

Type-checking knowledge graphs

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Abstract. We first present a formal view of a knowledge graph. On this basis, the type-checking rules are developed to define correct typing relationships among the triples of a knowledge graph. We discuss the algorithms for verifying the typing relationships against the given knowledge graph. Finally, we present the experimental results of type-checking the Yago4 knowledge graph.

Keywords: RDF stores · graph databases · knowledge graphs · database statistics · statistics of graph databases.

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1 Introduction

This is intro... [1].

– Topic: KGs are becoming KBs...

– Topic: Give an abstract insight into the structure of KB. Identifiers, schema, types, ...

– Topic: Show the ground triples, poset of triples, types triples, schema graph, etc.

2 Definition of knowledge graph

This section defines a knowledge graph as a RDF graph [6] using RDF-Schema [7] for the representation of the structural part of a knowledge base.

Let I be the set of URI-s, B be the set of blanks and L be the set of literals. Let us also define sets $S = I \cup B$, $P = I$, and $O = I \cup B \cup L$.

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RDF triple is a triple $(s, p, o) \in S \times P \times O$. *RDF graph* $g \subseteq S \times P \times O$ is a set of triples. Set of all graphs will be denoted as G . We suppose the existence of a set of variables V and the set of *terms* $T = O \cup V$. Term $t \in T$ is ground if $t \in O$.

We say that RDF graph g_1 is *sub-graph* of g_2 , denoted $g_1 \sqsubseteq g_2$, if all triples in g_1 are also triples from g_2 .

– Define major structure of KG on the basis of the sorts of data.

– ...the set I includes individual identifiers I_i , class identifiers I_c and predicate identifiers I_p .

3 Type system used

3.1 Product types

3.2 Intersection type

The instances of the intersection type $T_1 \wedge T_2$ are objects belonging to both T_1 and T_2 . The type $T_1 \wedge T_2$ is the greatest lower bound of the types T_1 and T_2 . In general, $\wedge[T_1 \dots T_n]$ is the greatest lower bound of types $T_1 \dots T_n$ [3, 4].

$$T_1 \wedge T_2 \preceq T_1 \quad (1)$$

$$T_1 \wedge T_2 \preceq T_2 \quad (2)$$

$$\wedge[T_1 \dots T_n] \preceq T_i \quad (3)$$

If the type S is more specific than the types $T_1 \dots T_n$ then S is more specific than $\wedge[T_1 \dots T_n]$. First, we present the rule for a pair of types T_1 and T_2 .

$$\frac{S \preceq T_1 \quad S \preceq T_2}{S \preceq T_1 \wedge T_2} \quad (4)$$

$$\frac{\text{forall } i, S \preceq T_i}{S \preceq \wedge[T_1 \dots T_n]} \quad (5)$$

3.3 Union type

The intersection and union types are dual. This can be seen also from the rules that are used for each particular type.

The instances from the union type $T_1 \vee T_2$ are either the instances of T_1 or T_2 , or the instances of both types. The type $T_1 \vee T_2$ is the smallest upper bound of the types T_1 and T_2 . In general, $\vee[T_1 \dots T_n]$ is the smallest upper bound of types $T_1 \dots T_n$ [2].

$$T_1 \preceq T_1 \vee T_2 \quad (6)$$

$$T_2 \preceq T_1 \vee T_2 \quad (7)$$

$$T_i \preceq \vee[T_1 \dots T_n] \quad (8)$$

If the type T is more general than the types $S_1 \dots S_n$ then T is more general than $\vee[S_1 \dots S_n]$. First, we present the rule for types T_1 and T_2 .

$$\frac{S_1 \preceq T \quad S_2 \preceq T}{S_1 \vee S_2 \preceq T} \quad (9)$$

$$\frac{\text{forall } i, S_i \preceq T}{\vee[S_1 \dots S_n] \preceq T} \quad (10)$$

4 Typing identifiers

- Introduction includes the formalization of RDF, RDF-Schema as given in Angles and Peres.
- Typing ids without considering and info about the triples.

– General.

- At the end of section define the lub type using $\wedge \vee$ types.
- 1. Define lub types as the closest to base types of given ground ident.
- 2. Collect all lub types using \wedge type in a single type.

– Details.

- 1. First define base type of identifiers $:_1$ and stored subtyping relationship \preceq_1 .
- 2. From the basis define the indent typing $:$ and subtyping rel \preceq among identifiers.
- 3. Include the link between subtyping and typing.
- 4. Define lub type using \wedge type for a given ground ident.

4.1 Typing literals

– *Literals are identifiers of atomic type!*

4.2 Stored typing and subtyping of identifiers.

The individual and class entities are represented by identifiers from the set \mathcal{I} . The individual identifiers \mathcal{I}_i stand for literals, concrete and abstract entities. The class identifiers \mathcal{I}_c represent abstract entities that have an unempty interpretation. The abstract entities include, besides the identifiers of user-defined classes, the types (classes) of literals.

A graph database includes stored definitions for typing the individual identifiers, and for representing the specialization/generalization hierarchies of classes and properties.

Let us introduce the typing and specialization/generalization relationships formally. The expression $i :_{\downarrow} C$ states that a class C is a type of an individual identifier i . The expression $i_1 \preceq_{\downarrow} i_2$ defines the sub-class relationship between the class identifiers i_1 and i_2 . The index ' \downarrow ' in relations $:_{\downarrow}$ and \preceq_{\downarrow} denotes that the relationships is stored in a database. Such notation allows us to address differently the stored and the derived parts of the graph database schema.

The rule for the one-step relationship $:_{\downarrow}$ is defined using the predicate `rdf:type`.

$$\frac{I \in \mathcal{I}_i \quad I_c \in \mathcal{I}_c \quad (I, \text{rdf:type}, I_c) \in \mathcal{D}}{I :_{\downarrow} I_c} \quad (11)$$

The individual entity I can have more than one stored types, e.g., I_{c1} and I_{c2} . Therefore, $I :_{\downarrow} I_{c1}$ and $I :_{\downarrow} I_{c2}$ holds, and we can instead write $I :_{\downarrow} I_{c1} \wedge I_{c2}$. All existing stored typings of I can be gathered by Rule 22 presented later.

A one-step subtyping relationship \preceq_{\downarrow} is defined by means of the RDF predicate `rdfs:subClassOf` in the following rule.

$$\frac{I_1, I_2 \in \mathcal{I}_c \quad (I_1, \text{rdfs:subClassOf}, I_2) \in \mathcal{D}}{I_1 \preceq_{\downarrow} I_2} \quad (12)$$

The rule for the definition of the one-step subtyping relationship \preceq_{\downarrow} is based on the predicate `rdfs:subPropertyOf`.

$$\frac{I_1, I_2 \in \mathcal{I}_p \quad (I_1, \text{rdfs:subPropertyOf}, I_2) \in \mathcal{D}}{I_1 \preceq_{\downarrow} I_2} \quad (13)$$

4.3 Typing and subtyping identifiers.

The one-step relationships $:\downarrow$ and $\preceq\downarrow$ are now extended with the reflexivity and transitivity to obtain the relationships $:$ and \preceq . The relation \preceq forms a partial ordering of class identifiers.

First, the one-step relationship \preceq_s is generalized to the relationship \preceq defined over class identifiers \mathcal{I}_c .

$$\frac{I_1, I_2 \in \mathcal{I}_c \quad I_1 \preceq\downarrow I_2}{I_1 \preceq I_2} \quad (14)$$

Next, the subtyping relationship \preceq is reflexive.

$$\frac{S \in \mathcal{I}_c}{S \preceq S} \quad (15)$$

The subtype relationship is also transitive.

$$\frac{S, U, T \in \mathcal{I}_c \quad S \preceq U \quad U \preceq T}{S \preceq T} \quad (16)$$

Finally, the subtype relationship is asymmetric which is expressed using the following rule.

$$\frac{S, U \in \mathcal{I}_c \quad S \preceq U \quad U \preceq S}{S = T} \quad (17)$$

As a consequence of the rules 15-17 the relation \preceq is a poset.

Knowledge graphs include a special class \top that represents the root class of the ontology. In RDF ontologies \top is usually represented by the predicate owl:Thing. The following rule specifies that all class identifiers are more specific than \top .

$$S \preceq \top \quad (18)$$

The stored typing relation $:_s$ is now extended to the typing relation $:$ that takes into account the subtyping relation \preceq . The following rule states that a stored type is a type.

$$\frac{I \in \mathcal{I}_i \quad C \in \mathcal{I}_c \quad I :_s C}{I : C} \quad (19)$$

The link between the typing relation and subtype relation is provided by adding a typing rule called *rule of subsumption* [5].

$$\frac{I \in \mathcal{I}_i \quad I : S \quad S \preceq T}{I : T} \quad (20)$$

- *Properties have dual role: they are instances and types at the same time.*
- *Present the features of properties from this point of view.*

5 Typing triples

- There are two basic aspects of a triple type.
- First, the type is computed bottom-up: from the stored types of triple components.
- Second, the type can be computed top-down: from the user-defined domain/range types of properties.
- Ground type of a triple is computed first using \downarrow_1 .
- Next, the lub type of a triple is derived using \downarrow_1 .
- From the top side of the ontology, the stored type \downarrow_s is determined based on p .
- Finally, the type \downarrow of t is determined by summing alternative \downarrow_s types.
- Interactions between the \wedge/\vee types of triple components and triples must be added.
- Analogy between the types of functions in lambda calculus and types of triples.
- Show rules relating \wedge/\vee types and triple types. Example.
- E.g., $(S_1 \wedge S_2) * p * R = S_1 * p * R \wedge S_2 * p * R$.
- Predicates should be treated in the same way as the classes.
- They can have a rich hierarchy.
- Note: Where to include discussion on special role of predicates and their relations to classes?
- Mention Cyc as the practical KB with rich hierarchy of predicates.

5.1 Deriving a ground type of a triple.

A ground type of an individual identifier i is a class C related to i by one-step type relationship \downarrow denoting a ground type. In terms of the concepts of a knowledge graph, C and i are related by the relationship `rdf:type`.

A ground type of a triple $t = (s, p, o)$ is a triple $T = T_s * p * T_o$ that includes the ground types of t 's components s and o , and the property p which now has the role of a type. A ground type of a triple is defined by the following rule.

$$\frac{t \in \mathcal{T}_i, t = (s, p, o) \quad I_s, I_o \in \mathcal{I}_c, s \downarrow I_s \wedge o \downarrow I_o \quad p \downarrow \text{rdf:Property}}{t \downarrow I_s * p * I_o} \quad (21)$$

The class I_s is one of the ground types of s , and the type I_o is one of the ground types of o . The predicates are treated differently to the subject and object components of triples. The predicates have the role of classes while they are instances of `rdf:Property`.

There can be multiple ground types of a triple. They may be gathered into a single \wedge -type by using the following rule. The types T_1, \dots, T_n are obtained using Rule 21.

$$\frac{t \in \mathcal{T}_i \quad \forall i \in [1, n], T_i \in \mathcal{T}_t \quad t \downarrow T_i}{t \downarrow \wedge [T_i]} \quad (22)$$

- Typing using lub types of $T_1..T_n$. Explain why this is needed?

Let us now define the least upper bound types (abbr. *lub*) of ground types derived by Rule 22. Since a partially ordered set is not a lattice, we can have more than one lub type for a given set of ground types.

The lub types of a given list of triple types $T_1..T_n$ are computed in two steps as before when gathering multiple ground types with conjunction. A single lub type is defined as follows.

$$\frac{t :_{\downarrow} \wedge[T_1..T_n] \quad T \in \mathcal{T}_t \quad \forall i \in [1..n], T_i \preceq T \quad \forall S \in \mathcal{T}_t, \forall i \in [1..n], T_i \preceq S \wedge T \preceq S}{\vdash t :_{\sqcup} T} \quad (23)$$

The above rule states that a lub type T is a ground type $\wedge[T_1..T_n]$ if all ground types T_i are subtypes of T . Furthermore, the lub type T is the least (closest) supertype of all members of ground \wedge -type T_1, \dots, T_n . The lub types can be now gathered using the following rule.

$$\frac{\forall i, T_i \in \mathcal{T}_t \quad t :_{\sqcup} T_i}{t :_{\sqcup} \wedge[T_1..T_n]} \quad (24)$$

5.2 Stored types of triples.

- *General comments.*
- *Analysis tool.* Show minimality of the stored types (either enumerated or gathered with \vee).
- *Reminder:* when a complete stored (user-defined) type is related to the base type of a triple, some of GLB types may be eliminated.
- *Present the complete story.*
- *Computing the minimal and valid stored type of a triple $t = (s, p, o) \in \mathcal{T}_i$.*
- *Stored types are defined by linking a predicate p to a domain and range classes.*
- *Only types (domains and ranges) defined for $p' \succeq p$ are valid stored types.*
- *There are no other valid types below, i.e., for $p' \prec p$.*
- *Among the valid stored types the most specific and unrelated stored types are selected.*
- *In other words, only glb types of valid stored types are selected.*
- *Finally, the minimal and complete type of t is an \vee -type including all previously selected glb types.*

We first find stored triple types for a given triple $t = (s, p, o)$. A stored schema triple is constructed by selecting types including a predicates $p' \succeq p$ that the domain and range defined.

$$\frac{t \in \mathcal{T}_i, t = (s, p, o) \quad p' \in \mathcal{I}_p, p \preceq p' \quad (p', \text{domain}, T_s) \in g \quad (p', \text{range}, T_o) \in g}{t :_{\uparrow} (T_s, p, T_o)} \quad (25)$$

- Comments and description of the above rule.
- Note p is used for all types. p should be in most specific type -
- It makes no sense to generate types with p' .

The domain and range of a predicate p can be defined for any super-predicate, they do not need to be defined particularly for p . In addition, the domain and range of a predicates do not need to be defined for the same predicate; they can be defined for any of the super-predicates separately. The following rule captures also the last statement.

- Somewhere here, the inheritance should be noted.
- Inheritance should be treated in knowledge graphs!
- Predicates inherit in the same way as the classes.

$$\frac{t \in \mathcal{T}_i, t = (s, p, o) \quad p_1, p_2 \in \mathcal{I}_p \quad p \preceq p_1 \quad p \preceq p_2 \quad (p_1, \text{domain}, T_s) \in g \quad (p_2, \text{range}, T_o) \in g}{t :_{\uparrow} (T_s, p, T_o)} \quad (26)$$

- Explanation of the rule.
- If p inherits from multiple $p' \succeq p$, then the above rule generates multiple types. Explain.
- Note that the type is determined only if the domain and range of p or some $p' \succeq p$ is defined.
- Otherwise, the domain and range should be \top . This should be included.

The following rule is a judgment for a (user-defined) type of a concrete triple $t = (s, p, o)$. A user-defined type of t is the greatest lower bound (abbr. glb) of stored types generated by the rule 25.

- Valid stored types of t : the smallest valid glb types of all stored types.
- Justification: smallest interpretation - smallest search space for queries.
- Valid stored types are solely those defined "above" p .
- The glb types of valid stored types "above" p is selected!
- The rule generates one glb type by one.
- These (glb types) are collected in a \vee -type including all GLB types.
- The meaning of $\not\sim$ is "not related".
- This can be either that we have two p roots with unrelated glb schema triples (trees up).
- Or, two p -rooted but unrelated stored types through multiple inheritance.
- Therefore, we can have more than one stored GLB types.

$$\frac{\forall (T_i \in \mathcal{T}_t), t :_{\uparrow} T_i \quad \forall (t :_{\uparrow} S), T_i \preceq S \vee T_i \not\sim S}{t :_{\sqcap} \vee [T_i]} \quad (27)$$

The first premise says that we identify all triple types T_i that are the types of t . The second premise says that for each T_i , all types S of t are either more general or equal, or not related to T_i . Hence, T_i is the glb type of the stored types of t .

The implementation view of the above rule is as follows. The schema triples are obtained from the inherited values of the predicates `rdfs:domain` and `rdfs:range`. The

inherited values have to be the closest when traveling from property p towards the more general properties.

– *What is the reason that we have multiple glb types?*

Multiple different stored types of t are possible only in the case of multiple inheritance, in the case of the definition of the disjunctive domain/range types, or if predicate is defined for semantically different concepts.

– *Describe each possibility in more detail.*

5.3 Typing a triple.

– *Two ways of defining semantics.*

– *1) enumeration style: stored types are enumerated as alternatives (\vee).*

– *2) packed together: alternative types are packed in one \vee type.*

– *One advantage of (1) is that individual glb types can be processed further individually.*

– *Advantage of (2) is the higher-level semantics without going in implementation.*

– *Now stored types have to be related to all lub base types to represent the correct type of a triple.*

– *It seems it would be easier to check the pairs one-by-one using (1) in algorithms.*

– *In case of using complete types in the phases, types would further have to be processed by \wedge, \vee rules.*

The type of a triple $t = (s, p, o)$ is computed by first deriving the base type T and the top type S of t . Then, we check if S is reachable from T through the sub-class and sub-property hierarchies, i.e., $T \preceq S$.

$$\frac{(s, p, o) :_1 T \quad (s, p, o) :_2 S \quad (T \preceq S)}{(s, p, o) : S} \quad (28)$$

– *How to compute $T \preceq S$? Refer to position where we have a description.*

– *Order the possible derivations, gatherings (groupings) ... of types.*

– *Possible diagnoses.*

– *Components not related to a top type of a triple?*

– *Components related to sub-types of a top type?*

– *Above pertain to all components.*

6 Typing a graph.

- *What is a type of a graph?*
- *A type of a graph is a graph!*
- *It includes a set of schema triples forming a schema graph.*
- *Typing a graph bottom-up?*
- *Checking that all the triples are of correct types.*

6.1 Typing a schema triple.

- *What can be checked?*
- *Is a schema triple properly related to the super-classes and types of components.*
- *Consistency of the placement of a class in an ontology. What is this?*
- *A class or predicate component not related to other classes?*
- *A class or predicate component attached to “conflicting” set of classes? What can be detected?*
- *@kiyoshi Do you see any other examples?*
-

7 Empirical analysis

8 Conclusions

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