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学位(専攻分野)　博士(情報学)

学 位 記 番 号　総研大甲第 2417 号

学位授与の日付　2023 年 3 月 24 日

学位授与の要件　複合科学研究科　情報学専攻
学位規則第6条第1項該当

学 位 論 文 題 目　Representation Learning for Knowledge Graph Completion and Meta-Learning Recommender System

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Summary of Doctoral Thesis

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Title Representation Learning for Knowledge Graph Completion and Meta-Learning Recommender System

Representation learning aims to discover the computationally convenient form of data for a given task. In the deep learning era, representation learning often converts the data into distributed representations. Input data are represented by low-dimensional dense vectors (embeddings) to extract active patterns, and each element in the embeddings involves different input data.

The thesis concerns the representation learning on the knowledge graph. Because representation learning must be discussed with a specific task, the thesis contains two tasks with facts in the knowledge graph as an indispensable component: (1) knowledge graph completion, i.e., adding new facts to the knowledge graph according to existing ones; (2) improving the performance of the recommender system in data-scarce scenarios with facts in a knowledge graph. Task 1 relates to the knowledge graph completion models, and task 2 relates to meta-learning recommender systems. These two tasks can constitute a pipeline: new facts added by the proposed methods for task 1 in a knowledge graph can be used as features for the recommender system in task 2. Both tasks need appropriately learning and adapting facts in the knowledge graph in the embedding form, and this is what all proposed methods in the thesis concern: learning and adapting facts in a knowledge graph as effective distributed representations in the given task.

To be specific, the thesis has two proposed methods for task 1 that modify and extend existing knowledge graph completion models to learn distributed representations for the implicit entity type and type constraints in relations to the link prediction task, which is a task that is directly related to knowledge graph completion. In task 2, the proposed method takes facts in the knowledge graph to alleviate the user-side cold-start problem in the recommender system by adapting these facts in embedding forms and learning other embeddings that represent user interests in item attributes and their contents to generate all parameters in the underlying recommendation network. All proposed methods focus on learning appropriate representations of facts in the knowledge graph for the corresponding task.

Chapter 1 contains the background of representation learning and brief introductions of the knowledge graph, knowledge graph completion models, the supervised and unsupervised methods for incorporating explicit or implicit entity types and type constraints in knowledge graph completion models, and the role of knowledge graphs

in meta-learning recommender systems for the user-side cold-start problem. Chapter 1 also briefly introduces the motivations and contributions of the proposed methods in the thesis and the notation convention used in all following contents.

Chapter 2 dives deeper into the related works for the two tasks in the thesis's scope. Chapter 2 starts with a more detailed introduction to the knowledge graph. And comes to the different types of knowledge graph completion models: the bilinear models, the translational models, and models in other forms. Next, it reviews the type representation learning in knowledge graph completion models, including the supervised methods for learning explicit entity type and type constraints in relations and the unsupervised methods for learning implicit entity type and type constraints in relations and the drawbacks of existing methods. These introductions are about task 1. For task 2, Chapter 2 introduces the concept of meta-learning and its vital component, the model-agnostic meta-learning framework, and the definition of hypernetwork, which is a vital part of the proposed method. It also discusses how facts in the knowledge graph help meta-learning alleviate the user-side cold-start problem.

Chapter 3 proposes a method for bilinear knowledge graph completion models. This chapter concerns task 1 in the thesis. The proposed method takes a type-agnostic bilinear knowledge graph completion model as its base model, and extends the score function to consider entity compatibility by using learned implicit type constraint representations. Unlike existing unsupervised methods for learning implicit entity type and type constraints with two separate feature spaces: one for the implicit entity type and type constraint representations and the other for entity and relation embeddings, the proposed method has a consistent feature space. It uses entity embedding locations as the implicit entity type representation and learns implicit type constraint representations for relations. It defines a statistic, the entity co-occurrence, and refines all embeddings (entity embeddings, relation embeddings, and the implicit type constraint embeddings for relations) according to the entity co-occurrence. Two loss functions have been induced in the proposed method: one for learning all embeddings and the other for refining the locations of entity embeddings and implicit type constraint embeddings. Two experiments on link prediction and entity clustering are conducted on three widely used datasets, namely, FB15k-237, WN18RR, and YAGO3-10. The results show that the proposed method can improve the performance of the type-agnostic bilinear knowledge graph completion model (the base model.) It has a better performance on the task of link prediction for non-domain-specific knowledge graphs, FB15k-237 and YAGO3-10, compared to the baseline methods. The entity clustering experiment result shows that it can capture the entity type by the entity embedding location.

Chapter 4 extends the method proposed in Chapter 3 to bilinear and translational knowledge graph completion models. It is about task 1 in the thesis. Chapter 4 formalizes the intuition and enables the proposed method to capture multiple type constraints in relations. The proposed method eliminates the dependency on the entity

co-occurrence in Chapter 3. Following the similar intuition in Chapter 3, the method in Chapter 4 uses entity embedding locations as the indicator for implicit entity types and extends the score function to consider type compatibility. It also uses a type-agnostic knowledge graph completion model (bilinear or translational) as its base model. It has two loss functions for learning and adjusting all embeddings. Unlike the one in Chapter 3 and other existing methods, it has multiple implicit type constraint embeddings for every relation and hence can capture the various implicit type constraints.

Experiments on link prediction and entity clustering are conducted. The datasets in use are the same as those in Chapter 3. Compared to the existing methods, the proposed method has a better improvement of the most underlying type-agnostic bilinear or translational knowledge graph completion models on the task of link prediction on all three datasets. The entity clustering experiment results show that the proposed method can capture multiple type constraints and has a better entity embedding distribution in the feature space that captures the corresponding entity type.

In addition, ablation experiments and discussions on the effect of the number of type constraint embeddings have been made. Furthermore, Chapter 4 compares the method in it with the method in Chapter 3. The experiment results show that for bilinear models if the dataset is with a high entity co-occurrence, the method in Chapter 3 outperforms the method in Chapter 4, and the method in Chapter 4 has a better performance when the entity co-occurrence is low.

Chapter 5 is about representation learning on the knowledge graph in the recommender system for the user-side cold-start problem, i.e., task 2. The proposed method takes attribute contents extracted from the knowledge graph to describe items and uses an underlying recommender network (a neural network) to predict users' interests in items. All parameters in the underlying recommender network are generated by another neural network, the hypernetwork, in the proposed method. Every user has two user-specific embeddings, a user embedding as the input for the recommender network and another user interest embedding as the input for the hypernetwork. The hypernetwork has a user-interest basis to span the feature space for inputs that feed into the other layers to generate the underlying network's parameters. Unlike the baseline models based on the model-agnostic meta-learning framework that uses direct parameter sharing, i.e., the learned initialization parameters for the recommender network are shared directly across all users, the proposed method uses indirect parameter sharing by the user interest basis. The proposed method decouples the connections between the shared parameters for all users and the item attribute content embeddings. In addition, the parameters in the underlying recommender network that transfer contents in different item attributes constitute the representations of user interests in attributes rather than the contents of item attributes. It is difficult for the model-agnostic meta-learning method to capture the user interests in item attributes because the initialization parameters are learned by the item attribute content embeddings.

The experiments are conducted on three datasets, Movielens-10m, TokyoTV, and Book datasets. The performances of all models are tested in two scenarios, namely, cold users with warm items and cold users with cold items, except for Tokyo TV dataset. Experiments on Tokyo TV dataset only considers the cold users with warm items case because it has a very limited number of users. Experiment results show that the proposed method outperforms other baseline models for the cold users with warm items case on all datasets. For Book dataset, the proposed method is only outperformed by one baseline model in the cold user cold item scenario. The possible reasons are discussed. The visualization of components that capture user interests in attributes shows that the proposed method can capture the corresponding user interests by the hypernetwork. For those attributes that attract the user, the hypernetwork would generate more prominent elements in the corresponding components and feed larger values into the next layer.

In addition, the ablation experiments on the various numbers of examples in the support and query sets are conducted on Movielens-10m. The experiment results show that the proposed method outperforms other baseline models for most evaluation measures under the different numbers of examples in support and query sets.

Furthermore, ablation experiments on the effect of different item attributes for the performance are conducted on all three datasets with the cold users with warm items setting and discuss the effect of different attributes on different datasets.

Chapter 6 concludes the thesis. It summarizes the contents in Chapter 2 to Chapter 5, and provides some probable interesting investigation ideas for the proposed methods to the readers.

Form8 : Separate Sheet
（様式８・別紙１）

Results of the doctoral thesis screening

博士論文審査結果

Name in Full
氏　　名　　Lu Yuxun

Title
論文題目　　Representation Learning for Knowledge Graph Completion and Meta-Learning Recommender System

表現学習(Representation Learning)は，与えられたタスクに対して，有用なデータの表現を学習することを目的とする．本論文では，知識グラフに対する効果的な表現学習手法の開発に取り組んだ．表現学習は，具体的なタスクとともに議論される必要があるため，本論文では，知識グラフを取り扱うための表現学習における重要なタスクとして，(1) 既知のファクトを使って新しいファクトを知識グラフに追加する知識グラフ補完，および，(2) データ不足のシナリオにおいて，知識グラフ上のファクトを利用した推薦システムの二つのタスクに取り組んだ．どちらのタスクも、知識グラフ上のファクトを適切な表現で学習する必要があり，本論文で提案する手法は，与えられたタスクに対して，知識グラフに関する適切な分散表現をどのように学習するかが課題となる．

本学位論文は，全６章からなる．第１章「Introduction」では，知識グラフにおける表現学習の問題に対して，研究の背景を述べると共に，本論文の貢献について説明している．

第２章「Related Work」では，本論文の理解に必要となる知識グラフ埋め込み手法や，関連研究について述べている．

第３章「Unsupervised Type Constraint Inference in Bilinear Knowledge Graph Completion Models」では，一番目の課題となる知識グラフ補完に関して，教師無しで型の制約を使った表現学習を行う新たな知識グラフ補完モデルを提案している．そして，その有効性を実験的に示している．

第４章「Enhancing Knowledge Graph Completion Models with Unsupervised Type Representation Learning」では，引き続き，一番目の課題となる知識グラフ補完に関して取り組み，第３章の手法が持つ共起性が低い場合などの問題点を解決した新たな表現学習手法を提案し，その有効性を実験的に示している．

第５章「Hypernetwork based Meta-Learning Recommender System for the User-side Cold-start Problem」では，二番目の課題となる推薦システムに関して取り組み，ハイパーネットワークを用いて知識グラフに関する新たな表現学習を行う推薦システムの手法を提案し，その有効性を実験的に示している．

最後の第６章「Conclusion」では，博士論文の総括を行うと共に，展望を述べ，結論をまとめている．

公開発表会では，博士論文の章立てに従って発表が行われた．その後に行われた論文審査会及び口述試験では，審査委員からの質疑に対して的確に回答がなされた．

質疑応答の後に審査委員会を開催し，審査委員で議論を行った．審査委員会では，出願者の博士研究が，二つの課題において，新たな視点を導入し，従来手法を上回る適切な表

現学習ができる方法を構築した点で評価された．また，本論文により，知識グラフに関する新たな表現学習方法が提示されたことで，知識グラフの応用の可能性が広がるため，基盤技術開発という観点からも評価された．

以上を要するに，本学位論文は，知識グラフに関して，適切な表現学習を行う手法を示したものであり，研究分野の発展に貢献しているという点で学術的価値が大きい．また，本学論文の成果は，学術雑誌論文２件，査読付き国際会議論文１件として発表され，社会的な評価も得ている．以上の理由により，審査委員会は，全員一致で本学位論文が学位の授与に値すると判断した．