SQALER: Scaling Question Answering by Decoupling Multi-Hop and Logical Reasoning

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Abstract

State-of-the-art approaches to reasoning and question answering over knowledge graphs (KGs) usually scale with the number of edges and can only be applied effectively on small instance-dependent subgraphs. In this paper, we address this issue by showing that multi-hop and more complex logical reasoning can be accomplished separately without losing expressive power. Motivated by this insight, we propose an approach to multi-hop reasoning that scales linearly with the number of relation types in the graph, which is usually significantly smaller than the number of edges or nodes. This produces a set of candidate solutions that can be provably refined to recover the solution to the original problem. Our experiments on knowledge-based question answering show that our approach solves the multi-hop MetaQA dataset, achieves a new state-of-the-art on the more challenging WebQuestionsSP, is orders of magnitude more scalable than competitive approaches, and can achieve compositional generalization out of the training distribution.

1 Introduction

Reasoning, namely the ability to infer conclusions and draw predictions based on existing knowledge, is a hallmark of human intelligence. Infusing the same ability into machine learning models has been a major challenge [34, 29] and has historically required complex systems made of several hand-crafted or learned components [47, 19]. Recently, the paradigm has shifted to deep learning approaches [43, 42], where neural networks are used to reason over structured knowledge or a text corpus. In this work, we assume that the source of knowledge is a structured knowledge graph (KG) and we tackle the problem of *knowledge-based question answering* (KBQA), namely finding answers to natural language queries involving multi-hop and logical reasoning over the KG.

Answering queries over a knowledge graph involves many challenges, among which scalability is a major issue. Real-world KGs often contain millions of nodes and even a 2-hop neighborhood of the entities mentioned in the query may comprise tens of thousands of nodes. Many state-of-the-art approaches [41, 42, 39] address the challenge of scalability by building small query-dependent subgraphs. To this end, they usually use simple heuristics [41] or, in some cases, iterative procedures based on learned classifiers [42]. This preprocessing step is usually needed because each forward pass in end-to-end neural networks for KBQA scales at least linearly with the number of edges in the subgraph. Training neural networks involves repeated evaluation, which renders even a linear complexity impractical for graphs of more than a few tens thousands of nodes.

In order to address this issue, we introduce a novel approach called **SQALER** (Scaling Question Answering by Leveraging Edge Relations). The method first learns a model that generates a set of candidate answers (entities in the KG) by *multi-hop reasoning*: the candidate solutions are obtained by starting from the set of entities mentioned in the question and seeking those that provide an answer by chained relational following operations. We refer to this module as the *relation-level* model.

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We show that this multi-hop reasoning step can be done efficiently and provably generates a set of candidates including all the actual answers to the original question. **SQALER** then uses a second-stage *edge-level* model that recovers the real answers by performing logical reasoning on a subgraph in the vicinity of the candidate solutions. A visual summary of our approach is depicted in Figure 1.

The main contributions and takeaway messages of this work are the following:

1. KBQA can be addressed by first performing multi-hop reasoning on the KG and then refining the result with more sophisticated logical reasoning without losing expressive power (we will elaborate this claim in more details in Section 2.3).
2. Multi-hop reasoning can be accomplished efficiently with a method that scales linearly with the number of relation types in the KG, which are usually significantly fewer than the number of facts or entities.

In the remainder of the paper, we first provide an extensive overview of our approach and a theoretical analysis of the expressive power and the computational complexity of **SQALER**. Our experimental results show that **SQALER** achieves better reasoning performance than state-of-the-art approaches, generalizes compositionally out of the training distribution, and scales to the size of real-world knowledge graphs with millions of entities.

2 Scaling KBQA with relation and edge-level reasoning

This section provides a detailed description of our approach. We start by defining the problem formally and giving an intuitive overview of **SQALER**. Then, we discuss the approach in more details and we analyze its computational complexity and expressive power

Problem statement. We denote a knowledge graph as $\mathcal{G} = (\mathcal{V}, \mathcal{R}, \mathcal{E})$, where $v \in \mathcal{V}$ represents an entity or node in $\mathcal{G}$, $r \in \mathcal{R}$ is a relation type, and we write $v \xrightarrow{r} v'$ to denote an edge in $\mathcal{E}$ labeled with relation type $r \in \mathcal{R}$ between two entities $v, v' \in \mathcal{V}$. We extend the same notation to sets of nodes by writing $\mathcal{V}_i \xrightarrow{r} \mathcal{V}_j$ if $\mathcal{V}_j = \{v_j \in \mathcal{V} \mid v_i \xrightarrow{r} v_j, v_i \in \mathcal{V}_i\}$. Given a knowledge graph $\mathcal{G} = (\mathcal{V}, \mathcal{R}, \mathcal{E})$ and a natural language question Q, expressed as a sequence of tokens $Q = (q_1, q_2, \ldots, q_{|Q|})$, in *knowledge-based question answering* the objective is to identify a set of nodes $\mathcal{A}_Q \subseteq \mathcal{V}$ representing the correct answers to Q. Following previous work [41, 42, 43], we assume that the set of entities mentioned in the question $\mathcal{V}_Q \subseteq \mathcal{V}$ is given. These nodes are also called the *anchor nodes* of the question and in practice are commonly obtained using an entity-linking module.

Overview. KBQA can be cast as an entity seeking problem on $\mathcal{G}$ by translating Q into a set of nodes $\mathcal{V}_Q \subseteq \mathcal{V}$ (the starting points of the search) and seeking for nodes that provide an answer [41, 42, 43]. Attempting to find $\mathcal{A}_Q$ directly on $\mathcal{G}$ is prohibitive in practice, as even the most efficient graph-based neural networks generally scale at least linearly with the number of edges. Our approach mitigates this issue by breaking the problem in two subproblems.

(a) We first utilize a *relation-level* model ϕ to obtain a set of *candidate answers* $\tilde{\mathcal{A}}_Q$, such that $\mathcal{A}_Q \subseteq \tilde{\mathcal{A}}_Q$. We refer to ϕ as "*relation-level*" because, as we will see, it operates on the *coalesced graph*, a simplified representation of $\mathcal{G}$, where edges of the same relation type are coalesced. The coalesced graph is constructed before training and incurs a one-time linear cost. By exploiting it during training, the relation-level model scales with the number of (distinct) relation types in the KG, which are usually significantly fewer than the number of edges or entities.

(b) The candidate answers are then refined using an *edge-level* model ψ applied on a subgraph $\mathcal{G}(\tilde{\mathcal{A}}_Q)$ of the original knowledge graph in the vicinity of $\tilde{\mathcal{A}}_Q$. We should note that the refining step is not always necessary. Indeed, we found that a relation-level model is sufficient to perfectly solve tasks like multi-hop question answering [50]. Figure 1 shows an overview of our approach.

2.1 Relational coalescing for efficient knowledge seeking

Our approach relies on a relation-level model ϕ that operates as a knowledge seeker in $\mathcal{G}$. The model identifies a node v as a candidate $v \in \tilde{\mathcal{A}}_Q$ based on the sequence of relations that connect it with $\mathcal{V}_Q$.

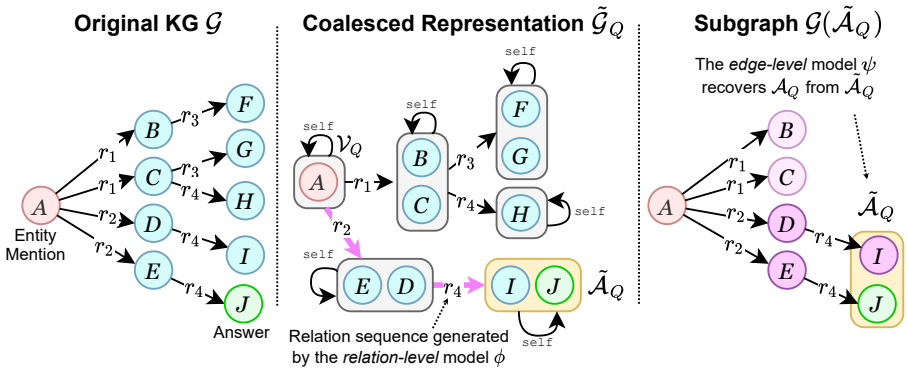


Figure 1: Overview of our approach. A *relation-level* model operates on a coalesced representation of the original KG to generate a set of candidate answers $\tilde{\mathcal{A}}_Q$. This approximate solution is then refined by an *edge-level* model applied on a subgraph of the original KG.

This can be achieved by using a neural network ϕ to predict how likely it is that the correct answer is reached from $\mathcal{V}_Q$ by following a sequence of relations R.

Reachability. To define how our method works, it will help to formalize the concept of reachability. Let $R = (r_1, \ldots, r_{|R|})$ be a sequence of relations. We say that "*v is R-reachable from $\mathcal{V}_Q$*" if there exists a path $P = (v_1, \ldots, v_{|R|}, v)$ in $\mathcal{G}$ such that:

$$v_1 \in \mathcal{V}_Q \quad \text{and} \quad v_i \xrightarrow{r_i} v_{i+1} \quad \text{for every} \quad i = 1, \ldots, |R|.$$

That is, we can reach v by starting from a node in $\mathcal{V}_Q$ and following a sequence of edges with relation types R. We also denote by $\mathit{reach}_{\mathcal{G}}(\mathcal{V}_Q, R)$ the set of nodes that are R-reachable from $\mathcal{V}_Q$:

$$\mathit{reach}_{\mathcal{G}}(\mathcal{V}_Q, R) = \{v \in \mathcal{V} \mid v \text{ is } R\text{-reachable from } \mathcal{V}_Q\}.$$

Relational coalescing. Given a knowledge graph $\mathcal{G}$, a question Q, and a set of entity mentions $\mathcal{V}_Q$, we consider a representation of the graph $\tilde{\mathcal{G}}_Q = (\tilde{\mathcal{V}}_Q, \tilde{\mathcal{R}}_Q, \tilde{\mathcal{E}}_Q)$, which allows us to efficiently compute sets of nodes that are reachable from $\mathcal{V}_Q$. We refer to this representation as the question-dependent coalesced KG, because edges with the same relation type are coalesced, as shown in Figure 1. The nodes of $\tilde{\mathcal{G}}_Q$ are sets of nodes of $\mathcal{G}$ that are reachable from $\mathcal{V}_Q$ by following any possible sequence of relations originating from $\mathcal{V}_Q$. The graph $\tilde{\mathcal{G}}_Q$ has an edge $\mathcal{V}_i \xrightarrow{r} \mathcal{V}_j$ if $\mathcal{V}_j$ is the set of nodes that are reachable from $\mathcal{V}_i$ by following relation r. For convenience, we include a relation type $\texttt{self} \in \tilde{\mathcal{R}}_Q$ to denote self loops. We refer the reader to Appendix A for a formal definition of $\tilde{\mathcal{G}}_Q$. The coalesced graph can be precomputed once as a preprocessing step for each question Q and incurs a one-time linear cost. In practice, however, we do not need to compute and store all the nodes in $\tilde{\mathcal{G}}_Q$ but only edge labels. This makes learning efficient because each forward/backward pass scales with the number of relation types and does not depend on the number of nodes or edges in the KG.

Knowledge seeking in $\tilde{\mathcal{G}}_Q$. The coalesced graph allows us to provide approximate answers to input questions in an efficient manner. Specifically, we seek $k \geq 1$ sequences of relations $R_i^\star$, such that:

$$\mathcal{A}_Q \subseteq \tilde{\mathcal{A}}_Q = \bigcup_{i=1}^{k} \mathit{reach}_{\mathcal{G}}(\mathcal{V}_Q, R_i^\star).$$

We can achieve this by using a model ϕ that only considers relation sequences originating from $\mathcal{V}_Q$. The model predicts the likelihood $\phi : \tilde{\mathcal{E}}_Q \to [0, 1]$ of following a certain edge in a relation sequence from $\mathcal{V}_Q$ to $\tilde{\mathcal{A}}_Q$. Then, given $R = (r_1, \ldots, r_{|R|})$ and a node in the coalesced graph $\mathcal{V}_Q$, we can compute the likelihood of R by multiplying the likelihood of all edges traversed by R in $\tilde{\mathcal{G}}_Q$:

$$\mathsf{P}(R \mid Q, \tilde{\mathcal{G}}_Q, \mathcal{V}_Q) \propto \prod_{i=1}^{|R|} \phi(\mathit{reach}_{\mathcal{G}}(\mathcal{V}_Q, R_{1\to i-1}), r_i, \mathit{reach}_{\mathcal{G}}(\mathcal{V}_Q, R_{1\to i}) \mid Q),$$

where $R_{1\to i} = (r_1, \ldots, r_i)$ is the subsequence of R up to the i-th relation. We generate $\tilde{\mathcal{A}}_Q$ by selecting the top k relation sequences $R_i^\star$ with maximum likelihood $\mathsf{P}(R_i^\star \mid Q, \tilde{\mathcal{G}}_Q, \mathcal{V}_Q)$. This can be done by an efficient search algorithm, such as beam search starting from $\mathcal{V}_Q$. Then, we compute $\tilde{\mathcal{A}}_Q$ as the union of all target nodes of the selected relation sequences. More details about the knowledge-seeking algorithm are provided in Appendix B.

2.2 Refining the solution on the original KG

In certain cases, like multi-hop question answering [50], the set of candidate answers $\tilde{\mathcal{A}}_Q$ may already be a reasonable estimate of $\mathcal{A}_Q$. We will substantiate this claim experimentally in Section 4. In general, however, we recover $\mathcal{A}_Q$ by using an *edge-level* model ψ applied on a subgraph $\mathcal{G}(\tilde{\mathcal{A}}_Q)$ of $\mathcal{G}$. Specifically, we construct $\mathcal{G}(\tilde{\mathcal{A}}_Q)$ as the subgraph induced by the set of nodes $\mathcal{V}(\tilde{\mathcal{A}}_Q)$, which includes all nodes visited when following the top-k relation sequences along with their neighbors (see Figure 1 for an example). Any existing method for KBQA can be used to instantiate ψ by running it on $\mathcal{G}(\tilde{\mathcal{A}}_Q)$ rather than $\mathcal{G}$. We opted to use a Graph Convolutional Network (GCN) conditioned on the input question with the same architecture as in [41]. The edge-level model is constrained to predict an answer among the candidates generated by the relation-level model.

2.3 Analysis of scalability and expressive power

This section provides a scalability analysis of our approach and shows that the relation-level model scales linearly with the number of relation types in the graph. Then, we analyse the expressive power of **SQALER** and we show the class of supported logical queries.

Computational complexity. As mentioned, we do not evaluate the likelihood ϕ for all edges in $\tilde{\mathcal{G}}_Q$, but we generate the most likely relation sequences using a knowledge-seeking procedure based on the beam search algorithm. At any given time step, only the β most likely relation sequences are retained and further explored at the next iteration. Hence, the time complexity required by our algorithm is $\mathcal{O}(\tau_{max} \cdot \beta \cdot d^+_{max}(\tilde{\mathcal{G}}_Q))$, where τ_{max} is the maximum allowed number of decoding time steps and $d^+_{max}(\tilde{\mathcal{G}}_Q)$ is the maximum outdegree of $\tilde{\mathcal{G}}_Q$. Note that $d^+_{max}(\tilde{\mathcal{G}}_Q)$ is bounded by the number of relations in the graph, whereas τ_{max} and β are constant parameters of the algorithm and are usually small. This gives a time complexity of:

$$\mathcal{O}(\tau_{max} \cdot \beta \cdot |\mathcal{R}|) = \mathcal{O}(|\mathcal{R}|).$$

Hence, the knowledge-seeking algorithm scales linearly with the number of relations in the KG. The space complexity is also $\mathcal{O}(\tau_{max} \cdot \beta \cdot |\mathcal{R}|)$. A more detailed analysis is provided in Appendix B.

Expressive power. Given a natural language question Q, we can represent the inferential chain needed to obtain $\mathcal{A}_Q$ from $\mathcal{V}_Q$ as a logical query Q on $\mathcal{G}$. As an example, the question in Figure 2, *"Who starred in films directed by George Lucas?"*, can be represented by the logical query: $\mathsf{Q}[\mathsf{V}_?] = \mathsf{V}_?.\exists \mathsf{V} : \mathsf{Directed}(\mathsf{George_Lucas}, \mathsf{V}) \wedge \mathsf{Starred}(\mathsf{V}, \mathsf{V}_?)$. We denote with $\mathsf{V}_?$ the target variable of the query and we say that $v \in \mathcal{V}$ satisfies Q if $\mathsf{Q}[v] = \mathsf{True}$. A query Q is an *existential positive first-order (EPFO) query* if it involves the existential quantification ($\exists$), conjunction ($\wedge$), and disjunction ($\vee$) [12] of literals corresponding to relations in the KG. Each literal is of the form $r(\mathsf{V}, \mathsf{V}')$, where V is either a node in $\mathcal{V}_Q$ or an existentially quantified bound variable, and V' is either an existentially quantified bound variable or the target variable. A literal $r(\mathsf{V}, \mathsf{V}')$ is satisfied if $\mathsf{V} \xrightarrow{r} \mathsf{V}'$, for $r \in \mathcal{R}$. Any EPFO query can be represented in *disjunctive normal form* (DNF) [15], namely as a disjunction of conjunctions. Note that, we do not consider queries with universal quantification ($\forall$), as we assume that in real-world KGs no entity connects to all the others. Then, the following proposition holds for any knowledge graph and EPFO query.

Proposition 1. *Let $\mathcal{G} = (\mathcal{V}, \mathcal{R}, \mathcal{E})$ be a knowledge graph and $\mathcal{V}_Q \subseteq \mathcal{V}$ denote a set of entities in $\mathcal{G}$. Let Q be a valid existential positive first-order query on $\mathcal{G}$ and let $n_\vee$ be the number of disjunction operators in the disjunctive normal form of Q. Then, there exist $k \leq n_\vee + 1$ sequences of relations $R_i^\star \in \mathcal{R}^*$ such that:*

$$\mathcal{A}_Q \subseteq \bigcup_{i=1}^{k} reach_{\mathcal{G}}(\mathcal{V}_Q, R_i^\star),$$

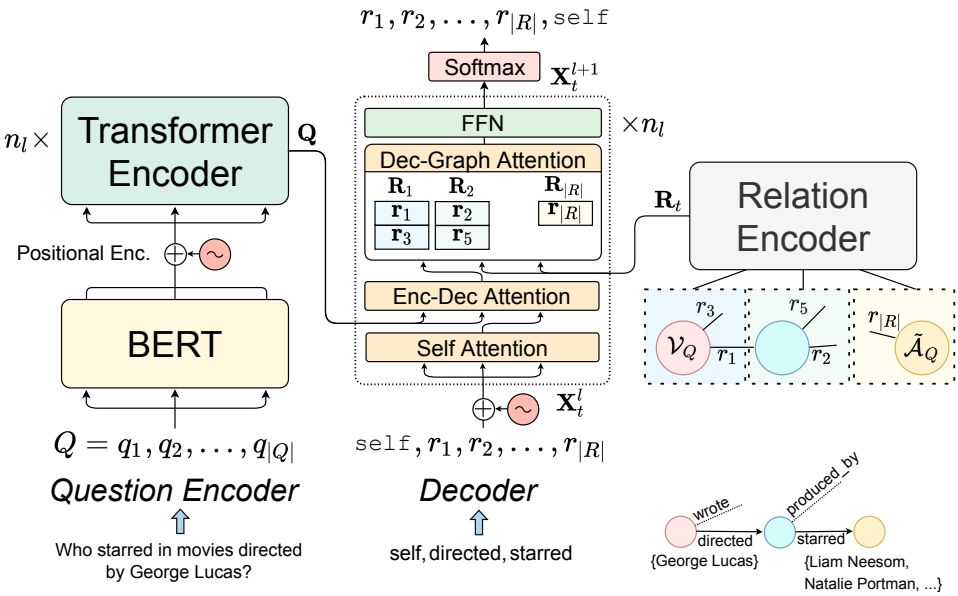


Figure 2: Architecture of the **SQALER** relation-level model. A question encoder is used to obtain a representation of tokens in the input natural language question. Then a graph-guided decoder is applied to obtain the likelihood of output relation sequences. The decoder is constrained to only attend to valid relations according to the structure of the coalesced KG.

where $\mathcal{A}_Q = \{v \in \mathcal{V} \mid \mathsf{Q}[v] = \mathsf{True}\}$ *is the denotation set of* Q*, namely the entities satisfying* Q.

This shows that sampling $n_\vee + 1$ sequences of relations allows generating a set of candidate answers $\tilde{\mathcal{A}}_Q$ that does not miss any of the real answers $\mathcal{A}_Q$. Then, assuming that the edge-level model ψ can recover $\mathcal{A}_Q$ from $\tilde{\mathcal{A}}_Q$, our approach can be used to answer any EPFO query on $\mathcal{G}$. More details about the expressive power of **SQALER** and the proof of Proposition 1 are provided in Appendix C.

3 Architecture of the relation-level model

For the relation-level model ϕ, we propose an auto-encoder, where the the decoder is constrained to follow sequences of relations in the coalesced representation $\tilde{\mathcal{G}}_Q$. We train the network with weak supervision, assuming that a sequence of relations is correct if it reaches a set of candidate answers $\tilde{\mathcal{A}}_Q$ that is the smallest reachable superset of the $\mathcal{A}_Q$. We found it useful to *pretrain* the model in order to infuse knowledge from the KG. In this case, we train the model to predict a path in the KG, given the representations of the source and target nodes. More details about training strategies are given in Appendix D.

The architecture of the model (see Figure 2) includes three main components: a *question encoder*, a *relation encoder* and a *graph-guided decoder*. We explain each one below.

Question encoder. The encoder receives as input a natural language question, which comprises a sequence of tokens $Q = (q_1, q_2, \ldots, q_{|Q|})$. The question is encoded using a pre-trained BERT [18] model and processed with the same positional encoding technique used in [44]. The resulting embeddings are then fed into $n_l = 3$ transformer encoder layers [44]. This results in a matrix $\mathbf{Q} \in \mathbb{R}^{|Q|+1 \times d_{model}}$, where the first row vector is an overall representation of the whole query Q (derived from the embedding of the `[CLS]` token introduced by BERT) and each remaining row represents the final d_{model}-dimensional encoding of a token in the input question.

Relation encoder. The relation encoder produces a representation $\mathbf{r} \in \mathbb{R}^{d_{model}}$ for each relation type $r \in \mathcal{R}$. We decided to encode relations based on their surface form, with the same pre-trained BERT model used in the question encoder. In this case, only the embedding of the `[CLS]` token is used in order to get the final representation $\mathbf{r}$ of each relation type $r \in \mathcal{R}$. At inference time, or in

case the BERT model is not fine-tuned, the embeddings of the relations can be precomputed as a preprocessing step to improve the efficiency of the approach.

Graph-guided decoder. The decoder's job is to predict a sequence of relations leading from $\mathcal{V}_Q$ to $\tilde{\mathcal{A}}_Q$ in $\tilde{\mathcal{G}}_Q$. At any time step t, it receives as input a sequence of relations $R_t = (\texttt{self}, r_1, \ldots, r_{t-1})$ and predicts the next relation r_t (`self` is used as a special token to denote the start of decoding). Note that the input sequence uniquely determines a node $\mathcal{V}_t$ in the graph $\tilde{\mathcal{G}}_Q$, namely the node reachable from $\mathcal{V}_Q$ by following R_t. The decoder thus selects r_t by choosing amongst the outgoing edges $\tilde{\mathcal{E}}_t$ of $\mathcal{V}_t$. We use the same number of layers n_l both for the question encoder and the decoder. Let $\mathbf{X}_t^l = [\mathbf{x}_0^l, \ldots, \mathbf{x}_{t-1}^l]^\top \in \mathbb{R}^{t \times d_{model}}$ denote the hidden state of the l-th layer of the decoder preceding time step t. Note that $\mathbf{X}_t^0$ is the representation of the sequence R_t, obtained by using the relation encoder described above and the same positional encoding technique used in the question encoder. For each decoder layer, we perform self-attention over the target sequence $\mathbf{X}_t^l$ by computing:

$$\bar{\mathbf{x}}_t^l = \textit{Attention}(\mathbf{x}_t^l, \mathbf{X}_t^l, \mathbf{X}_t^l),$$

where *Attention* is a function that performs multi-head scaled dot-product attention [44] with skip connections and layer normalization [4]. The above step allows each relation in the decoded sequence to attend to all the others predicted up to time step t. We then let the result attend to the question as:

$$\bar{\mathbf{x}}_t^{Q,l} = \textit{Attention}(\bar{\mathbf{x}}_t^l, \mathbf{Q}, \mathbf{Q}).$$

This is done in order to update the current state of the decoder based on the input question. Next, let $\mathbf{R}_t \in \mathbb{R}^{|\tilde{\mathcal{E}}_t| \times d_{model}}$ denote the encoding of the relations labeling all edges in $\tilde{\mathcal{E}}_t$. We constrain the decoded sequence to follow the structure of the graph by attending only to valid relations as follows:

$$\bar{\mathbf{x}}_t^{R,l} = \textit{Attention}(\bar{\mathbf{x}}_t^{Q,l}, \mathbf{R}_t, \mathbf{R}_t).$$

We get the hidden state of the next layer $\mathbf{x}_t^{l+1}$ by processing the result with a feed forward network. The model outputs a categorical distribution $\phi(e \mid Q) \in [0, 1]$ over the edges $e \in \tilde{\mathcal{E}}_t$, by applying a softmax function as follows:

$$\phi(\mathcal{V}_i \xrightarrow{r} \mathcal{V}_j \mid Q) = \frac{\exp(\mathbf{r}^\top \mathbf{x}_t^{n_l})}{\sum_{\mathcal{V}_i' \xrightarrow{r'} \mathcal{V}_j' \in \tilde{\mathcal{E}}_t} \exp(\mathbf{r}'^\top \mathbf{x}_t^{n_l})},$$

where $\mathbf{x}_t^{n_l}$ is the output of the final layer of the decoder, whereas $\mathbf{r}$ and $\mathbf{r}'$ denote the representations of relations r and r' respectively.

4 Experiments

This section presents an evaluation of our approach with respect to both reasoning performance and scalability. We first show that **SQALER** reaches state-of-the-art results on popular KBQA benchmarks and can generalize compositionally out of the training distribution. Then, we demonstrate the scalability of our approach on KGs with millions of nodes. We refer the reader to Appendix E for more details about the experiments.

4.1 Experimental setup

Datasets. We evaluate the reasoning performance of our approach on *MetaQA* [50] and *WebQuestionsSP* [49]. *MetaQA* includes multi-hop questions over the WikiMovies KB [35] and we consider both 2-hop (**MetaQA 2**) and 3-hop (**MetaQA 3**) queries. *WebQuestionsSP* (**WebQSP**) comprises more complex questions answerable over a subset of Freebase [21, 7], a large KG with millions of entities. We further assess the compositional generalization ability of **SQALER** on the *Compositional Freebase Questions* (*CFQ*) dataset [28]. Each question in *CFQ* is obtained by composing primitive elements (*atoms*). Whereas the training and test distribution of atoms are similar, the test set contains different *compounds*, namely new ways of composing these atoms. *CFQ* comprises three dataset splits (**MCD1**, **MCD2**, and **MCD3**), with maximal compound divergence (MCD) between the training and test distributions. We refer the reader to Appendix E.1 for an extensive description of the datasets.

Evaluation protocol. In our experiments on *MetaQA* and *WebQuestionsSP*, we assess the performance of three variants of our approach: (a) a version that only makes use of the relation-level model without the refinement step (**SQALER – Unrefined**), (b) a model that utilizes a key-value memory network to identify the correct answers from the candidates (**SQALER – KV-MemNN**), and (c) a model that uses a GNN architecture for the refinement step (**SQALER – GNN**), as explained in Section 2.2. Following previous work [41, 42, 43, 39], we evaluate the models based on the *Hits@1* metric. On the *CFQ* dataset, we evaluate the accuracy of the refined model with the GNN based on whether it predicts exactly the same answers given by the corresponding SPARQL query.

4.2 Main results

KBQA Performance. Table 1 summarizes the results of our experiments on the two benchmark datasets. For the two multi-hop *MetaQA* datasets, we achieve state-of-the-art performance by only using the relation-level model of **SQALER**. As shown in Table 1, **SQALER** outperforms all the baselines on **MetaQA 3**, demonstrating the ability of our approach to perform multi-hop reasoning over a KG. For the more complex questions in the *WebQuestionsSP* dataset, the unrefined **SQALER** model achieves better performance than all but one (**EmQL**) of the baselines. To achieve such performance, however, EmQL creates a custom set of logical operations tailored towards the specifics of the target KG and the kind of questions in the dataset, while our approach is agnostic with respect to such details. Combining the relation and edge-level models improves the performance on **WebQSP**. In particular, **SQALER – GNN** outperforms all considered baselines on the three datasets.

Table 1: Hits@1 on *MetaQA* and *WebQuestionsSP*

	MetaQA 2	MetaQA 3	WebQSP
KV-MemNN [35]	82.7	48.9	46.7
GRAFT-Net [41]	94.8	77.7	70.3
ReifKB + mask [10]	95.4	79.7	52.7
PullNet [42]	99.9	91.4	69.7
EmbedKGQA [39]	98.8	94.8	66.6
EmQL [43]	98.6	99.1	75.5
SQALER – Unrefined	99.9	99.9	70.6
SQALER – KV-MemNN	99.9	99.9	72.1
SQALER – GNN	99.9	99.9	76.1

Compositional generalization. In order to evaluate the compositional generalization ability of **SQALER**, we performed additional experiments on the *CFQ* dataset. Table 2 shows the accuracy on the three MCD splits and the mean accuracy (**MCD-mean**) in comparison to the other methods in the leaderboard. Note that the other approaches address a semantic parsing task and require additional supervision, as they are trained to predict the target query. On the other hand, we aim to predict directly the set of answers to the input question. The experiment shows that **SQALER** is able to achieve compositional generalization with an accuracy comparable to the state-of-the-art model on *CFQ* for semantic parsing.

Subgraph extraction. We analyzed the candidate solutions produced by the relation-level model in order to evaluate the suitability of our approach to building small question subgraphs that are likely to contain the answers to a natural language question. For this purpose, we computed the precision and recall of the set of candidate answers with varying number of relation sequences sampled by the relation-level model. Figure 3 shows the top relation sequences predicted by the relation-level model on two questions from the test set of *WebQuestionsSP*. The precision and recall curves are shown in Figure 4. As expected, on *MetaQA* the recall is high for all values of k, because selecting the most likely sequence of relations is sufficient to solve the multi-hop question answering task. On *WebQuestionsSP*, only 3 sequences of relations are sufficient to obtain a recall of 0.91, and we can improve it to 0.95 by generating still small subgraphs consisting of only 10 sequences of relations.

Table 2: Accuracy and 95% confidence interval on the *CFQ* dataset

	MCD1	MCD2	MCD3	MCD-mean
LSTM + Attention [28, 27, 5]	0.289 ± 0.018	0.050 ± 0.008	0.108 ± 0.006	0.149 ± 0.011
Transformer [28, 44]	0.349 ± 0.011	0.082 ± 0.003	0.106 ± 0.011	0.179 ± 0.009
Universal Transformer [28, 17]	0.374 ± 0.022	0.081 ± 0.016	0.113 ± 0.003	0.189 ± 0.014
Evolved Transformer [20, 40]	0.424 ± 0.010	0.093 ± 0.008	0.108 ± 0.002	0.208 ± 0.007
T5-11B [36, 20]	0.614 ± 0.048	0.301 ± 0.022	0.312 ± 0.057	0.409 ± 0.043
T5-11B-mod [20, 22]	0.616 ± 0.124	0.313 ± 0.128	0.333 ± 0.023	0.421 ± 0.091
HPD [23]	0.720 ± 0.075	0.661 ± 0.064	0.639 ± 0.057	0.673 ± 0.041
SQALER – GNN	0.734 ± 0.039	0.653 ± 0.040	0.627 ± 0.045	0.671 ± 0.041

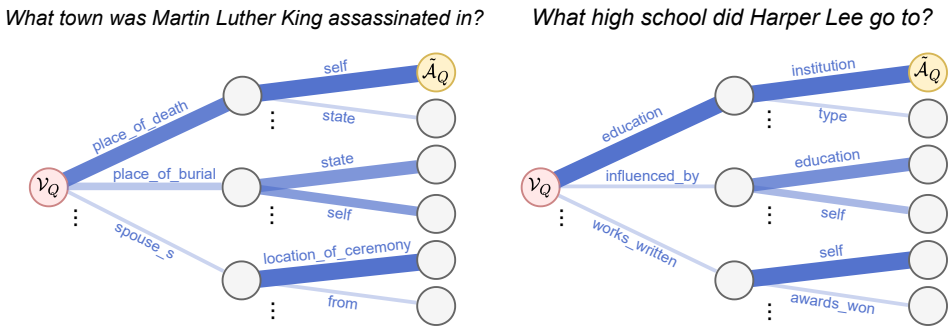


Figure 3: Attention weights given by the relation-level model to the edges of the coalesced graph for two questions in *WebQuestionsSP*. Thicker and darker edges represent higher attention weights.

4.3 Efficiency and scalability

We analyze the efficiency of our approach on synthetic KBs (as in [9, 10]) and then compare the scalability of different preprocessing methods on the KGs of *MetaQA* and *WebQuestiontsSP*. First, we perform experiments on KBs where the relational coalescing has no effect: the outdegree of each node is equal to the number of relation types and all edges originating from a node have different relation labels. We perform two experiments on such KBs. In the first one (Figure 5a), the number of relation types is fixed to $|\mathcal{R}| = 10$ and the number of entities varies from $|\mathcal{V}| = 10^2$ to $|\mathcal{V}| = 10^6$. In the second task (Figure 5b), the number of entities is fixed to $|\mathcal{V}| = 5000$ and the number of relations varies from $|\mathcal{R}| = 1$ to $|\mathcal{R}| = 10^3$. The single answer node is always two-hops away from the entities mentioned in the question. We compare **SQALER** (unrefined) against a GNN-based approach (**GRAFT-Net** [41]) and a key-value memory network (**KV-MemNN** [35]). The approaches are evaluated based on the queries per second at inference time with a mini-batch size of 1. The results show that increasing the number of entities has negligible impact on the performance of **SQALER**, whereas GRAFT-Net and the key-value memory network are limited to graphs with less than 10k nodes. This shows that, in large KGs like Freebase, the baselines would not be able to handle even a 2-hop neighborhood of the entities mentioned in the question (we refer the reader to Appendix E.5 for more details). Finally, from the results in Figure 5b, we see that the throughput of our approach decreases with the number of relation types. However, in practice, we can leverage the GPU to score the edges of the graph in parallel. This is why we observe only a minor drop in performance when the number of relation types grows from $|\mathcal{R}| = 1$ to $|\mathcal{R}| = 100$.

In order to assess the scalability of the proposed relational coalescing operation, we further compare commonly used preprocessing methods on the KG of *WebQuestionsSP*. We evaluate the time required to extract complete 2-hop neighborhoods of the entities mentioned in the question and the time to perform Personalized Page Rank (PPR) on such graphs. The results are shown in Figure 5c. Note that, at inference time, we can perform the coalescing only on the portion of the graph explored by the model, which makes **SQALER** much more efficient. At training time, the preprocessing is comparable to the 2-hop neighborhood extraction. Finally, Figure 5d shows the performance of the models with the respective preprocessing step at inference time on synthetic KBs with growing number of edges.

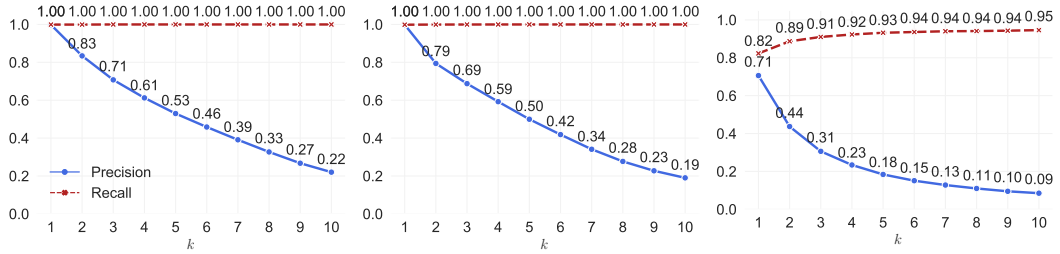
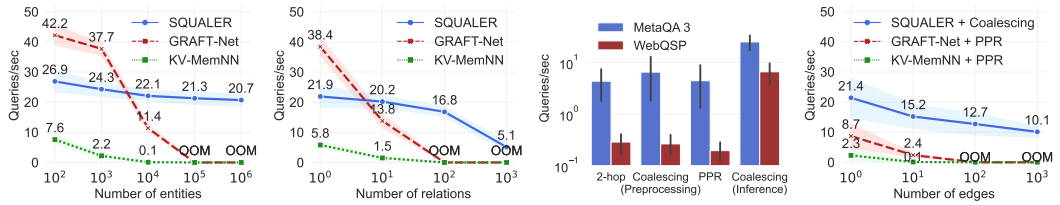


Figure 4: Precision and recall of the top k sequences of relations on MetaQA 2 (left), MetaQA 3 (center) and WebQSP (right)



(a) (b) (c) (d)

Figure 5: Inference time in queries/sec on synthetic KBs with increasing number of entities (a) and relation types (b). Time required by different preprocessing steps on the KG of *WebQuestionsSP* and *MetaQA* (c). Complete inference and preprocessing time on synthetic KBs with increasing number of edges (d). We set the queries/sec to 0 when the model runs out-of-memory (OOM).

4.4 Incomplete knowledge graphs

In order to evaluate the capability of our approach to cope with missing information in the knowledge graph, we performed two additional experiments. In the first experiment, we evaluated our approach (the **SQALER – GNN** variant) on *WebQuestionsSP* using incomplete knowledge graphs with only 50% of the original edges (**50% KG**). Then, following previous work [41, 42], we tried to mitigate the missing information using additional sources of external knowledge. In particular, for each question, we used the same text documents extracted from Wikipedia as done by Sun et al. [41] (**50% KG + Text**). In this experiment, the relation-level model is unaware of the additional source of knowledge, but the information from the text documents is infused into the edge-level GNN with the same strategy used in GRAFT-Net [41] (note that this makes the edge-level GNN-based model essentially equivalent to the full version of GRAFT-Net, with both KG and text support). We compare our approach against **GRAFT-Net** and **PullNet**, namely the two baselines designed for open-domain question answering with incomplete KGs and text documents.

The results of the experiments are reported in Table 3. We observe that, despite not being designed for incomplete KGs, **SQALER** outperforms the baselines on both experimental settings. This is not surprising, as **GRAFT-Net** relies on a simple heuristic process to construct question subgraphs and **PullNet** is constrained to follow the structure of the incomplete graph, because its iterative retrieval process can only expand nodes that are reachable from the set of anchor entities. This means that, in principle, any node retrieved by **PullNet**'s iterative process can also be reached by **SQALER**'s relation-level model. Similarly to the baselines, we note only a minor gain in performance when using the text documents as an additional source of information.

Table 3: Hits@1 on *WebQuestionsSP* with incomplete KGs (50% of the edges) and additional text

	50% KG	**50% KG + Text**
GRAFT-Net [41]	48.2	49.9
PullNet [42]	50.3	51.9
SQALER – GNN	53.5	55.2

5 Related work

Several lines of research in the past few years have focused on introducing deep learning approaches aimed at reasoning over structured knowledge. In particular, this paper is closely related to methods for learning to traverse KGs [14, 13, 24] and recent works on answering conjunctive queries using deep learning approaches [25, 16]. In this context, several KB and query embedding methods have been proposed [45]. Many KB embedding approaches support the same operation performed by our relation-level model, namely relation projection [10, 43, 25, 38]. Some KB embedding methods also explicitly learn to follow chains of relations and traverse KGs [24, 30, 13]. Notably, Query2Box [38] is a query embedding method that represents sets using box embeddings and the more recent beta embeddings [37] extend the framework to support a complete set of first-order logic operators. The main difference with our model is that these methods operate on vector space, whereas our approach is constrained on the graph structure and learns to traverse the KG while keeping the ability to scale to large graphs. Also, our method answers questions in natural language, while the above methods are primarily designed for query answering. Recently, Sun et al. [43] introduced EmQL, a query embedding method which has also been integrated in a question answering model.

Other lines of research on KBQA have focused on unsupervised semantic parsing [3, 2, 1] or on the introduction of supervised models, like graph neural networks (GNNs) designed for reasoning over knowledge graphs [41, 42, 48]. These approaches pose the KBQA problem as a node classification task. For this reason, they have been applied succesfully only on small query-dependent graphs. Cohen et al. [10] addressed the problem of creating a representation of a symbolic KB that enables building neural KB inference modules that are scalable enough to perform non-trivial inferences with large graphs. Another recent work [39] has explored using KG embeddings for question answering and handle incompleteness in the KG.

In our work, we combine relation projection with an edge-level GNN to address the KBQA problem. The same idea of combining GNNs with relational following was introduced in Gretel [11], which learns to complete natural paths in a graph given a path prefix. Also, our idea of accelerating GNNs by operating on a reduced graph representation has strong connections with graph coarsening and sparsification [32, 33, 6].

Methods based on reinforcement learning (RL) have also been proposed to perform multi-hop reasoning over knowledge graphs. Xiong et al. [46] proposed DeepPath, which relies on a policy-based agent that learns to reason over multi-hop paths by sampling relations at each step. Also, Das et al. [14] introduced MINERVA, a RL agent that learns how to navigate the graph conditioned only on an input entity and on a query. These approaches are designed for simple query answering and KB completion rather than KBQA. A main difference with our work is that **SQALER** samples multiple paths and employs an edge-level model to reach higher expressivity.

6 Conclusion

This paper introduced **SQALER**, a scalable approach to reasoning and question answering over KGs. Our method is expressive and can reach state-of-the-art performance on widely used and challenging datasets. Further, **SQALER** scales with the number of (distinct) relation types in the graph and can effectively handle large-scale knowledge graphs with millions of entities. Our empirical evaluation also showed that our approach can generalize compositionally and that it can be used to generate question-dependent subgraphs that strike a good trade-off between precision and recall.

Overall, our work proposes an improvement to existing KBQA technology which carries impact to several practical applications. Nevertheless, we remind that the deployment of such models needs to be done cautiously. KBQA replaces a mature technology (traditional KBs and query languages) with less understood methods. The underlying KB may be incomplete, contain misinformation or biases that could negatively affect the decisions of the learned model. We hope that our work will spur further research in this area and contribute to the development of reliable KBQA systems.

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References

[1] Mattia Atzeni and Maurizio Atzori. Towards semantic approaches for general-purpose end-user development. In *Second IEEE International Conference on Robotic Computing, IRC 2018, Laguna Hills, CA, USA, January 31 - February 2, 2018*, pages 369–376. IEEE Computer Society, 2018. doi:10.1109/IRC.2018.00077. URL https://doi.org/10.1109/IRC.2018.00077.

[2] Mattia Atzeni and Maurizio Atzori. Translating natural language to code: An unsupervised ontology-based approach. In *First IEEE International Conference on Artificial Intelligence and Knowledge Engineering, AIKE 2018, Laguna Hills, CA, USA, September 26-28, 2018*, pages 1–8. IEEE Computer Society, 2018. doi:10.1109/AIKE.2018.00009. URL https://doi.org/10.1109/AIKE.2018.00009.

[3] Mattia Atzeni and Maurizio Atzori. What is the cube root of 27? Question answering over codeontology. In *The Semantic Web - ISWC 2018 - 17th International Semantic Web Conference*, volume 11136 of *Lecture Notes in Computer Science*, pages 285–300. Springer, 2018.

[4] Lei Jimmy Ba, Jamie Ryan Kiros, and Geoffrey E. Hinton. Layer normalization. *CoRR*, abs/1607.06450, 2016. URL http://arxiv.org/abs/1607.06450.

[5] Dzmitry Bahdanau, Kyunghyun Cho, and Yoshua Bengio. Neural machine translation by jointly learning to align and translate. In *ICLR 2015*, 2015.

[6] Joshua D. Batson, Daniel A. Spielman, Nikhil Srivastava, and Shang-Hua Teng. Spectral sparsification of graphs: theory and algorithms. *Commun. ACM*, 56(8):87–94, 2013. doi:10.1145/2492007.2492029. URL https://doi.org/10.1145/2492007.2492029.

[7] Kurt Bollacker, Colin Evans, Praveen Paritosh, Tim Sturge, and Jamie Taylor. Freebase: A collaboratively created graph database for structuring human knowledge. In *Proceedings of the 2008 ACM SIGMOD International Conference on Management of Data*, SIGMOD '08, page 1247–1250. Association for Computing Machinery, 2008.

[8] Antoine Bordes, Nicolas Usunier, Alberto García-Durán, Jason Weston, and Oksana Yakhnenko. Translating embeddings for modeling multi-relational data. In *Advances in Neural Information Processing Systems 26: 27th Annual Conference on Neural Information Processing Systems 2013*, pages 2787–2795, 2013.

[9] William W. Cohen, Fan Yang, and Kathryn Mazaitis. TensorLog: Deep learning meets probabilistic dbs. *CoRR*, abs/1707.05390, 2017. URL http://arxiv.org/abs/1707.05390.

[10] William W. Cohen, Haitian Sun, R. Alex Hofer, and Matthew Siegler. Scalable neural methods for reasoning with a symbolic knowledge base. In *ICLR 2020*, 2020.

[11] Jean-Baptiste Cordonnier and Andreas Loukas. Extrapolating paths with graph neural networks. In Sarit Kraus, editor, *Proceedings of the Twenty-Eighth International Joint Conference on Artificial Intelligence, IJCAI 2019, Macao, China, August 10-16, 2019*, pages 2187–2194. ijcai.org, 2019. doi:10.24963/ijcai.2019/303. URL https://doi.org/10.24963/ijcai.2019/303.

[12] Nilesh N. Dalvi and Dan Suciu. The dichotomy of probabilistic inference for unions of conjunctive queries. *J. ACM*, 59(6):30:1–30:87, 2012. doi:10.1145/2395116.2395119. URL https://doi.org/10.1145/2395116.2395119.

[13] Rajarshi Das, Arvind Neelakantan, David Belanger, and Andrew McCallum. Chains of reasoning over entities, relations, and text using recurrent neural networks. In *Proceedings of the 15th Conference of the European Chapter of the Association for Computational Linguistics, EACL 2017, Volume 1: Long Papers*, pages 132–141. Association for Computational Linguistics, 2017.

[14] Rajarshi Das, Shehzaad Dhuliawala, Manzil Zaheer, Luke Vilnis, Ishan Durugkar, Akshay Krishnamurthy, Alex Smola, and Andrew McCallum. Go for a walk and arrive at the answer: Reasoning over paths in knowledge bases using reinforcement learning. In *ICLR 2018*, 2018.

[15] B. A. Davey and H. A. Priestley. *Introduction to Lattices and Order*. Cambridge University Press, 2 edition, 2002.

[16] Daniel Daza and Michael Cochez. Message passing for query answering over knowledge graphs. *CoRR*, abs/2002.02406, 2020. URL https://arxiv.org/abs/2002.02406.

[17] Mostafa Dehghani, Stephan Gouws, Oriol Vinyals, Jakob Uszkoreit, and Lukasz Kaiser. Universal transformers. In *ICLR 2019*, 2019.

[18] Jacob Devlin, Ming-Wei Chang, Kenton Lee, and Kristina Toutanova. BERT: pre-training of deep bidirectional transformers for language understanding. In *NAACL 2019*, 2019.

[19] David Ferrucci, Eric Brown, Jennifer Chu-Carroll, James Fan, David Gondek, Aditya Kalyanpur, Adam Lally, J William Murdock, Eric Nyberg, John Prager, Nico Schlaefer, and Christopher Welty. Building Watson: An Overview of the DeepQA Project. *AI Magazine*, 2010.

[20] Daniel Furrer, Marc van Zee, Nathan Scales, and Nathanael Schärli. Compositional generalization in semantic parsing: Pre-training vs. specialized architectures. *CoRR*, abs/2007.08970, 2020. URL `https://arxiv.org/abs/2007.08970`.

[21] Google. Freebase data dumps. `https://developers.google.com/freebase/data`.

[22] Jiaqi Guo, Zecheng Zhan, Yan Gao, Yan Xiao, Jian-Guang Lou, Ting Liu, and Dongmei Zhang. Towards complex text-to-sql in cross-domain database with intermediate representation. In *Proceedings of the 57th Conference of the Association for Computational Linguistics, ACL 2019*, pages 4524–4535. Association for Computational Linguistics, 2019.

[23] Yinuo Guo, Zeqi Lin, Jian-Guang Lou, and Dongmei Zhang. Hierarchical poset decoding for compositional generalization in language. In *Advances in Neural Information Processing Systems 33: Annual Conference on Neural Information Processing Systems 2020, NeurIPS 2020*, 2020.

[24] Kelvin Guu, John Miller, and Percy Liang. Traversing knowledge graphs in vector space. In *Proceedings of the 2015 Conference on Empirical Methods in Natural Language Processing, EMNLP 2015*, pages 318–327. The Association for Computational Linguistics, 2015.

[25] William L. Hamilton, Payal Bajaj, Marinka Zitnik, Dan Jurafsky, and Jure Leskovec. Embedding logical queries on knowledge graphs. In *NeurIPS 2018*, 2018.

[26] Xu Han, Shulin Cao, Lv Xin, Yankai Lin, Zhiyuan Liu, Maosong Sun, and Juanzi Li. Openke: An open toolkit for knowledge embedding. In *Proceedings of EMNLP*, 2018.

[27] Sepp Hochreiter and Jürgen Schmidhuber. Long short-term memory. *Neural computation*, 9(8): 1735–1780, 1997.

[28] Daniel Keysers, Nathanael Schärli, Nathan Scales, Hylke Buisman, Daniel Furrer, Sergii Kashubin, Nikola Momchev, Danila Sinopalnikov, Lukasz Stafiniak, Tibor Tihon, Dmitry Tsarkov, Xiao Wang, Marc van Zee, and Olivier Bousquet. Measuring compositional generalization: A comprehensive method on realistic data. In *8th International Conference on Learning Representations, ICLR 2020*. OpenReview.net, 2020.

[29] Brenden M. Lake and Marco Baroni. Generalization without systematicity: On the compositional skills of sequence-to-sequence recurrent networks. In *ICML*, 2018.

[30] Yankai Lin, Zhiyuan Liu, Huan-Bo Luan, Maosong Sun, Siwei Rao, and Song Liu. Modeling relation paths for representation learning of knowledge bases. In *Proceedings of the 2015 Conference on Empirical Methods in Natural Language Processing, EMNLP 2015*, pages 705–714. The Association for Computational Linguistics, 2015.

[31] Ilya Loshchilov and Frank Hutter. Decoupled weight decay regularization. In *7th International Conference on Learning Representations, ICLR 2019*. OpenReview.net, 2019.

[32] Andreas Loukas. Graph reduction with spectral and cut guarantees. *J. Mach. Learn. Res.*, 20: 116:1–116:42, 2019. URL `http://jmlr.org/papers/v20/18-680.html`.

[33] Andreas Loukas and Pierre Vandergheynst. Spectrally approximating large graphs with smaller graphs. In Jennifer G. Dy and Andreas Krause, editors, *Proceedings of the 35th International Conference on Machine Learning, ICML 2018, Stockholmsmässan, Stockholm, Sweden, July 10-15, 2018*, volume 80 of *Proceedings of Machine Learning Research*, pages 3243–3252. PMLR, 2018. URL `http://proceedings.mlr.press/v80/loukas18a.html`.

[34] Gary Marcus. The next decade in ai: Four steps towards robust artificial intelligence, 2020.

[35] Alexander H. Miller, Adam Fisch, Jesse Dodge, Amir-Hossein Karimi, Antoine Bordes, and Jason Weston. Key-value memory networks for directly reading documents. In *Proceedings of the 2016 Conference on Empirical Methods in Natural Language Processing, EMNLP 2016*, pages 1400–1409. The Association for Computational Linguistics, 2016.

[36] Colin Raffel, Noam Shazeer, Adam Roberts, Katherine Lee, Sharan Narang, Michael Matena, Yanqi Zhou, Wei Li, and Peter J. Liu. Exploring the limits of transfer learning with a unified text-to-text transformer. *J. Mach. Learn. Res.*, 21:140:1–140:67, 2020.

[37] Hongyu Ren and Jure Leskovec. Beta embeddings for multi-hop logical reasoning in knowledge graphs. In *Advances in Neural Information Processing Systems 33: Annual Conference on Neural Information Processing Systems 2020, NeurIPS 2020*, 2020.

[38] Hongyu Ren, Weihua Hu, and Jure Leskovec. Query2box: Reasoning over knowledge graphs in vector space using box embeddings. In *ICLR*, 2020.

[39] Apoorv Saxena, Aditay Tripathi, and Partha P. Talukdar. Improving multi-hop question answering over knowledge graphs using knowledge base embeddings. In *Proceedings of the 58th Annual Meeting of the Association for Computational Linguistics, ACL 2020*, pages 4498–4507. Association for Computational Linguistics, 2020.

[40] David R. So, Quoc V. Le, and Chen Liang. The evolved transformer. In *Proceedings of the 36th International Conference on Machine Learning, ICML 2019*, volume 97 of *Proceedings of Machine Learning Research*, pages 5877–5886. PMLR, 2019.

[41] Haitian Sun, Bhuwan Dhingra, Manzil Zaheer, Kathryn Mazaitis, Ruslan Salakhutdinov, and William W. Cohen. Open domain question answering using early fusion of knowledge bases and text. In *EMNLP*, 2018.

[42] Haitian Sun, Tania Bedrax-Weiss, and William W. Cohen. Pullnet: Open domain question answering with iterative retrieval on knowledge bases and text. In *EMNLP*, 2019.

[43] Haitian Sun, Andrew O. Arnold, Tania Bedrax-Weiss, Fernando Pereira, and William W. Cohen. Faithful Embeddings for Knowledge Base Queries. In *NeurIPS 2020*, 2020.

[44] Ashish Vaswani, Noam Shazeer, Niki Parmar, Jakob Uszkoreit, Llion Jones, Aidan N. Gomez, Lukasz Kaiser, and Illia Polosukhin. Attention is all you need. In *Advances in Neural Information Processing Systems 30, NeurIPS 2017*, pages 6000–6010, 2017.

[45] Quan Wang, Zhendong Mao, Bin Wang, and Li Guo. Knowledge graph embedding: A survey of approaches and applications. *IEEE Trans. Knowl. Data Eng.*, 29(12):2724–2743, 2017.

[46] Wenhan Xiong, Thien Hoang, and William Yang Wang. DeepPath: A reinforcement learning method for knowledge graph reasoning. In *EMNLP*, 2017.

[47] Xuchen Yao and Benjamin Van Durme. Information extraction over structured data: Question answering with freebase. In *Proceedings of the 52nd Annual Meeting of the Association for Computational Linguistics, ACL 2014, Volume 1: Long Papers*, pages 956–966. The Association for Computer Linguistics, 2014.

[48] Michihiro Yasunaga, Hongyu Ren, Antoine Bosselut, Percy Liang, and Jure Leskovec. QA-GNN: Reasoning with language models and knowledge graphs for question answering. In *North American Chapter of the Association for Computational Linguistics (NAACL)*, 2021.

[49] Wen-tau Yih, Ming-Wei Chang, Xiaodong He, and Jianfeng Gao. Semantic parsing via staged query graph generation: Question answering with knowledge base. In *Proceedings of the 53rd Annual Meeting of the ACL*, 2015.

[50] Yuyu Zhang, Hanjun Dai, Zornitsa Kozareva, Alexander J. Smola, and Le Song. Variational reasoning for question answering with knowledge graph. In *AAAI*, 2018.