more relevant and solvable tasks to the primary task learner.

3.1 Meta-path Prediction as a self-supervised task

Most existing graph neural networks have been studied focusing on homogeneous graphs that have a single type of nodes and edges. However, in real-world applications, heterogeneous graphs \[56\] which have multiple types of nodes and edges, commonly occur. Learning models on the heterogeneous graphs requires different considerations to effectively represent their node and edge heterogeneity.

**Heterogeneous graph \[57\].** Let \( G = (V, E) \) be a graph with a set of nodes \( V \) and edges \( E \). A heterogeneous graph is a graph equipped with a node type mapping function \( f_v : V \rightarrow \mathcal{T}^\nu \) and an edge type mapping function \( f_e : E \rightarrow \mathcal{T}^\nu \), where \( \mathcal{T}^\nu \) is a set of node types and \( \mathcal{T}^\nu \) is a set of edge types. Each node \( v_i \in V \) (and edge \( e_{ij} \in E \) resp.) has one node type, i.e., \( f_v(v_i) \in \mathcal{T}^\nu \), (and one edge type \( f_e(e_{ij}) \in \mathcal{T}^\nu \) resp.). In this paper, we consider the heterogeneous graphs with \(|\mathcal{T}^\nu| > 1\) or \(|\mathcal{T}^\nu| = 1\). When \(|\mathcal{T}^\nu| = 1\) and \(|\mathcal{T}^\nu| = 1\), it becomes a homogeneous graph.

**Meta-Path \[55,58\]** is a path on a heterogeneous graph \( G \) that a sequence of nodes connected with heterogeneous edges, i.e., \( v_1 \xrightarrow{t_1} v_2 \xrightarrow{t_2} \ldots \xrightarrow{t_l} v_{l+1} \), where \( t_l \in \mathcal{T}^\nu \) denotes an \( l \)-th edge type of the meta-path. The meta-path can be viewed as a composite relation \( R = t_1 \circ t_2 \ldots \circ t_l \) between node \( v_1 \) and \( v_{l+1} \), where \( R_1 \circ R_2 \) denotes the composition of relation \( R_1 \) and \( R_2 \). The definition of meta-path generalizes multi-hop connections and is shown to be useful to analyze heterogeneous graphs. For instance, in Book-Crossing dataset, ‘user-item-written.series-item-user’ indicates that a meta-path that connects users who like a same book series.

We introduce **meta-path prediction** as a self-supervised auxiliary task to improve the representational power of graph neural networks. To our knowledge, the meta-path prediction has not been studied in the context of self-supervised learning for graph neural networks in the literature.

**Meta-path prediction** is similar to link prediction but meta-paths allow heterogeneous composite relations. The meta-path prediction can be achieved in the same manner as link prediction. If two nodes \( u \) and \( v \) are connected by a meta-path \( p \) with the heterogeneous edges \( (t_1, t_2, \ldots, t_l) \), then \( y^p_{u,v} = 1 \), otherwise \( y^p_{u,v} = 0 \). The labels can be generated from a heterogeneous graph without any manual labeling. They can be obtained by \( A_p = A_{t_1} \ldots A_{t_l} A_{t_1} \), where \( A_t \) is the adjacency matrix of edge type \( t \). The binarized value at \( (u, v) \) in \( A_p \) indicates whether \( u \) and \( v \) are connected with the meta-path \( p \). In this paper, we use meta-path prediction as a self-supervised auxiliary task.

Let \( X \in \mathbb{R}^{|V| \times d} \) and \( Z \in \mathbb{R}^{|V| \times d'} \) be input features and their hidden representations learnt by GNN \( f \), i.e., \( Z = f(X; w, A) \), where \( w \) is the parameter for \( f \), and \( A \in \mathbb{R}^{|V| \times |V|} \) is the adjacency matrix. Then link prediction and meta-path prediction are obtained by a simple operation as

\[
y^p_{u,v} = \sigma(\Phi_t(z_u)^\top \Phi_t(z_v)), \tag{1}
\]

where \( \Phi_t \) is the task-specific network for task \( t \in \mathcal{T} \) and \( z_u \) and \( z_v \) are the node embeddings of node \( u \) and \( v \), e.g., \( \Phi_0 \) (and \( \Phi_1 \) resp.) for link prediction (and the first type of meta-path prediction resp.).

**The architecture** is shown in Fig. \[\] To optimize the model, as the link prediction, cross entropy is used. The graph neural network \( f \) is shared by the link prediction and meta-path predictions. As any auxiliary learning methods, the meta-paths (auxiliary tasks) should be carefully chosen and properly weighted so that the meta-path prediction does not compete with link prediction especially when the capacity of GNNs is limited. To address this issues, we propose our framework that automatically select meta-paths and balance them with the link prediction via meta-learning.

3.2 Self-Supervised Auxiliary Learning

Our framework SELAR is learning to learn a primary task with multiple auxiliary tasks to assist the primary task. This can be formally written as

\[
\min_{w,\Theta} \mathbb{E}_{(x,y) \sim D^{pr}} \left[ L^{pr}(w^*(\Theta)) \right] \quad \text{s.t.} \quad w^*(\Theta) = \arg\min_{w} \mathbb{E}_{(x,y) \sim D^{pr+au}} \left[ L^{pr+au}(w; \Theta) \right], \tag{2}
\]
where \( \mathcal{L}^{pr} (\cdot) \) is the primary task loss function to evaluate the trained model \( f(x; w^* (\Theta)) \) on meta-data \( \mathcal{D}^{pr} \) and \( \mathcal{L}^{pr+au} \) is the loss function to train a model on training data \( \mathcal{D}^{pr+au} \) with the primary and auxiliary tasks. To avoid cluttered notation, \( f, x, \) and \( y \) are omitted. Each task \( T_t \) has \( N_t \) samples and \( T_0 \) and \( \{ T_t \}_{t=1}^T \) denote the primary and auxiliary tasks respectively. The proposed formulation in Eq. (2) learns how to assist the primary task by optimizing \( \Theta \) via meta-learning. The nested optimization problem given \( \Theta \) is a regular training with properly adjusted loss functions to balance the primary and auxiliary tasks. The formulation can be more specifically written as

\[
\min_{w,\Theta} \frac{1}{M_0} \sum_{t=1}^{M_0} 1 \sum_{i=1}^{N_t} 1 \sum_{j=1}^{N} \mathcal{L}(j_i^{(0,\text{meta})}, f(x_i^{(0,\text{meta})}; w^*(\Theta)) \)  
\text{s.t. } w^*(\Theta) = \arg\min_w \frac{1}{N_t} \sum_{t=0}^{T} \mathcal{L}(y_i^{(t,\text{train})}, f(x_i^{(t,\text{train})}; w)),
\]

where \( \ell^t \) and \( f^t \) denote the loss function and the model for task \( t \). We overload \( \ell^t \) with its function value, i.e., \( \ell^t = \ell^t (y_i^{(t,\text{train})}, f^t(x_i^{(t,\text{train})}; w), \xi_i^{(t,\text{train})} \) is the embedding vector of \( i^{th} \) sample for task \( t \). In our experiment, \( \xi_i^{(t,\text{train})} \) is the concatenation of one-hot representation of task types, the label of the sample (positive/negative), and its loss value, i.e., \( \xi_i^{(t,\text{train})} = [\ell^t; \epsilon_t; y_i^{(t,\text{train})}] \in \mathbb{R}^{T+2} \). To derive our learning algorithm, we first shorten the objective function in Eq. (3) and Eq. (4) as \( \mathcal{L}^{pr}(w^*(\Theta)) \) and \( \mathcal{L}^{pr+au}(w; \Theta) \). This is equivalent to Eq. (5) without expectation. Then, our formulation is given as

\[
\min_{w,\Theta} \mathcal{L}^{pr}(w^*(\Theta)) \text{ s.t. } w^*(\Theta) = \arg\min_w \mathcal{L}^{pr+au}(w; \Theta),
\]

To circumvent the difficulty of the bi-level optimization, as previous works \cite{47, 48} in meta-learning we approximate it with the updated parameters \( w \) using the gradient descent update as

\[
\hat{w}^k(\Theta) = w^k - \alpha \nabla_w \mathcal{L}^{pr+au}(w^k; \Theta),
\]

where \( \alpha \) is the learning rate for \( w \). We do not numerically evaluate \( \hat{w}^k(\Theta) \) instead we plug the computational graph of \( \hat{w}^k \) in \( \mathcal{L}^{pr}(w^*(\Theta)) \) to optimize \( \Theta \). Let \( \nabla_0 \mathcal{L}^{pr}(w^*(\Theta^k)) \) be the gradient evaluated at \( \Theta^k \). Then updating parameters \( \Theta \) is given as

\[
\Theta^{k+1} = \Theta^k - \beta \nabla_0 \mathcal{L}^{pr}(\hat{w}^k(\Theta^k)),
\]

where \( \beta \) is the learning rate for \( \Theta \). This update allows softly selecting useful auxiliary tasks (meta-paths) and balance them with the primary task to improve the performance of the primary task. Without balancing tasks with the weighting function \( V(\cdot; \Theta) \), auxiliary tasks can dominate training and degrade the performance of the primary task.

The model parameters \( w^k \) for tasks can be updated with optimized \( \Theta^{k+1} \) in Eq. (7) as

\[
w^{k+1} = w^k - \alpha \nabla_w \mathcal{L}^{pr+au}(w^k; \Theta^{k+1}).
\]
Remarks. The proposed formulation can suffer from the meta-overfitting [59, 60] meaning that the parameters \( \Theta \) to learn weights for softly selecting meta-paths and balancing the tasks with the primary task can overfit to the small meta-dataset. In our experiment, we found that the overfitting can be alleviated by meta-validation sets [59]. To learn \( \Theta \) that is generalizable across meta-training sets, we optimize \( \Theta \) across \( k \) different meta-datasets like \( k \)-fold cross validation using the following equation:

\[
\Theta^{k+1} = \Theta^k - \beta \mathbb{E}_{D^{pr} \sim CV} \left[ \nabla_{\Theta} L^{pr}(\hat{w}^k(\Theta^k)) \right],
\]

where \( D^{meta} \sim CV \) is a meta-dataset from cross validation. We used 3-fold cross validation and the gradients of \( \Theta \) w.r.t different meta-datasets are averaged to update \( \Theta^k \), see Algorithm 1. The cross validation is crucial to alleviate meta-overfitting and more discussion is Section 4.3.

Algorithm 1 Self-supervised Auxiliary Learning

**Input:** training data for primary/auxiliary tasks \( D^{pr}, D^{au} \), mini-batch size \( N^{pr}, N^{au} \)

**Output:** network parameter \( w^K \) for the primary task

1: for \( k = 1 \) to \( K \) do
2: \( D^{pr}_m \leftarrow \text{MiniBatchSampler}(D^{pr}, N^{pr}) \)
3: \( D^{au}_m \leftarrow \text{MiniBatchSampler}(D^{au}, N^{au}) \)
4: for \( c = 1 \) to \( C \) do
5: \( D^{pr}_{m(train)}, D^{pr}_{m(meta)} \leftarrow \text{CVSplit}(D^{pr}_m, c) \)
6: \( \hat{w}^k(\Theta) \leftarrow w^k - \alpha \nabla_{w} L^{pr+au}(w^k; \Theta) \) with \( D^{pr}_{m(train)} \cup D^{au}_m \) \( \triangleright \) Eq. (6)
7: \( g_c \leftarrow \nabla_{\Theta} L^{pr}(\hat{w}^k(\Theta^k)) \) with \( D^{pr}_{m(meta)} \) \( \triangleright \) Eq. (7)
8: end for
9: Update \( \Theta^{k+1} \leftarrow \Theta^k - \beta \sum_c g_c \) \( \triangleright \) Eq. (9)
10: \( w^{k+1} = w^k - \alpha \nabla_{w} L^{pr+au}(w^k; \Theta^{k+1}) \) with \( D^{pr} \cup D^{au} \) \( \triangleright \) Eq. (8)
11: end for

### 3.3 Hint Networks

Meta-path prediction is generally more challenging than link prediction and node classification since it requires the understanding of long-range relations across heterogeneous nodes. The meta-path prediction gets more difficult when mini-batch training is inevitable due to the size of datasets or models. Within a mini-batch, important nodes and edges for meta-paths are not available. Also, a small learner network, e.g., two-layer GNNs, with a limited receptive field, inherently cannot capture long-range relations. The challenges can hinder representation learning and damage the generalization of the primary task. We proposed a Hint Network (HintNet) which makes the challenge tasks more solvable by correcting the answer with more information at the learner’s need. Specifically, in our experiments, the HintNet corrects the answer of the learner with its own answer from the augmented graph with hub nodes, see Fig. 2.

![Diagram](image)

Figure 2: HintNet helps the learner network to learn even with challenging and remotely relevant auxiliary tasks. As our framework selects effective auxiliary tasks, our framework with HintNet learns \( V_H(\cdot) \) to decide to use hint \( \hat{y}_H \) in the orange line from HintNet or not via meta-learning. \( \hat{y} \) in the blue line denotes the prediction from the learner network.

The amount of help (correction) by HintNet is optimized maximizing the learner’s gain. Let \( V_H(\cdot) \) and \( \Theta_H \) be a weight function to determine the amount of hint and its parameters which are optimized
We evaluate our proposed methods on four public benchmark datasets on heterogeneous graphs. We believe that ACM dataset is already saturated and the room for improvement is limited. However, our methods still show small yet consistent improvement over all the architecture of all the GNN models and the improvements are more significant on IMDB which is larger than the ACM. We conjecture that the efficacy of our proposed methods differs depending on graph structures. However, it is worth noting that the introducing meta-path prediction as auxiliary tasks by meta-learning. Then, our formulation with HINTNet is given as

$$\min_{\mathbf{w}, \Theta} \sum_{i=1}^{M_0} \frac{1}{M_0} f^0(y_{i}^{(0, \text{meta})}, f(x_{i}^{(0, \text{meta})}; \mathbf{w}^*(\Theta, \Theta_H))$$

$$\text{s.t.} \quad \mathbf{w}^*(\Theta) = \arg\min_{\mathbf{w}} \sum_{i=0}^{T} \sum_{t=1}^{N_i} \frac{1}{N_i} \mathcal{V}(\xi_{i}^{(t, \text{train})}, \ell_{t}; \Theta)\ell_{t}(y_{i}^{(t, \text{train})}, \hat{y}_{i}^{(t, \text{train})}(\Theta_H)), \quad (10)$$

where $\hat{y}_{i}^{(t, \text{train})}(\Theta_H)$ denotes the convex combination of the learner’s answer and HINTNet’s answer, i.e., $\mathcal{V}(\xi_{i}^{(t, \text{train})}; \Theta_H) f^t(x_{i}^{(t, \text{train})}; \mathbf{w}) + (1 - \mathcal{V}(\xi_{i}^{(t, \text{train})}; \Theta_H)) f^t_H(x_{i}^{(t, \text{train})}; \mathbf{w}).$ The sample embedding is $\xi_{i}^{(t, \text{train})} = [e_i^t; y_{i}^{(t, \text{train})}; \ell_t^t; \ell_H^t] \in \mathbb{R}^{T+3}.$

4 Experiments

We evaluate our proposed methods on four public benchmark datasets on heterogeneous graphs. Our experiments answer the following research questions: Q1. Is meta-path prediction effective for representation learning on heterogeneous graphs? Q2. Can the meta-path prediction be further improved by the proposed methods (e.g., SELAR, HINTNet)? Q3. Why are the proposed methods effective, any relation with hard negative mining?

Datasets. We use two public benchmark datasets from different domains for link prediction: Music dataset Last-FM and Book dataset Book-Crossing, released by KGNN-LS [61], RippleNet [30]. We use two datasets for node classification: citation network datasets ACM and Movie dataset IMDB, used by HAN [55] for node classification tasks. ACM has three types nodes (Paper(P), Author(A), Subject(S)), four types of edges (PA, AP, PS, SP) and labels (categories of papers). IMDB contains three types of nodes (Movie (M), Actor (A), Director (D)), four types (MA, AM, MD, DM) of edges and labels (genres of movies). ACM and IMDB have node features, which are bag-of-words of keywords and plots. Dataset details are in the supplement.

Baselines. We evaluate our methods with four graph neural networks: GCN [12], GAT [11], GIN [34] and SGCConv [62]. We compare four learning strategies: Vanilla, standard training of base models only with the primary task samples; w/o meta-path, learning a primary task with sample weighting function $\mathcal{V}(\xi; \Theta);$ w/ meta-path, training with the primary task and auxiliary tasks (meta-path prediction) with a standard loss function; SELAR proposed in Section 3.2 learning the primary task with optimized auxiliary tasks by meta-learning; SELAR+Hint introduced in Section 3.3. Implementation details are in the supplement.

4.1 Learning Link Prediction with meta-path prediction

We used five types of meta-paths of length 2 to 4 for auxiliary tasks. Table 1 shows that our methods consistently improve link prediction performance for all the GNNs, compared to the Vanilla and the method using Meta-Weight-Net only without meta-paths (denoted as w/o meta-path). Overall, a standard training with meta-paths shows 2% improvement on average on Last-FM and about 3% improvement on Book-Crossing whereas meta-learning that learns sample weights improves only 0.4% and 0.6% on average and two cases, e.g., GCN on Last-FM and SGC on Book-Crossing, show degradation compared to the standard training (Vanilla). As we expected, SELAR and SELAR with HINTNet provide more optimized auxiliary learning resulting in 2.2% and 2.5% absolute improvement on Last.fm and 4.1% and 4.4% on the Book-Crossing dataset. Further, in particular, GIN on Book-crossing, SELAR+HINTNet provides ∼8.1% absolute improvement compared to the vanilla algorithm.

4.2 Learning Node Classification with meta-path prediction

Similar to link prediction above, our SELAR consistently enhances node classification performance of all the GNN models and the improvements are more significant on IMDB which is larger than the ACM dataset. We believe that ACM dataset is already saturated and the room for improvement is limited. However, our methods still show small yet consistent improvement over all the architecture on ACM. We conjecture that the efficacy of our proposed methods differs depending on graph structures. However, it is worth noting that the introducing meta-path prediction as auxiliary tasks
Table 1: Link prediction performance ($AUC$) of GNNs trained by various learning strategies.

| Dataset    | Base GNNs | Vanilla | w/o meta-path | w/ meta-path | Ours      | SELAR     | SELAR+Hint |
|------------|-----------|---------|---------------|-------------|-----------|-----------|------------|
| Last-FM    | GCN       | 0.7898  | *0.7850       | 0.8135      | **0.8163**| 0.8162    |            |
|            | GAT       | 0.8090  | 0.8100        | 0.8184      | 0.8319    | **0.8349**|            |
|            | GIN       | 0.7895  | 0.8081        | **0.8304**  | 0.8211    | 0.8255    |            |
|            | SGC       | 0.7725  | 0.7759        | 0.7801      | 0.7803    | **0.7857**|            |
| Avg. Gain  | -         | -       | +0.0046       | +0.0204     | +0.0222   | +0.0253   |            |
| Book-Crossing | GCN       | 0.6918  | 0.6967        | 0.6970      | 0.7081    | 0.7075    |            |
|            | GAT       | 0.6704  | 0.6759        | 0.7026      | 0.7136    | **0.7247**|            |
|            | GIN       | 0.6782  | 0.6968        | 0.7442      | 0.7554    | **0.7587**|            |
|            | SGC       | 0.6781  | *0.6732       | 0.6933      | 0.7070    | 0.7039    |            |
| Avg. Gain  | -         | -       | +0.0061       | +0.0297     | +0.0414   | +0.0441   |            |

remarkably improves the performance of primary tasks such as link and node prediction with consistency compared to the existing methods. “w/o meta-path”, the meta-learning to learn sample weight function on a primary task shows marginal degradation in five out of eight settings highlighted with *. Remarkably, SELAR improved the F1-score of GAT on the IMDB by (6.54%) compared to the vanilla learning scheme.

4.3 Analysis of Weighting Function and Meta-overfitting

The effectiveness of meta-path prediction and the proposed learning strategies are answered above. To address the last research question Q3, why the proposed method is effective, we provide analysis on the weighting function $\mathcal{V}(\xi; \Theta)$ learned by our framework. Also, we show the evidence that meta-overfitting occurs and can be addressed by cross-validation as in Algorithm[1].

**Weighting function.** Our proposed methods can automatically balance multiple auxiliary tasks to improve the primary task. To understand the ability of our method, we analyze the weighting function and the adjusted loss function by the weighting function, i.e., $\mathcal{V}(\xi; \Theta)$, $\mathcal{V}(\xi; \Theta)\ell_t(y, \hat{y})$. The positive and negative samples are solid and dash lines respectively. We present the weighting function learnt by SELAR+HintNet for GAT which is the best-performing construction on Last-FM. The weighting function is from the epoch with the best validation performance. Fig. 3 shows that the learnt weighting function attends to hard examples more than easy ones with a small loss range from 0 to 1.

Also, the primary task-positive samples are relatively less down weighted than auxiliary tasks even when the samples are easy (i.e., the loss is ranged from 0 to 1). Our adjusted loss $\mathcal{V}(\xi; \Theta)\ell_t(y, \hat{y})$ is closely related to the focal loss, $-(1 - p_t)^\gamma \log(p_t)$. When $\ell_t$ is the cross-entropy, it becomes $\mathcal{V}(\xi; \Theta)\log(p_t)$, where $p$ is the model’s prediction for the correct class and $p_t$ is defined as $p$ if $y = 1$, otherwise $1 - p$ as [63]. The weighting function differentially evolves over iterations. At the early stage of training, it often focuses on easy examples first and then changes its focus over time.
Figure 3: Weighting function $V(\cdot)$ learnt by SELAR+HintNet. $V(\cdot)$ gives overall high weights to the primary task positive samples (red) in (a). $V(\cdot)$ decreases the weights of easy samples with a loss ranged from 0 to 1. In (b), the adjusted cross entropy, i.e., $-V(\xi; \Theta) \log(\hat{y})$, by $V(\cdot)$ acts like the focal loss, which focuses on hard examples by $-(1 - p_t)^\gamma \log(\hat{y})$.

Also, the adjusted loss values by the weighting function learnt by our method differ across tasks. To analyze the contribution of each task, we calculate the average of the task-specific weighted loss on the Last-FM and Book-Crossing datasets. Especially, on the Book-Crossing, our method has more attention to ‘user-item’ (primary task) and ‘user-item-literary.series.item-user’ (auxiliary task) which is a meta-path that connects users who like a book series. This implies that two users who like a book series likely have a similar preference. More results and discussion are available in the supplement.

Meta cross-validation, i.e., cross-validation for meta-learning, helps to keep weighting function from over-fitting on meta-data. Table 3 evidence that our algorithms as other meta learning methods can overfit to meta-data. As in Algorithm 1 our proposed methods, both SELAR and SELAR with HintNet, with cross-validation denoted as ‘3-fold’ alleviates the meta-overfitting problem and provides a significant performance gain, whereas without meta cross-validation denoted as ‘1-fold’ the proposed method can underperform the vanilla training strategy.

Table 3: Comparison between 1-fold and 3-fold as meta-data on Last-FM datasets.

| Model | Vanilla | SELAR 1-fold | SELAR 3-fold | SELAR+Hint 1-fold | SELAR+Hint 3-fold |
|-------|---------|--------------|--------------|------------------|------------------|
| GCN   | 0.7898  | 0.7885       | **0.8163**   | 0.7716           | **0.8162**       |
| GAT   | 0.8090  | 0.8293       | **0.8319**   | 0.8002           | **0.8349**       |
| GIN   | 0.7895  | 0.8182       | **0.8211**   | 0.8176           | **0.8255**       |
| SGC   | 0.7725  | 0.7391       | **0.7803**   | 0.7416           | **0.7857**       |

5 Conclusion

We proposed meta-path prediction as self-supervised auxiliary tasks on heterogeneous graphs. Our experiments show that the representation learning on heterogeneous graphs can benefit from meta-path prediction which encourages to capture rich semantic information. The auxiliary tasks can be further improved by our proposed method SELAR, which automatically balances auxiliary tasks to assist the primary task via a form of meta-learning. The learnt weighting function identifies more beneficial meta-paths for the primary tasks. Within a task, the weighting function can adjust the cross entropy like the focal loss, which focuses on hard examples by decreasing weights for easy samples. Moreover, when it comes to challenging and remotely relevant an auxiliary tasks, our HintNet helps the learner by correcting the learner’s answer dynamically and further improves the gain from auxiliary tasks. Our framework based on meta-learning provides learning strategies to balance primary task and auxiliary tasks, and easy/hard (and positive/negative) samples. Interesting future directions include applying our framework to other domains and various auxiliary tasks.
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A Summary

We provide additional experimental results and implementation details that are not included in the main paper due to the space limit. This supplement includes (1) additional experimental results showing that our methods can be further improved by regularization alleviating meta-overfitting, (2) details of datasets, (3) implementation details, (4) task selection, and (5) behaviours of the weighting function at different training stages.

B Meta-Learning and Regularization

We compare the learning strategies: Vanilla, standard training of base models only with the primary task; Graph-MW w/o mp, modified MW-Net [48] for graph neural networks, which learns a primary task for weighting the primary task samples; Graph-MW w/ mp, MW-Net [48] for graph neural networks, which learns training with the primary and auxiliary tasks. SELAR and SELAR+Hint denote our models introduced in the main. Regularized SELAR+Hint is the exactly same model as SELAR+Hint but it is trained with a regularization.

We added a regularizer to HintNet introduced in main paper (Section 3): Avg. Gain, averaged gain of all GNNs from Vanilla.

Table 4 shows that SELAR, SELAR+Hint, and Regularized SELAR+Hint consistently improve the link prediction performance on Last-FM and Book-Crossing datasets, compared to the Vanilla and Graph-MW. Graph-MW with meta-paths shows 0.25% improvement on average on Last-FM while our SELAR+Hint provides 2.5% improvement on average. In particular, Our regularized SELAR+Hint has 2.9% gains compared to the Vanilla. On Book-Crossing, Graph-MW without meta-paths and with meta-paths show 0.6% and 3.8% improvements from the Vanilla respectively. It indicates that the auxiliary tasks are helpful on the primary task on Book-Crossing. Also, our regularized SELAR+Hint has 4.8% absolute improvement compared to the Vanilla. The regularization which is applied to alleviate overfitting improves the overall performance of the SELAR+Hint.

C Details of datasets

We use two datasets (Last-FM, Book-Crossing) for link prediction tasks and two datasets (ACM, IMDB) for node classification tasks. Last-FM and Book-Crossing do not have node features, while ACM and IMDB have node features, which are bag-of-words of keywords and plots. The Last-FM dataset with a knowledge graph have 122 types of edges, e.g., "artist.origin", "musician.instruments.played", "person.or.entity.appearing.in.film", and "film.actor.film", etc. Book-Crossing with a knowledge graph has 52 types of edges, e.g., "book.genre", "literary.series", "date.of.first.publication", and "written.work.translation", etc. ACM has three types of nodes (Paper(P), Author(A), Subject(S)), four types of edges (PA, AP, PS, SP), and labels (categories of papers). IMDB contains three types of nodes (Movie (M), Actor (A), Director (D)), four types (MA, AM, MD, DM) of edges and labels (genres of movies). Statistics of the datasets are in Table 5.

D Implementation details

All the models are randomly initialized and optimized using Adam [64] optimizers. Hyperparameters such as learning rate and weight decay rate are tuned using validation sets for all models. For a fair comparison, the number of layers is fixed to two and the dimension of output node embedding is the same across models. The node embedding z for Last-FM has 16 dimensions and for the rest of the datasets 64 dimensions. Since datasets have a different number of samples, we train models for a different number of epochs; Last-FM (100),
Table 5: Datasets on heterogeneous graphs.

| Datasets                  | # Nodes | # Edges      | # Edge type | # Features |
|---------------------------|---------|--------------|-------------|------------|
| Link prediction           |         |              |             |            |
| Last-FM                   | 15,084  | 73,382       | 122         | N/A        |
| Book-Crossing             | 110,739 | 442,746      | 52          | N/A        |
| Node classification       |         |              |             |            |
| ACM                       | 8,994   | 25,922       | 4           | 1,902      |
| IMDB                      | 12,772  | 37,288       | 4           | 1,256      |

Book-Crossing (50), ACM (200), and IMDB (200). The model with the best validation set performance is chosen for the test. For link prediction, the neighborhood sampling algorithm [4] is used and the neighborhood size is 8 and 16 in Last-FM and Book-Crossing respectively. For node classification, the neighborhood size is 8 in all datasets. The test performance was reported with the best models on the validation sets.

E Task selection

Our proposed methods identify useful auxiliary tasks and balance them with the primary task. In other words, the loss functions for tasks are differentially adjusted by the weighting function learnt by SELAR+HintNet. To analyze the weights of the tasks, we calculate the average of the task-specific weighted loss. Table 6 shows tasks in descending order of the task weights. ‘user-item-actor-item’ has the largest weight followed by ‘user-item’ (primary task), ‘user-item-appearing.in.film-item’, ‘user-item-instruments-item’, ‘user-item-user-item’ and ‘user-item-artist.origin-item’ on the Last-FM. It indicates that the preference of a given user is closely related to other items connected by an actor, e.g., specific edge type ‘film.actor.film’ in the knowledge graph. Moreover, our method focuses on ‘user-item’ interaction for the primary task. On the Book-Crossing data, our method has more attention to ‘user-item’ for the primary task and ‘user-item-literary.series.item-user’ which means that users who like a series book have similar preferences.

Table 6: The average of the task-specific weighted loss on Last-FM and Book-Crossing datasets.

| Meta-paths (Last-FM)              | Avg. | Meta-paths (Book-Crossing) | Avg. |
|-----------------------------------|------|----------------------------|------|
| user-item-actor-item              | 7.675| user-item                   | 6.439|
| user-item                        | 7.608| user-item-literary.series-item-user | 6.217|
| user-item-appearing.in.film-item  | 7.372| item-genre-item             | 6.163|
| user-item-instruments-item        | 7.049| user-item-user-item         | 6.126|
| user-item-user-item               | 6.878| user-item-user              | 6.066|
| item-user-item                    | 6.727| item-user-item              | 6.025|

* primary task

F Weighting function at different training stages

The weighting functions of our methods dynamically change over time. In Fig. 4, each row is the weighting function learnt by SELAR+HintNet for GCN, GAT, GIN, and SGC on Last-FM. From left, columns are from the first epoch, the epoch with the best validation performance, and the last epoch respectively. The positive and negative samples are illustrated in solid and dash lines respectively in Fig. 4. At the begging of training (the first epoch), one noticeable pattern is that the weighting function focuses more on ‘easy’ samples. At the epoch with the highest performance, easy samples are down-weighted and the weight is large when the loss is large. It implies that hard examples are more focused. At the last epoch, most weights converge to zero when the loss is extremely small or large in the last epoch. Since learning has almost been done, the weighting function is learned in a direction that considers both easy and difficult examples less. Especially, for GCN and GAT in the epoch with the highest performance, the weights are increasing and it means that our weighting function imposes that easy samples to smaller importance and more attention on hard samples. Among all tasks, the scale of weights in the primary task is relatively high compared to that of auxiliary tasks. This indicates that our method focuses more on the primary task.
Figure 4: Weight inf function $V(\cdot)$ learnt by SELAR+HintNet on Last-FM on GCN, GAT, GIN and SGC.