

# LightGCN+

## A Graph Convolutional Network for Matrix Completion

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**Abstract**—Personalized recommendation systems are critical for businesses aiming to enhance user experience and satisfaction. In this study, we address the task of collaborative filtering through the lens of matrix completion. While the primary objective of collaborative filtering is to rank preferences for unobserved user-item interactions, accurate rating predictions can offer deeper insights into user preferences, thereby informing better decision-making across various use cases.

In this work, we propose LightGCN+, an advanced graph convolutional encoder-decoder model that extends the original LightGCN architecture. Whereas LightGCN was primarily designed for item recommendation through ranking, LightGCN+ is tailored to predict real-valued ratings. LightGCN+ leverages the graph convolutional framework of LightGCN, modified to handle real-valued rating matrices. Additionally, we introduce a multi-layer perceptron (MLP) at the decoder stage. Our approach proves to be robust, achieving comparable performance to state-of-the-art models.

### I. INTRODUCTION

Collaborative filtering (CF) is a widely used approach in recommendation systems that leverages historical user-item interactions to predict future preferences [1]. The core idea is to exploit patterns in the collective behavior of users to make personalized recommendations. A common formulation of CF is as a matrix completion problem, where the goal is to predict missing entries in a sparse user-item interaction matrix [2]. Traditional matrix factorization techniques like singular value decomposition have been successful for CF [1]. More recently, deep learning approaches have achieved state-of-the-art performance on CF tasks. Models like Neural Collaborative Filtering [3] and Deep Matrix Factorization [4] use neural networks to learn nonlinear latent representations. Graph-based models have emerged as a powerful paradigm for CF by naturally representing user-item interactions as a bipartite graph [5]. Graph Convolutional Networks (GCNs) in particular have shown promising results by leveraging higher-order connectivity information [6]. LightGCN [7] simplified the GCN architecture for recommendation by removing feature transformation and nonlinear activation, demonstrating strong performance with a lightweight design. In this work, we propose LightGCN+, an extension of LightGCN tailored for explicit rating prediction rather

than ranking. While LightGCN focuses on binary interactions, LightGCN+ is designed to handle real-valued rating matrices. We modify the graph convolution operation to incorporate rating information and introduce a multi-layer perceptron decoder to predict continuous ratings. This allows our model to capture fine-grained user preferences beyond just positive interactions. The key contributions of this work are:

- We extend LightGCN to handle explicit rating prediction for collaborative filtering.
- We propose a novel graph convolution formulation that leverages rating information.
- We introduce a flexible decoder architecture to map latent representations to ratings.
- We demonstrate competitive performance compared to state-of-the-art rating prediction models.

The rest of this paper is organized as follows: Section II describes our proposed LightGCN+ model in detail. Section III presents the experiments conducted on the ETHZ-CIL-Collaborative-Filtering-2024 dataset. Section IV presents the results, Section V discusses them, and Section VI concludes the paper.

### II. MODEL AND METHODS

#### A. Problem Formulation

Given a sparse user-item rating matrix  $R \in \mathcal{R}^{m \times n}$ , with observed ratings  $r_{u,i}$  for observed interaction pairs  $(u, i) \in \Omega$ , the task of matrix completion consists of predicting the missing ratings in  $R$ .

Graph based methods approach matrix completion by representing the user-item interactions as a bipartite graph  $G = (U, I, E)$ , where  $U$  and  $I$  are the sets of users and items (nodes), respectively, and  $E$  is the set interactions (edges) with weights  $r_{u,i}$ . The adjacency matrix  $A \in \mathcal{R}^{(m+n) \times (m+n)}$  of the bipartite graph  $G$  is defined as:

$$A = \begin{bmatrix} 0 & R \\ R^T & 0 \end{bmatrix} \quad (1)$$

The adjacency matrix may be preprocessed using different normalization techniques. We define the standardized adja-

gency matrix  $\hat{A}$  as:

$$\hat{A} = \begin{bmatrix} 0 & Z_{\text{col}} \\ Z_{\text{row}}^T & 0 \end{bmatrix} \quad (2)$$

where  $Z_{\text{col}}$  and  $Z_{\text{row}}$  represent the standardized user-item ratings, derived using z-score normalization on the columns and rows of  $R$ , respectively.

### B. Model Architecture

The LightGCN+ model consists of an encoder-decoder architecture, with the encoder comprising a multi-layer graph convolutional network and an aggregation function, and the decoder consisting of a multi-layer perceptron (MLP).

Users and items are represented by node embeddings  $e_v \in \mathbb{R}^K$ , for all  $v \in U \cup I$ , which are learned during training.

### C. Encoder

The encoder of LightGCN+ takes the embedding matrix  $E \in \mathbb{R}^{(m+n) \times K}$  and the standardized adjacency matrix  $\hat{A}$  as inputs, and generates hidden representations  $H$ , which are then passed to the decoder.

1) *Graph Convolution*: Graph convolution is a form of message passing over the graph, where each node updates its representation by aggregating information from its neighbors, reflecting the local graph structure. Applying this operation multiple times, in a layered fashion, enables the model to capture higher-order relationships between nodes. For a given node  $v$ , the hidden representation  $h_v^{(l+1)}$  at layer  $l+1$  is computed as:

$$h_u^{(l+1)} = \sum_{i \in N(u)} \frac{z_{\text{col},u,i}}{\sqrt{|N(u)| \cdot |N(i)|}} h_i^{(l)} \quad \forall u \in U \quad (3)$$

$$h_i^{(l+1)} = \sum_{u \in N(i)} \frac{z_{\text{row},u,i}}{\sqrt{|N(u)| \cdot |N(i)|}} h_u^{(l)} \quad \forall i \in I \quad (4)$$

where  $N(v)$  is the set of neighbors of  $v$ . Finally, the symmetrical normalization term  $\sqrt{|N(u)| \cdot |N(i)|}$  ensures that the hidden representations are scaled appropriately. Note that the hidden representations  $h_v^{(0)}$  at the input layer correspond to the learnable embeddings  $e_v$ .

The  $L$ -layered convolution operation can be expressed more compactly as:

$$H^{(l+1)} = \tilde{A} H^{(l)} \quad (5)$$

where  $\tilde{A} = D^{-\frac{1}{2}} \hat{A} D^{-\frac{1}{2}}$  is the normalized standardized adjacency matrix,  $D$  is the diagonal degree matrix of  $\hat{A}$ , and  $H^{(l)}$  is the matrix of hidden representations at layer  $l$ .

2) *Aggregation*: After  $L$  layers of graph convolution, the hidden representations  $h_v^{(L)}$  of node  $v$  are aggregated to obtain the final representations. In contrast to the original LightGCN model, instead of averaging we use concatenation as aggregation function:

$$h_v = h_v^{(0)} \parallel h_v^{(1)} \parallel \dots \parallel h_v^{(L)} \quad (6)$$

where  $\parallel$  denotes concatenation operator. Concatenating layered representations is a natural choice of aggregation for LightGCN+, given the use of a multi-layer perceptron (MLP) as the decoder.

### D. Decoder

The decoder of LightGCN+ is a multi-layer perceptron (MLP) that takes the concatenated hidden representations  $h_u$  and  $h_i$  for a user-item pair  $(u, i)$  and outputs the predicted rating  $\hat{r}_{u,i}$ :

$$\hat{r}_{u,i} = \text{MLP}(h_u \parallel h_i) \quad (7)$$

During training, user-item pairs  $(u, i) \in \Omega$  (the set of observed interactions), while during inference,  $(u, i) \notin \Omega$ .

### E. Objective Function

A natural choice of loss function for rating prediction is the mean squared error (MSE) between the predicted ratings  $\hat{R}$  and the true ratings  $R$ :

$$\mathcal{L} = \frac{1}{|\Omega|} \sum_{(u,i) \in \Omega} (\hat{r}_{u,i} - r_{u,i})^2 \quad (8)$$

Other loss functions could be used, depending on the specific use case. Learnable parameters of the model include user and item embeddings and the parameters of the MLP.

## III. EXPERIMENTS

### A. Dataset

We evaluate the performance of LightGCN+ on the ETHZ-CIL-Collaborative-Filtering-2024 dataset. The dataset consists of 10,000 users and 1,000 items, with 1176952 observed ratings, which corresponds to a sparsity of 88.23%. The ratings are integers in the range  $[1, 5]$ , with a mean rating of 3.86 and a standard deviation of 1.12.

### B. Preprocessing

We find that normalizing  $\hat{A}$  using  $Z_{\text{col}}$  and  $Z_{\text{row}}$ , as shown in Equation 2, significantly enhances the model's generalization ability. The rationale behind this dual standardization is that it reduces biases and variances from individual user or item rating patterns. This makes them comparable across the graph, which is crucial for the effectiveness of the convolution operation.

### C. Training

The model is trained end-to-end using the Adam optimizer. We avoid mini-batching to ensure that the model can learn the global structure of the graph, while also speeding up convergence. To prevent overfitting we tune the weight decay strength  $\lambda$  and the dropout rate  $p$  accordingly. We initialize the embeddings using a normal distribution with tunable standard deviation  $\sigma_{\text{init}}$ , and the MLP weights using Xavier initialization [8]. Different models are trained for different amounts of epochs, ranging between 1000 and 5000.

#### D. Model Design Choices

During the design phase of the model we conduct several experiments to determine the best architecture for LightGCN+.

1) *Graph Convolution*: To normalize  $\hat{A}$ , we follow the standard GCN [9] approach, using the symmetric normalization term  $\sqrt{|N(u)| \cdot |N(i)|}$ .

2) *Layer Aggregation*: We verify the hypothesis that concatenation is a better choice of aggregation function than averaging, both by averaging using equal weights  $\alpha^{(l)} = 1/(L+1)$  and by learning the weights  $\alpha^{(l)}$ . We also experiment with graph attention [10], to learn the weights  $\alpha_{u,i}^{(l)}$  for each user-item pair. We find that attention performs best with  $L = 1$ , but does not enhance model performance.

3) *MLP Architecture*: We find that the choice of activation function and hidden layer sizes has a significant impact on the model's performance. Thus, we leave the MLP architecture to be determined entirely in the hyperparameter tuning phase. However, we decide to use dropout, following the results of [5].

#### E. Hyperparameter Tuning

To get an approximation of the individual hyperparameters' impact on the model's performance, we perform an initial grid-search over the following ranges:

- Initialization standard deviation  $\sigma_{\text{init}} \in [0.01, 0.1]$
- Learning rate  $\eta \in [0.001, 0.1]$
- Weight decay  $\lambda \in [1e-5, 1e-3]$
- Dropout rate  $p \in [0.1, 0.7]$
- Activation function  $f \in \{\text{ReLU}, \text{LeakyReLU}, \text{GELU}\}$
- Number of convolutional layers  $L \in [1, 10]$
- Embedding dimension  $K \in [24, 38]$
- MLP hidden layer sizes  $C$ :  
 $\{(12K, 6K), (10K, 5K), (8K, 4K), (4K, 2K)\}$

To narrow down the search space, we set the activation function to GELU, as it consistently outperforms other activation functions, and perform a second grid search over different values for  $\sigma_{\text{init}}$ ,  $\eta$ ,  $\lambda$ ,  $p$ , and  $f$ , testing them on a simple working model  $L = 4$ ,  $K = 32$ , and  $C = (8K, 4K)$ .

Finally, we tune the remaining and most impactful hyperparameters in the following ranges:

- Embedding dimension:  $K \in [16, 32]$
- Number of convolutional layers:  $L \in [1, 6]$
- MLP hidden layer sizes:  $\{(12K, 6K), (10K, 5K)\}$

We find that multiple models with different hyperparameters can achieve similar performance, but there is a clear range of best performing hyperparameters.

#### F. Ensemble Model: LightGCN++

We take advantage of the insights gained in the tuning phase of the base model, defining a LightGCN++ model, which ensembles the top  $M$  performing LightGCN+ models of the grid search. We find that this additional step makes

predictions more robust and improves the overall performance of the model.

The ensembled prediction matrix is obtained by computing a weighted average of the predictions of the individual models:

$$\hat{R} = \sum_{m=1}^M w_m \hat{R}_m \quad (9)$$

The ensemble weights  $w_m$  are determined by splitting the original validation set used during training, into a set for fitting the ensemble weights and a set for evaluating the ensemble's performance. To prevent overfitting we cap the number of models in the ensemble at  $M = 10$ .

#### IV. RESULTS

Our results, summarized in Table I, compare the performance of various configurations of LightGCN+, including the LightGCN+ ensemble, against two baseline models: Neural Collaborative Filtering (NCF) and Alternating Least Squares (ALS). We use the root mean squared error (RMSE) as the evaluation metric.

Model		RMSE Score
LightGCN++	Ensemble	0.9771,
LightGCN+	K=28, L=4, C=(12K, 6K)	0.9844
LightGCN+	K=28, L=5, C=(12K, 6K)	0.9875
NCF		1.0940
ALS		1.4260

Table I  
MODEL PERFORMANCE COMPARISON

#### A. LightGCN+

The LightGCN+ variants significantly outperformed the baseline models, even with a single convolutional layer. Performance improved further with the addition of multiple convolutional layers, with the highest performance achieved by models with  $L = 4, 5, 6$ . The optimal embedding dimension  $K$  was found to be in the interval  $K = [28, 30]$ . Models with higher  $K$  values tended to have unstable training runs and overfit quickly to the training data. The MLP architecture significantly impacted performance, with a two-layer MLP with hidden layer sizes around  $10K$  in first layer and  $5K$  in the second layer performing best.

The highest-performing model was trained with the following hyperparameters:

- Embedding dimension  $K = 28$
- Number of convolutional layers  $L = 5$
- MLP hidden layers sizes =  $[12K, 6K]$
- Initialization standard deviation:  $\sigma_{\text{init}} = 0.075$
- Learning rate:  $\eta = 0.01$
- Weight decay:  $\lambda = 5e-5$
- Dropout:  $p = 0.5$
- Activation function: GELU

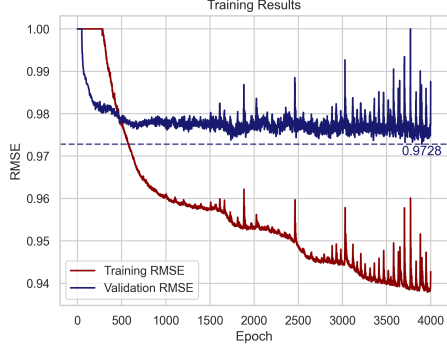


Figure 1. Train run of the top performing model

These parameters also stabilized the training process most consistently. Figure 1 shows a training run of this model.

Finally, ensembling multiple models further improved performance, with the LightGCN++ ensemble model achieving the best RMSE score of 0.9771.

### B. Baselines

To evaluate the robustness and effectiveness of our proposed LightGCN+ model, we compare its performance against two well-established baseline models: Alternating Least Squares (ALS) and Neural Collaborative Filtering (NCF).

1) *Alternating Least Squares (ALS)*: The Alternating Least Squares (ALS) algorithm iteratively optimizes user and item matrices to factorize the interaction matrix. It alternates between fixing the user matrix and optimizing the item matrix, and vice versa, to minimize the reconstruction error. We used a hidden dimension of 10 for the latent factors. When evaluated on the public test set, the ALS model achieved a Root Mean Squared Error (RMSE) score of 1.426.

2) *Neural Collaborative Filtering (NCF)*: The Neural Collaborative Filtering (NCF) model employed in this study consists of two embedding layers followed by a feed-forward neural network. We use the ReLU activation function. The model was trained using the Adam optimizer with a learning rate of 0.001 and Mean Squared Error (MSE) loss. The embedding dimension was set to 16. After training for 25 epochs, the NCF model achieved an RMSE score of 1.094 on the public test set.

## V. DISCUSSION

The results of our experiments demonstrate the effectiveness of the LightGCN+ model in the task of collaborative filtering through matrix completion. Our model consistently outperformed the baseline models, Alternating Least Squares (ALS) and Neural Collaborative Filtering (NCF), and demonstrates competitive performance compared to state-of-the-art models.

The competitive performance of LightGCN+ can be attributed to several key factors. Firstly, the proposed dual standardization of the adjacency matrix  $\hat{A}$ , using z-score normalization, significantly enhances the graph convolution operation. Secondly, the use of a multi-layer perceptron (MLP) at the decoder stage enables the model to capture this information directly, allowing it to make accurate predictions. Finally, the ensemble approach, LightGCN++, further boosts performance by combining the strengths of multiple models. This method effectively reduces variance and improves the robustness of the predictions, demonstrating the utility of model aggregation in collaborative filtering tasks.

Our model integrates the simplicity of the LightGCN architecture with the flexibility of an MLP decoder. This combination allows the model to naturally capture higher-order relationships between nodes in the graph without the need for complex architectures or feature transformations. In addition, the model is also highly flexible, since it can be easily adapted to different datasets and domains by tuning only a few hyperparameters.

Our findings underscore the importance of leveraging graph convolutional networks for collaborative filtering tasks. Future research could explore several avenues to further enhance the performance of LightGCN+. One promising direction is the integration of advanced graph techniques, such as attention mechanisms, to dynamically weigh the importance of neighboring nodes, or sampling methods to improve the scalability of the architecture. Finally, applying LightGCN+ to diverse datasets and domains would further validate its robustness and applicability in real-world scenarios.

## VI. CONCLUSION

In this paper, we introduced LightGCN+, an advanced graph convolutional network model for collaborative filtering through matrix completion. Our model extends the original LightGCN architecture [7] to handle explicit rating prediction, incorporating a novel graph convolution formulation and a flexible decoder architecture. Through extensive experiments on the ETHZ-CIL-Collaborative-Filtering-2024 dataset, we demonstrated that LightGCN+ consistently outperforms traditional baseline models and achieves competitive performance compared to state-of-the-art approaches.

Our work highlights the potential of graph-based methods in recommendation systems and opens up several avenues for future research, including the integration of advanced graph techniques and exploration of the model's performance across diverse domains. As personalized recommendation systems continue to play a crucial role in enhancing user experience, LightGCN+ represents a significant step forward in addressing the challenges of collaborative filtering.

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