

Soft Reasoning Paths for Knowledge Graph Completion

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Abstract

Reasoning paths are reliable information in knowledge graph completion (KGC) in which algorithms can find strong clues of the actual relation between entities. However, in real-world applications, it is difficult to guarantee that computationally affordable paths exist toward all candidate entities. According to our observation, the prediction accuracy drops significantly when paths are absent. To make the proposed algorithm more stable against the missing path circumstances, we introduce soft reasoning paths. Concretely, a specific learnable latent path embedding is concatenated to each relation to help better model the characteristics of the corresponding paths. The combination of the relation and the corresponding learnable embedding is termed a soft path in our paper. By aligning the soft paths with the reasoning paths, a learnable embedding is guided to learn a generalized path representation of the corresponding relation. In addition, we introduce a hierarchical ranking strategy to make full use of information about the entity, relation, path, and soft path to help improve both the efficiency and accuracy of the model. Extensive experimental results illustrate that our algorithm outperforms the compared state-of-the-art algorithms by a notable margin. The code will be made publicly available after the paper is officially accepted.

1 Introduction

Knowledge graphs (KGs) have emerged as a foundational framework for organizing and utilizing structured information in mission-critical domains, including question answering [Sun *et al.*, 2019a; Dinan *et al.*, 2019], recommendation systems [Huang *et al.*, 2018], and information retrieval [Edge *et al.*, 2024]. Structurally, KGs are composed of triples

(h, r, t) , where h denotes the head entity, r specifies the semantic relationship and t identifies the tail entity. However, despite their practical importance, KGs often exhibit incompleteness. This inherent limitation underscores the importance of Knowledge Graph Completion (KGC) techniques, which play a pivotal role in automating the knowledge graph construction and validation processes.

Existing knowledge graph completion methods can be broadly categorized into two main categories: embedding-based methods [Bordes *et al.*, 2013; Sun *et al.*, 2019b; Balazevic *et al.*, 2019] and text-based methods [Wang *et al.*, 2022a; Qiao *et al.*, 2023; Chen *et al.*, 2023]. With the advent of language models, their advanced linguistic understanding capabilities have significantly improved the performance of text-based methods. Taking full advantage of the semantic relationships between candidate tail entities and the query, text-based approaches have gained widespread adoption due to their substantial improvements in accuracy.

Recent studies [Iwamoto and Kameiwa, 2024; Zha *et al.*, 2021] have investigated the incorporation of reasoning path information into text-based knowledge graph completion, where reasoning paths serve as valuable indicators for predicting entity relationships, leading to significant improvements in prediction accuracy. However, our empirical analysis reveals that these algorithms exhibit a marked decrease in performance when reasoning paths are not available. Furthermore, through a detailed statistical evaluation, we found that approximately 82% of the triples in the WN18RR test set and roughly 27% of the triples in the FB15K-237 test set do not contain valid 2-hop or 3-hop reasoning paths. This observation suggests that a substantial portion of entities lack accessible reasoning paths that could be utilized for relation prediction. Consequently, this limitation severely constrains the performance ceiling of these methods. Moreover, prior path-based methods require reasoning path searches and ranking for all candidate tail entities to achieve high prediction accuracy, resulting in long testing times and limiting their practical application in real-world scenarios.

To address the aforementioned challenges, we propose a knowledge graph completion method based on soft reasoning

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paths (SRP-KGC). Specifically, the proposed soft reasoning paths are formed by combining relations and learnable embeddings. By assigning an independent learnable embedding to each type of relation and then aligning it with the paths of that relation, our approach enables the modeling of various path information corresponding to the same relation using soft reasoning paths. In cases where reasoning paths are missing, soft reasoning paths effectively fill the gaps, thereby enhancing the stability and robustness of the algorithm in such scenarios.

Additionally, to improve the scalability of the algorithm and mitigate the negative impact of extensive path searches on efficiency while maintaining the accuracy of the ranking, we propose a hierarchical ranking strategy. This approach utilizes a combination of relation, reasoning path, and soft reasoning path evaluation metrics to perform tiered filtering, effectively ensuring the scalability of the algorithm for test entities. Our contributions are summarized as follows:

- We identify an overlooked issue of performance degradation in path-based algorithms when paths are missing and propose a KGC method based on soft reasoning paths that enhances the algorithm’s stability against the candidate entities whose path information is absent.
- We propose a hierarchical ranking method based on relations, reasoning paths, and soft reasoning paths, which alleviate the scalability defect of the path-based algorithm and enhances its practical value.
- Extensive experimental results demonstrate that the soft reasoning paths constructed based on trainable embeddings can effectively narrow the semantic gap between relations and their corresponding holistic reasoning paths, while enhancing the discriminative ability of relational representations in path discrimination.

2 Related work

2.1 Knowledge Graph Completion

Existing methods can be broadly classified into two categories: embedding-based methods and text-based methods. Embedding-based methods represent entities and relations as vectors. Translational models, such as TransE [Bordes *et al.*, 2013] and TransH [Wang *et al.*, 2014], are computationally efficient but struggle to capture complex relationships. Tensor decomposition models like ComplEx [Trouillon *et al.*, 2016] are effective at modeling diverse patterns but face scalability challenges. Graph neural networks, such as CompGCN [Vashishth *et al.*, 2019], enhance entity and relation representations by incorporating neighborhood information, though they require careful design to handle complex data structures. Text-based methods utilize textual descriptions or context associated with entities and relations to perform knowledge graph completion (KGC). For instance, KBERT [Yao *et al.*, 2021] employs BERT to encode triples as text sequences and classifies their validity. SimKGC [Wang *et al.*, 2022a] and C-LMKE [Wang *et al.*, 2022b] propose a contrastive learning framework to build more discriminative knowledge graph models. Despite their potential, text-based methods typically determine the target triple based solely on

the similarity between the pair (h, r) and candidate entity text embeddings, often overlooking other valuable auxiliary information.

2.2 Reasoning path in KGC

In knowledge graph completion, reasoning plays a pivotal role in accurately predicting missing links or facts. While traditional approaches typically rely on direct embeddings of entities and relations, reasoning path-based methods enhance the model’s capacity to capture higher-order relationships between entities. These methods focus on identifying paths through the graph that may represent logical or semantic relations, thereby guiding the completion process. GraIL [Teru *et al.*, 2020] utilizes GNNs to evaluate the relevance between reasoning path relations and the target relation, while BERTRL [Zha *et al.*, 2021] employs BERT to encode reasoning paths and candidate triples to compute their scores. ReDistLP [Iwamoto and Kameiwa, 2024] completes the task by aggregating information from various reasoning paths. These methods have demonstrated strong performance in inductive KGC tasks. However, they face challenges when dealing with situations involving missing reasoning paths and a large number of candidate triples.

2.3 Prompt tuning

Prompt tuning, through the use of prompts, enables pre-trained language models (PLMs) to achieve exceptional performance across various downstream tasks with minimal computational cost. CSProm-KG [Chen *et al.*, 2023] is the first work to incorporate prompt tuning into KGC tasks. By applying prefix tuning in conjunction with GNNs, it effectively completes the KGC task under low-parameter conditions. AutoKG [Zhu *et al.*, 2023] also explores the application of prompt engineering within the knowledge graph domain. A frequently overlooked aspect of prompt tuning is its capacity to learn general representations of data during the training process, a feature that our method leverages. This enables our model not only to handle specific tasks but also to extract and utilize general patterns from the data, thereby enhancing the model’s generalization ability and overall performance.

3 Method

3.1 Problem Statement

Given a knowledge graph $G = \{(h, r, t) \mid h, t \in E, r \in R\}$, where E and R are the set of entities and relations of the KG, respectively. h and t are the head and tail entities, while r is the relation between them. The KGC task aims to predict the missing triples. In the entity ranking evaluation protocol, tail entity prediction $(h, r, ?)$ ranks all entities based on h and r , while head entity prediction $(?, r, t)$ does the same. In this paper, we follow the SimKGC [Wang *et al.*, 2022a] setup and add an inverse triple (t, r^{-1}, h) for each triple (h, r, t) , simplifying the task to only tail entity prediction.

3.2 Network Framework based on contrastive learning

The proposed SRP-KGC method is based on a dual-encoder contrastive learning architecture and consists of three main

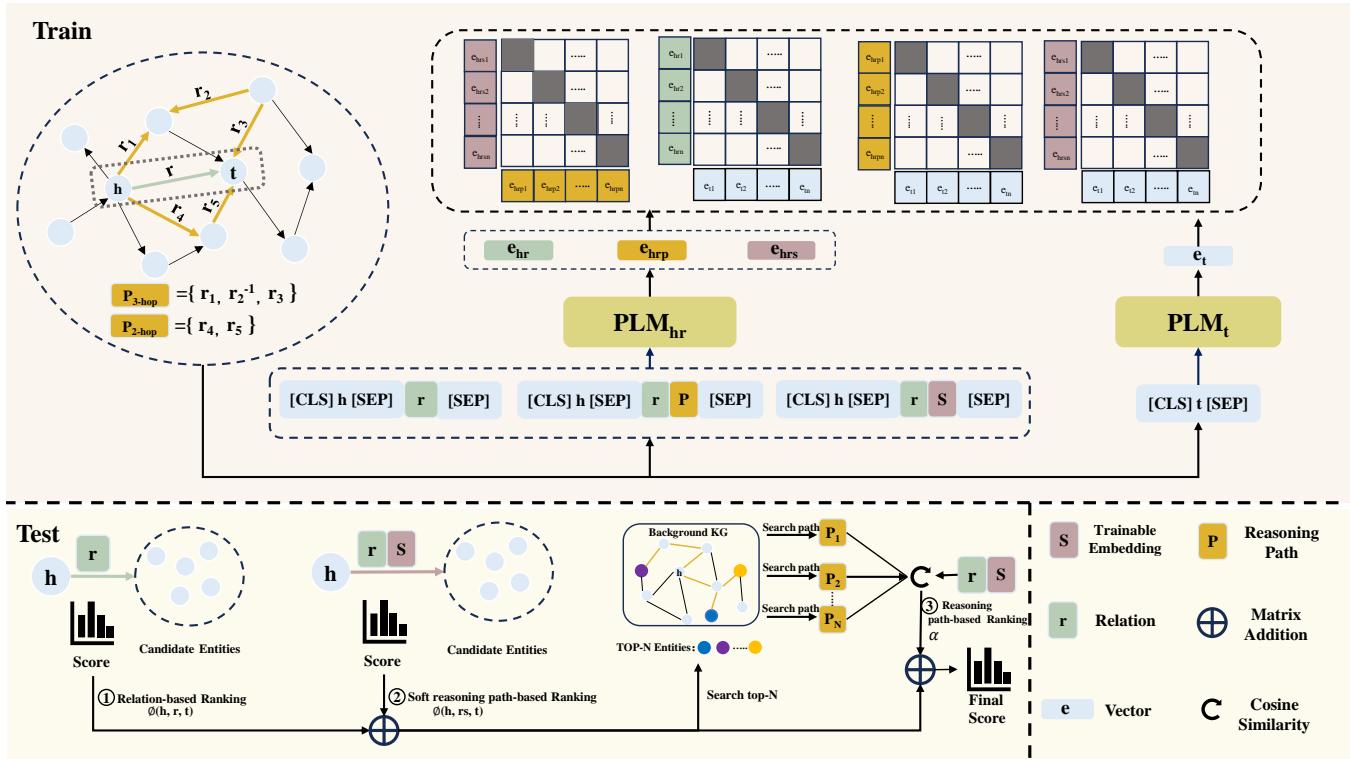


Figure 1: SRP-KGC Framework: During the training process, we introduced three types of positive samples. By incorporating these diverse positive samples, the model’s ability to understand reasoning paths was enhanced, while the soft reasoning path learns the generalized representation of reasoning paths. In the testing phase, we employed a hierarchical ranking strategy, combining information from entities, relations, soft reasoning paths, and reasoning paths to further improve the model’s accuracy.

components. First, we use multi-type positive samples for contrastive learning, introducing reasoning paths during the training phase to guide the model in enhancing its ability to discriminate reasoning paths. Next, we introduce soft reasoning paths, and by aligning soft reasoning paths with reasoning paths, we guide the model to learn generalized path representations of the corresponding relations to alleviate the issue of missing reasoning paths. Finally, during the testing phase, to fully utilize the information from entities, relations, reasoning paths, and soft reasoning paths, we introduce a hierarchical ranking strategy, combining multiple sources of information to further improve the accuracy of predictions.

3.3 Multi-type positive samples

In the contrastive learning framework, we use three types of positive samples: relation positive samples, reasoning path positive samples, and soft reasoning path positive samples. Relation positive samples are triples (h, r, t) where the head and tail entities are directly related by relation r . Reasoning path positive samples replace the direct relation with a reasoning path from h to t , while soft reasoning path positive samples involve learning a generalized representation of the reasoning path through trainable embeddings, which will be explained in the next section.

Reasoning paths are the foundation of our approach. To ensure their generalization, we focus on relations and ignore entity information, represented as $p = \{r_1, r_2, \dots\}$. Paths are

classified based on the number of hops n , with 2-hop and 3-hop paths being considered. We use a path constraint resource allocation algorithm from [Lin *et al.*, 2015] to compute the confidence of each path and retain the highest-scoring ones. Additionally, we add the original relations as prefixes to each path to improve their expressiveness, creating a composite representation.

$$I_r^p = [\text{CLS}]h[\text{SEP}]r[\text{SEP}] \quad (1)$$

$$I_{rp2}^p = [\text{CLS}]h[\text{SEP}]rp_2[\text{SEP}] \quad (2)$$

$$I_{rp3}^p = [\text{CLS}]h[\text{SEP}]rp_3[\text{SEP}] \quad (3)$$

In our framework, each relation or reasoning path, combined with the corresponding head entity, forms query texts (I_r^p , I_{rp2}^p , I_{rp3}^p). These query texts are paired with the correct tail entity t to generate positive samples. Then, these text pairs are processed through two BERT modules: the relation-aware module ($Bert_{hr}$) encodes the query text, generating embeddings e_{hr} , e_{hrp2} , and e_{hrp3} . The entity-specific module ($Bert_t$) independently encodes the tail entity and generates the embedding e_t .

$$\mathcal{L}_{hr,t} = \mathcal{L}(e_{hr}, e_t), \mathcal{L}_{hp,t} = \mathcal{L}(e_{hrp2}, e_t) + \mathcal{L}(e_{hrp3}, e_t) \quad (4)$$

Here, \mathcal{L} represents the loss function, and its specific form will be introduced in detail later.

3.4 Soft Reasoning Paths

To alleviate the issue of absent reasoning paths, we introduce soft reasoning paths. Specifically, for each relation r or inverse relation r^{-1} , we append a trainable embedding $\mathbf{S}_r \in \mathbb{R}^{d_{out} \times m}$ to it. By concatenating trainable embedding with the original relation representation, we construct soft reasoning paths that are capable of generalizing path semantics. During training, we design a contrastive learning objective to align the soft reasoning path embedding e_{hrs} with the encoded authentic reasoning paths e_{hp2} and e_{hp3} in vector space. This alignment guides the soft reasoning paths to learn generalized path patterns of relations from a limited set of path samples. This design allows soft reasoning paths to simulate latent reasoning logic through generalized representations during testing, even when reasoning paths are absent, thus significantly mitigating the impact of missing paths on prediction performance.

Specifically, we first construct sentence pairs I_r^p . After token embedding, we append a trainable embedding \mathbf{S}_r to the embedding vector of the relation. We define the soft reasoning path as I_{rs}^p .

$$I_{rs}^p = [CLS]h[SEP]rS_r[SEP], S_r = W_2 \cdot (\text{ReLU}(W_1 \cdot x_r)) \quad (5)$$

where $x_r \in \mathbb{R}^{d_{in} \times m}$, m denotes the number of relations, and d_{in} represents the dimensionality of the trainable embeddings we define. $W_1 \in \mathbb{R}^{d_h \times d_{in}}$ and $W_2 \in \mathbb{R}^{d_{out} \times d_h}$ are trainable weight matrices. d_h denotes the dimensionality of the hidden layer, while d_{out} represents the dimensionality of the output layer. The output layer is typically expressed as $l \times 768$, where l is the number of trainable embeddings, and 768 is the default dimensionality of BERT input embeddings. A corresponding x_r is assigned to each relation. Specifically, if the knowledge graph contains 247 types of relations, there will be a total of 247×2 instances of x_r (accounting for both forward and inverse relations). Notably, W_1 and W_2 are shared parameters across all relations. The soft reasoning path plays a role in learning the representations of reasoning paths to better capture complex reasoning information.

$$\mathcal{L}_{hrs.t} = \mathcal{L}(e_{hrs}, e_t) \quad (6)$$

$$\mathcal{L}_{hrs.p} = \mathcal{L}(e_{hrs}, e_{hp2}) + \mathcal{L}(e_{hrs}, e_{hp3}) \quad (7)$$

Here, e_{hrs} is the result of encoding I_{rs}^p with $Bert_{hr}$.

3.5 Hierarchical Ranking

During the testing phase, we predict the tail entities using the known head entities and relations. In this process, in addition to the relational information, we can also leverage the soft reasoning paths learned during training (i.e., (h, r) and (h, rs)). By employing a dual-encoder architecture, we preprocess all candidate tail entities, enabling efficient and rapid computation. Although reasoning paths are highly valuable, performing path searches for every candidate entity would incur substantial computational costs. For instance, in the Wikidata5M dataset, each triple contains 4,594,485 candidate tail entities, making exhaustive computation impractical. To address this challenge, our approach strikes a balance between computational cost and performance through a hierarchical

ranking strategy. During the reasoning phase, we first perform a quick filtering using the relations and soft reasoning paths, and then conduct reasoning path searches only for the high-confidence candidate entities.

$$\text{Logits} = \phi(h, r, t) + \phi(h, rs, t), \hat{E} = \text{Top-N}(\text{Logits}) \quad (8)$$

Here, we define $\phi(h, r, t) = \cos(\mathbf{e}_{hr}, \mathbf{e}_t) \in [-1, 1]$, and similarly, $\phi(h, rs, t) = \cos(\mathbf{e}_{hrs}, \mathbf{e}_t) \in [-1, 1]$. Next, we select the top N candidate entities with the highest scores for the current triple (h, r) , and perform path searches in the known graph between the head entity and these candidate entities. Here, N is a tunable ranking parameter that can be adjusted flexibly based on the characteristics of the dataset.

$$Path_2, Path_3 = \text{Search}(h, \hat{E}) \quad (9)$$

Here, we still limit the search to only 2-hop and 3-hop paths, i.e., $Path_2$ and $Path_3$. After combining the searched paths with the head entity and passing them through $Bert_h$, we obtain the embeddings \mathbf{e}_{hp2} and \mathbf{e}_{hp3} . Then, we calculate the similarity between these two vectors and \mathbf{e}_{hrs} by computing the cosine similarity, yielding a value $\alpha \in [-1, 1]$. From these results, we select the one with the highest score.

$$\alpha = \max(\cos(\mathbf{e}_{hp2}, \mathbf{e}_{hrs}), \cos(\mathbf{e}_{hp3}, \mathbf{e}_{hrs})) \quad (10)$$

We add the obtained α values to the high-confidence candidate entities in order to further optimize the results. This adjustment allows the model to prioritize the most relevant entities, improving the overall performance of the KGC task.

3.6 Loss function

In the training process, to further enhance the generalizability of the knowledge learned by the soft reasoning paths, inspired by [Khosla *et al.*, 2020], we improve the InfoNCE loss function. We extend InfoNCE [Chen *et al.*, 2020] to handle multiple positive samples simultaneously by maximizing the likelihood of these positive samples, thus integrating shared semantic information. This modification allows the model to better capture diverse patterns in the data, improving its performance on KGC tasks.

$$\mathcal{L} = -\frac{1}{|P|} \sum_{r* \in P} \log \frac{e^{\phi(h, r*, t)/\tau}}{\sum_{i=1}^{|N|} e^{\phi(h, r*, t_i)/\tau}} \quad (11)$$

Here, P is the set of all previously mentioned positive samples, that is, the relation r , 2-hop path rp_2 , 3-hop path rp_3 , and the soft reasoning path rs . At the same time, we retain the temperature parameter τ to balance the importance between the samples. In addition to the in-batch negative samples, we do not introduce any additional negative samples.

$$\mathcal{L}_{all} = w_1 \mathcal{L}_{hr.t} + w_2 \mathcal{L}_{hp.t} + w_3 \mathcal{L}_{hrs.t} + w_4 \mathcal{L}_{hrs.p} \quad (12)$$

Where w_i is tunable hyper-parameters for adapting to specific knowledge graph characteristics.

4 Experiments

In this section, we evaluate the overall performance of SRP-KGC and the effectiveness of its individual modules. The experiments aim to answer the following four research questions:

Table 1: Main results on WN18RR,FB15k-237 and Wikidata5M-Trans datasets. Bold numbers represent the best and underlined numbers represent the second best.

Methods	WN18RR				FB15k-237				Wikidata5M-Trans			
	MRR	Hits@1	Hits@3	Hits@10	MRR	Hits@1	Hits@3	Hits@10	MRR	Hits@1	Hits@3	Hits@10
Embedding-based methods												
TransE	24.3	4.3	44.1	53.2	27.9	19.8	37.6	44.1	25.3	17.0	31.1	39.2
ComplEx	44.9	40.9	46.9	53.0	27.8	19.4	29.7	45.0	28.2	22.6	-	39.7
RotatE	47.6	42.8	49.2	57.1	33.8	24.1	37.5	53.3	29.0	23.4	32.2	39.0
ConvE	45.6	41.9	47.0	53.1	31.2	22.5	34.1	49.7	-	-	-	-
CompGCN	48.1	44.8	49.2	54.8	35.5	26.4	39.0	53.5	-	-	-	-
TuckER	47.0	44.3	48.2	52.6	35.8	26.6	39.4	54.4	-	-	-	-
CompoundE	49.2	45.2	51.0	57.0	35.0	26.2	39.0	54.7	-	-	-	-
KPACL	52.7	48.2	54.7	61.3	36.0	26.6	39.5	54.8	-	-	-	-
RotatE-VLP	49.8	45.5	51.4	58.2	36.2	27.1	39.7	54.2	-	-	-	-
Text-based methods												
KG-BERT	21.6	4.1	30.2	52.4	-	-	-	42.0	-	-	-	-
STAR	40.1	24.3	49.1	70.9	29.6	20.5	32.2	48.2	-	-	-	-
KG-S2S	57.4	53.1	59.5	66.1	33.6	25.7	37.3	49.8	-	-	-	-
C-LMKE	61.9	52.3	67.1	78.9	30.6	21.8	33.1	48.4	-	-	-	-
SimKGC	67.1	58.7	73.1	81.7	33.3	24.6	36.2	51.0	35.3	30.1	37.4	44.8
CSProm-KG	57.5	52.2	59.6	67.8	35.8	26.9	39.3	53.8	38.0	34.3	39.9	44.6
LP-BERT	48.2	34.3	56.3	75.2	31.0	22.3	33.6	49.0	-	-	-	-
GS-KGC	-	34.6	51.6	-	-	28.0	42.6	-	-	-	-	-
GHN	67.8	59.6	71.9	82.1	33.9	25.1	36.4	51.8	36.4	31.7	38.0	45.3
SRP-KGC	70.5	63.6	74.4	83.1	43.1	35.3	46.1	58.5	40.9	36.6	43.0	48.8

- RQ1. How does the proposed SRP-KGC perform compared to the state-of-the-art methods under both transductive and inductive settings? (see Section 4.2)
- RQ2. Will the introduction of soft paths improve the discriminability of the reasoning path embedding? (see Section 4.3)
- RQ3. How does the soft reasoning path perform when reasoning paths are missing or present? (see Section 4.4)
- RQ4. How does hierarchical ranking work? Is it effective? (see Section 4.5)

4.1 Experimental Settings

We evaluated our method on three commonly used datasets: WN18RR, FB15k-237, and Wikidata5M-Trans. Detailed information about these datasets is shown in Table 2. During the evaluation on these datasets, the candidate entities included all entities in the respective datasets. In addition, [Teru *et al.*, 2020] extracted four inductive versions (v1,v2,v3,v4) of datasets for both WN18RR and FB15k-237. When testing on these inductive datasets, we followed the conventional setup and used only 50 candidate entities that included the target tail entity for fair comparison. Due to space constraints, the detailed descriptions of the inductive datasets are provided in the appendix.

We adopted the text-based model SimKGC [Wang *et al.*, 2022a] as our baseline, retaining the BERT parameter settings from the original paper. Our implementation was built using PyTorch. Hyperparameters w_i were optimized via grid search over the set $\{0.2, 0.4, 0.6, 0.8, 1\}$. All experiments ran on 4

Table 2: Statistics of the datasets.

Dataset	# Ent	# Rel	# train	# valid	# test
WN18RR	40,943	11	86,835	3,034	3,134
FB15k-237	14,541	237	272,115	17,535	20,466
Wikidata5M-Trans	4,594,485	822	20,614,279	5,163	5,163

NVIDIA RTX 4090 24GB GPUs. Evaluation used four automated metrics: MRR: Mean reciprocal rank of test triples; Hit@ k : Proportion of correct entities in top- k predictions ($k = 1, 3, 10$). The detailed hyperparameters can be found in the appendix.

4.2 Performance Comparison with SOTA Method

In this study, we conducted a comparative analysis of SRP-KGC, comparing it with both embedding-based and text-based approaches. The embedding-based methods include TransE [Bordes *et al.*, 2013], ComplEx [Trouillon *et al.*, 2016], RotatE [Sun *et al.*, 2019b], ConvE [Dettmers *et al.*, 2017], CompGCN [Vashishth *et al.*, 2019], TuckER [Balazevic *et al.*, 2019], CompoundE [Ge *et al.*, 2023], KRAACL [Tan *et al.*, 2022], and RotatE-VLP [Li *et al.*, 2023]. On the other hand, the text-based methods include KG-BERT [Yao *et al.*, 2021], STAR [Wang *et al.*, 2021], KG-S2S [Chen *et al.*, 2022], C-LMKE [Wang *et al.*, 2022b], SimKGC [Wang *et al.*, 2022a], CSProm-KG [Chen *et al.*, 2023], LP-BERT [Li *et al.*, 2022], GS-KGC [Yang *et al.*, 2024] and GHN [Qiao *et al.*, 2023].

The main results are summarized in Table 1. Several conclusions can be drawn from these findings. Firstly, our

method outperforms previous works across all metrics on the three datasets. Specifically, on the WN18RR dataset, our SRP-KGC improves the MRR and Hits@1 metrics by 4% and 6.7%, respectively. On Wikidata5M-Trans, it improves by 7.6% and 6.7%. Notably, on FB15k-237, our SRP-KGC improves by 19% and 26.1%. These results indicate that our SRP-KGC method demonstrates strong competitiveness in knowledge graphs with both sparse and dense topologies, as well as in large-scale knowledge graphs.

Table 3: The Hits@10 of WN18RR under inductive scenario. The optimal values of each metric are marked in bold.

Methods	WN18RR.ind				
	V1	V2	V3	V4	Avg
GraIL	82.4	78.6	58.4	73.4	73.2
SimKGC	95.8	97.2	96.2	97.4	96.7
GLAR	93.6	94.7	93.3	92.4	93.5
SRP-KGC	97.8	98.9	96.1	98.4	97.8

To further explore the generalization capability of our method, we conducted experiments under the inductive KGC setting. The datasets used include WN18RR (v1, v2, v3, v4) and FB15k-237 (v1, v2, v3, v4), which were extracted by [Teru *et al.*, 2020]. Due to space constraints, we compared SRP-KGC with the following three approaches: GraIL [Teru *et al.*, 2020], which is one of the most classic methods for completing KGC tasks using reasoning paths; SimKGC [Wang *et al.*, 2022a], which has a similar structure; and GLAR [Xie *et al.*, 2024], the current state-of-the-art method. For a fair comparison, we adopted the experimental setup of GraIL, retaining only 50 candidate entities containing the target tail entity by default, and used Hits@10 as the evaluation metric. Tables 3 and Tables 4 present the experimental results on these two datasets.

Table 4: The Hits@10 of FB15k-237 under inductive scenario. The optimal values of each metric are marked in bold.

Methods	FB15k-237.ind				
	V1	V2	V3	V4	Avg
GraIL	64.2	81.8	95.7	89.3	82.7
SimKGC	90.5	93.2	91.0	90.1	91.2
GLAR	91.3	96.6	96.0	96.4	95.1
SRP-KGC	96.3	98.1	96.2	95.3	96.5

The experiments demonstrate that SRP-KGC improves upon the best-performing method by 1.1% and 1.5%, respectively, in these two tasks. Through this approach, the model is able to effectively capture the underlying patterns of reasoning paths, demonstrating strong generalization ability even when handling previously unseen entities.

4.3 Ability to comprehend the reasoning path

We compared the discriminative features obtained from different head entities pointing to the same tail entity through different paths and validated the effectiveness of incorporat-

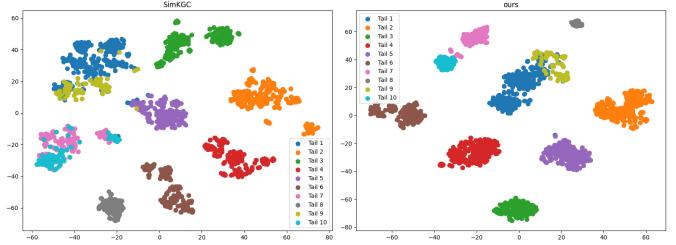


Figure 2: Visualization of embeddings with the different head entities and relations using t-SNE under the settings of SimKGC and SRP-KGC. In the visualization, points with the same color represent embeddings that share the same target tail entity.

ing multiple types of positive samples into the training process to enhance the model’s ability to understand reasoning paths. In the experiment, we selected 10 tail entities that are highly relevant to triples from the FB15k-237 test set. For these tail entities and their related triples, we performed path searches and combined the resulting paths with their corresponding head entities. Subsequently, we encoded these combinations using BERT models trained with SimKGC and SRP-KGC. We visualized the encoded outcomes using t-SNE in Figure 2. The visualization shows that after training with SRP-KGC, the embeddings for the same tail entity are significantly closer in the embedding space, demonstrating better feature discriminability.

4.4 Effectiveness of Soft Reasoning Paths

To validate the effectiveness of the soft reasoning path, we designed a series of comparative experiments, focusing on its performance in different scenarios. Specifically, we conducted comparisons under two conditions based on the existence of reasoning paths, and analyzed the impact of introducing the soft reasoning path:

Table 5: For the comparison of results in the absence of reasoning paths, R represents testing using relationships, while RS represents testing using soft reasoning paths.

Testing settings	MRR	Hits@1	Hits@3	Hits@10
R	26.9	18.0	29.6	44.1
RS	33.2	24.4	36.5	51.0

Without reasoning paths: In this scenario, previous models rely solely on the direct relationships within the triples for prediction, which fails to provide more effective information. Our approach introduces soft reasoning paths, and we conduct a comparative analysis. We collected 5,560 triplets from the FB15k-237 test set that do not have reasoning paths, and performed a separate analysis. As shown in Table 5, the proposed Soft reasoning paths, in the case of missing paths, showed improvements over traditional methods by 23.4%, 35.6%, 23.3%, and 15.6% on the MRR, Hits@1, Hits@3, and Hits@10 metrics, respectively. These results demonstrate that Soft reasoning paths, by learning the representation of the same relationship under different paths, effectively alleviate the issue of missing reasoning paths in KGC tasks.

With reasoning paths: In this scenario, existing path-based methods determine the target tail entity by the correlation between the reasoning path and the target relation. However, reasoning paths are often stacks of relationships, resulting in a significant semantic gap from the target relation. To alleviate this, we compared the correlation between reasoning paths and relations, as well as the correlation between reasoning paths and soft reasoning paths, to evaluate the role of soft reasoning paths in reducing the semantic gap.

Replacing the soft reasoning path with relationships and applying it to the final step of our proposed hierarchical ranking strategy is an effective comparative method. We conducted comparisons on the structurally relatively dense FB15k-237 dataset, as shown in Table 6, indicate that using Soft reasoning paths, compared to using relationships, led to improvements of 23.3%, 30.5%, 23.2%, and 15.9% in MRR, Hit@1, Hit@3, and Hit@10, respectively.

Table 6: The comparison of results during the ranking phase using relationships and soft reasoning paths is as follows: R represents relationships, and RS represents Soft reasoning paths.

Rank settings	MRR	Hits@1	Hits@3	Hits@10
R	33.8	26.2	36.1	48.5
RS	41.7	34.2	44.5	56.2

To further validate the effectiveness of soft reasoning paths, we collected 14,806 triples with reasoning paths and searched for their 2-hop and 3-hop paths. We performed relation prediction using both relations and soft reasoning paths for these paths. Specifically, the embedding vectors e_r of the relations involved in these triples, as well as the soft reasoning paths e_{rs} corresponding to each relation, were computed. Subsequently, we encoded the embeddings of these reasoning paths using the same encoder to obtain e_p . Finally, we calculated the similarities between e_p and e_r , as well as between e_p and e_{rs} and evaluated the results within their respective sets. As shown in Table 7, compared to using only relations, the use of soft reasoning paths improved the Hits@10, F1, and ROC-AUC metrics by 4.6%, 4.8%, and 2.1%, respectively. Furthermore, if soft reasoning paths were not used during training, the corresponding improvements in the metrics would be 15.6%, 94.7%, and 6.3%, respectively.

Table 7: Relation prediction performance across training and testing configurations. R represents relationships, and RS represents soft reasoning paths.

Training Settings	Testing Settings	Hits@10	F1	ROC-AUC
w/o RS	R	74.5	19.0	49.5
w RS	R	82.3	35.3	51.5
w RS	RS	86.1	37.0	52.6

4.5 Case Study

To further illustrate the effectiveness of the hierarchical ranking, we selected “Contac” as the head entity and “language

Table 8: The rankings and scores predicted by the model under different information conditions. The target entity is indicated in bold.

information	Contact, language film, English Language		Answer
	Top 3 candidate entities	probabilities	
(h,r)	Greek Language	0.547	7
	Japanese Language	0.543	
	Hebrew Language	0.530	
(h,r)+(h,rs)	Japanese Language	1.034	2
	English Language	1.025	
	Greek Language	1.021	
(h,r)+(h,rs)+(p)	English Language	1.458	1
	Japanese Language	1.262	
	Greek Language	1.249	

film” as the relation for a prediction experiment. Specifically: Using (h, r) (head entity and relation) as the query, we calculated the similarity with all candidate entities, resulting in a rank of 7. Next, we added (h, rs) (head entity and soft reasoning path) as the query and performed similarity calculations again, improving the rank to 2. Finally, we conducted a search for the reasoning path and calculated the similarity between the reasoning paths and soft reasoning paths. Adding this score to the original score further improved the final rank to 1. This process demonstrates that integrating multiple types of information can effectively improve the accuracy of the model’s predictions.

5 Limitations

Although SRP-KGC enhances KGC tasks by introducing soft reasoning paths, this leads to increased computational demands during ranking. To assess this, we examined the trade-off between performance gains and computational costs. Comparing SRP-KGC with BERTRL and SimKGC, SRP-KGC strikes the best balance between speed and accuracy. BERTRL takes 60 seconds per batch for a 3.5 MRR improvement, while SRP-KGC achieves an 8.1 MRR boost in just 15 seconds. Despite SRP-KGC requiring five times more processing time than SimKGC (which has a 0.8 MRR improvement), it offers ten times greater performance gains. The results show that SRP-KGC effectively enhances model precision through strategic computational allocation, surpassing BERTRL in efficiency and SimKGC in effectiveness. (The BERTRL results are from our reproduced experiments. We used our hierarchical ranking strategy to handle many candidate entities; without it, testing would take about 36 minutes per batch.)

Table 9: Comparison of ranking time and performance with SimKGC and BERTRL in FB15k-237.

Ranking Time Per Batch (512)		
Methods	Time	Ability (MRR)
SimKGC	3s	32.8→33.6
BERTRL	60s	32.0→35.5
SRP-KGC	15s	33.6→41.7

6 Conclusion

This paper proposes the SRP-KGC, which effectively alleviate issues such as missing reasoning paths, semantic gaps, and scalability in existing KGC tasks. By introducing learnable embeddings to construct soft reasoning paths and employing a hierarchical ranking strategy to fully leverage the available information, SRP-KGC significantly outperforms existing methods across multiple datasets, demonstrating its potential in large-scale KGC tasks. Although there is an increase in computational overhead, the substantial performance improvement indicates clear advantages of the method. Future research will focus on optimizing computational efficiency and further reducing time costs to enhance the practical applicability of the method.

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A Appendix

A.1 Hyperparameters

The Table 10 presents the hyperparameters for our proposed SRP-KGC model across three datasets: WN18RR, FB15k-237, and Wikidata5M-Trans. It lists various hyperparameters, including the input dimension d_{in} , hidden layer dimension d_h , output dimension d_{out} , trainable embedding number l , relation number m , learning rate, learning rate scheduler, and warmup steps. Additionally, other critical training parameters are provided, such as the initial temperature, number of epochs, batch size, gradient clipping value, and maximum tokens. Notably, the learning rates vary across datasets, and the weight vector w_i differs for the FB15k-237 dataset. These hyperparameter choices are designed to optimize model performance across different tasks and datasets.

Table 10: Hyperparameters for our proposed SRP-KGC model.

Hyperparameters	WN18RR	FB15k-237	Wikidata5M-Trans
d_{in}	144	144	144
d_h	72	72	72
d_{out}	$l \times 768$	$l \times 768$	$l \times 768$
l	10	8	8
m	22	474	1644
Learning rate	5e-5	1e-5	3e-5
LR Scheduler	Linear Warmup	Linear Warmup	Linear Warmup
Warmup steps	400	400	400
Initial temperature	0.05	0.05	0.05
Epochs	100	10	1
Batch size	512	512	512
Gradient clipping	10	10	10
Max tokens	50	50	50
w_i	[1, 1, 1, 1]	[1, 1, 1, 0.2]	[1, 1, 1, 1]

A.2 Inductive datasets

Due to space limitations in the main text, we present the relevant information for the datasets used in the inductive setting in Table 11. Each inductive dataset has four versions, with progressively increasing sizes.

Table 11: Statistics of WN18RR-ind and FB15k237-ind datasets. #R, #E and #T are the numbers of relations, entities and triples.

	train	WN18RR-ind			FB15k237-ind		
		#R	#E	#T	#R	#E	#T
v1	train	9	2746	6678	183	2000	5226
	test	9	922	1991	146	1500	2404
v2	train	10	6954	18968	203	3000	12085
	test	10	2923	4863	176	2000	5092
v3	train	11	12078	32150	218	4000	22394
	test	11	5084	7470	187	3000	9137
v4	train	9	3861	9842	222	5000	33916
	test	9	7208	15157	204	3500	14554

A.3 The effectiveness of hierarchical ranking.

The comparison of integrating different types of information for knowledge graph completion clearly shows the effectiveness of hierarchical ranking. As demonstrated by the results,

the baseline model, which uses only the head entity and relation (h, r) , shows solid performance on both the WN18RR and FB15K-237 datasets. However, when additional contextual information is introduced, such as the soft reasoning path (h, rs) , the performance improves, with increases observed in both MRR and Hits@1 metrics.

Notably, incorporating the reasoning path (p) alongside the previous two types of information provides the most significant improvement. This is especially evident on the FB15K-237 dataset, where the addition of reasoning paths substantially enhances the model’s ability to rank the correct entities, evidenced by a large increase in both MRR and Hits@1. This suggests that the hierarchical integration of multiple layers of reasoning paths allows the model to better understand complex relationships within the knowledge graph, leading to more accurate and effective completion results.

The results underline the importance of hierarchical ranking in improving the model’s performance, particularly in more challenging datasets like FB15K-237. The effectiveness of this approach highlights how layering different types of information can significantly enhance the model’s ability to perform knowledge graph completion tasks, offering a compelling argument for the benefits of hierarchical ranking in such scenarios.

Table 12: Comparison of the effects of integrating different types of information.

Infomation	WN18RR		FB15K-237	
	MRR	Hits@1	MRR	Hits@1
(h,r)	68.3	61.2	30.1	20.5
(h,r)+(h,rs)	69.7	62.6	33.6	24.4
(h,r)+(h,rs)+(p)	70.3	63.4	41.7	34.2

A.4 Ablation Study

In this section, we focus on conducting ablation study for two important parameters: the number of trainable embeddings and the size of N in hierarchical ranking.

Table 13: The impact of trainable embeddings number on the FB15k-237 and WN18RR datasets

embedding num	FB15K237		WN18RR	
	MRR	Hits@1	MRR	Hits@1
2	39.8	32.1	69.8	62.1
4	40.9	33.4	70.2	63.0
6	40.0	32.3	70.3	62.9
8	41.7	34.2	70.3	63.4
10	41.6	34.1	70.7	63.6
12	41.5	34.1	70.0	62.9

We conducted ablation experiments with different numbers of trainable embeddings (i.e., 2, 4, 6, 8, 10, 12) on the FB15k-237 and WN18RR datasets, evaluating the performance using MRR and Hits@1 (with a default rank number

N of 100). As shown in Table 13, we observed the following trends: FB15K237 Dataset: The performance improved with the increase in the number of embeddings from 2 to 8. Specifically, the MRR increased from 39.8 at 2 embeddings to 41.7 at 8 embeddings, and Hits@1 increased from 32.1 to 34.2. This indicates that adding more learnable embeddings enhanced the model’s ability to capture and generalize path representations. However, the performance slightly decreased when the number of embeddings was increased beyond 8 (at 10 and 12 embeddings), where the MRR and Hits@1 values plateaued or showed slight declines. This suggests a diminishing return or potential overfitting as the embeddings become more complex and difficult to optimize effectively. WN18RR Dataset: Similar patterns were observed, with the MRR and Hits@1 improving steadily from 2 embeddings (69.8 and 62.1, respectively) to 8 embeddings (70.3 and 63.4, respectively). Beyond 8 embeddings, the performance continued to improve slightly at 10 embeddings (MRR 70.7, Hits@1 63.6) but dropped slightly at 12 embeddings (MRR 70.0, Hits@1 62.9). Again, this trend indicates that while adding embeddings initially improves the model’s performance, the gains become less significant and even start to reverse as the embedding space becomes too large to train effectively.

In summary, the experiment suggests that adding learnable embeddings enhances the model’s performance up to a point (8 embeddings for both datasets), beyond which further increases lead to diminishing returns or instability in training. This behavior may be due to the model becoming too complex or overfitting as the number of embeddings grows.

Table 14: Impact of Top-N Filter Size on WN18RR and FB15k-237 Datasets.

N	WN18RR		FB15K237	
	MRR	Hits@1	MRR	Hits@1
0	69.7	62.6	33.6	24.4
100	70.3	63.4	41.7	34.2
200	70.4	63.5	42.5	34.8
300	70.4	63.5	42.9	35.1
400	70.5	63.6	43.1	35.3

We conducted an ablation study to analyze the sensitivity of model performance to the Top-N filter size (N) across two benchmark datasets. As shown in Table 14, we evaluated five configurations of $N \in \{0, 100, 200, 300, 400\}$, where $N = 0$ serves as the baseline without entity filtering. Key observations include: WN18RR Dataset: Incremental gains in both MRR and Hits@1 were observed as N increased from 0 to 400. The marginal improvements suggest that smaller candidate subsets (e.g., $N \leq 400$) sufficiently preserve high-quality entities in sparse knowledge graphs. FB15k-237 Dataset: Performance exhibited stronger dependency on N , with MRR improving by 28.3% and Hits@1 by 44.7% as N increased from 0 to 400. Notably, 60% of these gains were achieved at $N = 100$, indicating that even moderate filtering significantly benefits dense knowledge graphs. This phenomenon aligns with our hypothesis that structural

density amplifies the importance of selective entity retention during reasoning. In addition, we calculated that for every 100 increase in N , the ranking time increases by approximately 15 seconds per batch.

A.5 Train time analysis

In this section, we compared the time required to train one epoch between our method and SimKGC. Although our method incurs an increase in training time compared to other approaches, the performance improvement is substantial enough to justify the additional time cost. On the WN18RR and FB15K237 datasets, the training time per epoch for our method is 4 minutes and 27 seconds, and 14 minutes and 38 seconds, respectively, which is an increase of approximately 1 to 4 minutes compared to the SimKGC method. However, as training progresses, our method achieves scores of 70.5 and 43.1 on the ability evaluation metric (MRR), which represent improvements of 3.4 and 9.8 points, respectively, compared to SimKGC. Therefore, despite the higher time cost, the performance gains are significant and acceptable.

Table 15: Training time of one epoch and final performance compared to SimKGC

Methods	Training Time Per Epoch			
	WN18RR	Ability (MRR)	FB15K237	Ability (MRR)
SimKGC	2m45s	67.1	10m24s	33.3
ours	4m27s	70.5	14m38s	43.1

A.6 Trainable parameters

Table 16: Compare the trainable parameters with SimKGC

Methods	Trainable parameters		
	WN18RR	FB15K-237	Wikidata5M-Trans
SimKGC	218.0M	218.0M	218.0M
ours	219.7M	220.0M	220.6M

Our method introduces only a minimal increase in the number of trainable parameters. As shown in Table 16, we compared the number of parameters when the number of learnable embeddings is 8. On the WN18RR, FB15K-237, and Wikidata5M-Trans datasets, the number of trainable parameters for SimKGC and our method are 218.0M and 219.7M, 220.0M and 220.6M, respectively, with a very limited increase in the number of parameters. Therefore, our method provides significant performance improvements while maintaining minimal additional parameter overhead, demonstrating its high efficiency and optimization potential.

A.7 Case Study

In Table 17-22, we present more examples of predictions made by SRP-KGC to help better understand the testing process of our model.

Table 17: The rankings and scores predicted by the model for forward tail entity inference under varying information conditions are presented. The target entity is highlighted in bold.

Sandra Bernhard, profession person people, Actor-GB			Answer
test set	Top3 candidate entites	probabilities	Rank
(h,r)	Spokesperson-GB	0.548	
	Activism	0.543	7
	Presenter-GB	0.539	
(h,r)+(h,rs)	Activism	1.051	
	Spokesperson-GB	1.044	3
	Actor-GB	1.004	
(h,r)+(h,rs)+(p)	Actor-GB	1.526	
	Activism	1.309	1
	Spokesperson-GB	1.302	

Table 18: The rankings and scores predicted by the model for forward tail entity inference under varying information conditions are presented. The target entity is highlighted in bold.

The Painted Veil, language film, French Language			Answer
test set	Top3 candidate entites	probabilities	Rank
(h,r)	Persian Language	0.578	
	Arabic Language	0.573	
	Hebrew Language	0.559	32
(h,r)+(h,rs)	Persian Language	1.107	
	Arabic Language	1.102	
	Hebrew Language	1.062	21
(h,r)+(h,rs)+(p)	French Language	1.553	
	Persian Language	1.517	
	Arabic Language	1.512	1

Table 19: The rankings and scores predicted by the model for forward tail entity inference under varying information conditions are presented. The target entity is highlighted in bold.

Curly Howard, profession person people, Actor-GB			Answer
test set	Top3 candidate entites	probabilities	Rank
(h,r)	Clown	0.522	
	Screenwriter	0.521	
	Film Producer-GB	0.519	5
(h,r)+(h,rs)	Clown	1.047	
	Actor-GB	1.009	
	Screenwriter	0.995	2
(h,r)+(h,rs)+(p)	Actor-GB	1.487	
	Clown	1.426	
	Screenwriter	1.412	1

Table 20: The rankings and scores predicted by the model for backward tail entity inference under varying information conditions are presented. The target entity is highlighted in bold.

Nas, artist genre music ⁻¹ , Hip hop music			Answer
test set	Top3 candidate entites	probabilities	Rank
(h,r)	Jazz rap	0.686	
	G-funk	0.679	
	Underground hip hop	0.670	9
(h,r)+(h,rs)	Jazz rap	1.326	
	G-funk	1.322	
	Underground hip hop	1.293	7
(h,r)+(h,rs)+(p)	Hip hop music	2.173	
	Jazz rap	1.893	
	G-funk	1.889	1

Table 21: The rankings and scores predicted by the model for backward tail entity inference under varying information conditions are presented. The target entity is highlighted in bold.

Dick Clark, cause of death people ⁻¹ , Myocardial infarction			Answer
test set	Top3 candidate entites	probabilities	Rank
(h,r)	Renal failure	0.667	
	Cancer	0.658	
	Lung cancer	0.655	20
(h,r)+(h,rs)	Renal failure	1.306	
	Cancer	1.286	
	Lung cancer	1.269	17
(h,r)+(h,rs)+(p)	Myocardial infarction	1.707	
	Renal failure	1.575	
	Cancer	1.555	1

Table 22: The rankings and scores predicted by the model for backward tail entity inference under varying information conditions are presented. The target entity is highlighted in bold.

George Clinton, artist record label music ⁻¹ , Casablanca Records			Answer
test set	Top3 candidate entites	probabilities	Rank
(h,r)	Motown Records	0.594	
	Jive Records	0.554	
	Atlantic Records	0.531	7
(h,r)+(h,rs)	Motown Records	1.127	
	Jive Records	1.035	
	MCA Records	1.006	6
(h,r)+(h,rs)+(p)	Casablanca Records	1.604	
	Motown Records	1.481	
	Jive Records	1.389	1