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journal homepage: www.elsevier.com/locate/datakSkiQL: A unified schema query language[☆]Carlos J. Fernández Candel, Jesús J. García-Molina^{*}, Diego Sevilla Ruiz

Faculty of Computer Science, University of Murcia, Murcia, Spain

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ABSTRACT

Most NoSQL systems are schema-on-read: data can be stored without first having to declare a schema that imposes a structure. This schemaless feature offers flexibility to evolve data-intensive applications when data change frequently. However, freeing from declaring schemas does not mean their absence, but rather that they are implicit in data and code. Therefore, diagramming tools similar to those available for relational systems are also needed to help developers and administrators to design and to understand NoSQL schemas.

Visualizing diagrams is not practical if schemas contain hundreds of database entities, so exploration or query facilities are then needed. In schemaless NoSQL stores, data of the same entity can be stored with different structure (e.g., non-uniform types and optional fields), which can increase the difficulty of having readable diagrams.

NoSQL schema management tools should therefore have three main components: schema extraction, schema visualization, and schema query. As there are four main NoSQL data models, it is convenient for such tools to be built on a generic data model so that they provide platform-independence (of data models and data stores) to query and visualize schemas. With the aim of favoring the creation of generic database tools, the authors of this paper defined the U-Schema unified data model that integrates the four main NoSQL data models as well as the relational model.

This paper is focused on querying NoSQL and relational schemas which are represented as U-Schema models. We present the SkiQL language designed on U-Schema to achieve a platform-independent schema query service. SkiQL provides two constructs: schema-query and relationship-query. The former allows to obtain information of entity or relationship types, and the latter that of the aggregations or references (relations among types). We will show how SkiQL was evaluated by calculating well-known metrics for languages as well as using a survey with developers with experience in NoSQL.

1. Introduction

When data structure frequently changes, as occurs in modern applications, the need of formally specifying database schemas hampers agile development. Thus, most NoSQL systems are schemaless, and developers are not forced to declare schemas prior to store data. However, not having to declare schemas does not mean their absence, but that they are implicit in stored data or application code. Managing data always requires to design, create, and evolve database schemas by developers or administrators. Developers must always keep in mind the schema to write code, and administrators have to know the schema in order to perform

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^{*} Corresponding author.

E-mail addresses: cjferna@um.es (C.J. Fernández Candel), jmolina@um.es (J.J. García-Molina), dsevilla@um.es (D. Sevilla Ruiz).

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common tasks such as optimizing queries. Therefore, database tools to manage schemas are as essential for NoSQL systems as they have been for relational systems [1,2].

Data modeling tools offer diagramming facilities to help developers to create and understand schemas. In the case of schemaless NoSQL stores, they should support the extraction of schemas as they are not declared, as well as addressing the variety of data models that are currently used. Moreover, the need for schema query languages is even greater than in relational databases, as discussed below.

Diagramming is not practical when schemas include many entities (e.g., tables in a relational schema), and a schema query language is then convenient. In relational databases, this language can be the proper SQL, as the standard SQL-92 [3] specifies how information on schemas could be represented in form of tables. In the case of schemaless NoSQL stores, no data checking against the schema is performed (schema-on-read strategy),¹ and data of the same entity can be stored with different structures, which we will refer to as *structural variations*. Variations can complicate the visualization of a readable schema, in particular if most of the entities have variations or some entity has a large number of variations. In fact, thousands of variations for a database entity have been found in datasets of some domains, such as DBpedia or molecular biology, so that using query languages is proposed in [4]. In [5], a visual notation was proposed for NoSQL schemas, and that work evidenced that diagramming is not useful when information on variations is desired, even when the number of variations is small, so a query language is essential to inspect NoSQL schemas.

There are four main categories of NoSQL systems: columnar, document, key-value, and graph [6,7]. The lack of a data model standard for these four categories causes that NoSQL systems of the same kind can significantly vary in their features and in the structure of the data. This variety has motivated that existing relational modeling tools (e.g., Erwin and ERStudio) are evolving to support several models and new multi-model tools are appearing (e.g., Hackolade). Another fact that requires the building of multi-model systems is the emergence of *polyglot persistence*: one kind of database does not fit all the needs [8].

With the aim of favoring the creation of generic database tools and languages, the authors of this paper defined the U-Schema unified data model that integrates the four main NoSQL data models and the relational model, as described in [9]. In that paper, we implemented U-Schema schema extractors for NoSQL and relational stores. In this paper, we will focus on logical schema querying. We will present the SkiQL schema query language defined on the U-Schema unified data model. Using U-Schema, SkiQL will be a language that is independent of a particular data model and data store.

SkiQL offers two constructs that are applicable to any database schema represented as a U-Schema model: *entity-query* and *from-to-query*. The former allows to obtain information of an entity type, and the latter returns a sub-schema that includes the relationships (aggregations and references) between entity types specified in the query. Additionally, SkiQL includes the *relationship-query* construct aimed to obtain information from a relationship type, and it is only applicable in the case of U-Schema schemas coming from graph stores. The SkiQL engine executes queries on the schema and builds a new schema with the selected elements. This result schema is returned in form of a diagram. It should be noted that the work is focused on the query language rather than on the visualization of the query results. SkiQL is independent of the visual representation of the result returned by queries. An evaluation of the language has been performed through an experiment with experienced NoSQL researchers and developers, and calculating some well-known metrics for domain-specific languages.

Research contributions. The main contributions of this work are the following.

- As far as we know, SkiQL is the first proposal of a generic language to query schemas. SkiQL is applicable to relational and NoSQL logical schemas thanks to the usage of U-Schema as the pivotal data model. Relationship types can be queried in graph stores.
- The creation of a schema query language for NoSQL systems has only been addressed for document stores in [4]. In that work, the interest of querying large document schemas is illustrated with some examples of queries expressed in a SQL-like notation, but the design and implementation of the language is not tackled. SkiQL is a full-fledged schema query language which allows a very rich set of queries to be performed. In addition, it is independent of a particular database system, unlike the approach outlined in [4].
- SkiQL takes advantage of the U-Schema characteristics to allow entity variations to be explored and the schemas to be traversed through aggregation and reference relationships between entity types. Also, it supports a more traditional approach using union types collapsing variation information.

This article has been organized as follows. Related work is discussed in Section 2. Before describing the proposed language, Section 3 will introduce the U-Schema generic data model for which it is defined. Then, Section 4 presents the diagramming notation designed to represent query results. Next, SkiQL syntax and semantics are described in detail in Section 5, and the implementation of the language in Section 6. The two works of evaluation of SkiQL are shown in Section 7. Finally, Section 8 exposes some conclusions and further works.

¹ In the latest versions of MongoDB, this system offers a mechanism to write validation rules for the fields of a collection, which is based on JSON Schema. In this way, developers can specify to what extent a schema-on-write strategy is desired.

2. Related work

Querying database schemas requires (i) a format to represent information on schemas (i.e. metadata), and (ii) a language to query the recorded information. In relational systems, the *data dictionary* includes the database schema and information about aspects such as physical implementation, security, and programs (i.e., triggers). The SQL-92 standard [3] specifies the structure of data dictionaries in form of tables and views. SQL can therefore be used to recover information from data dictionaries, and queries can return information on the logical schema, e.g., tables without primary keys, or tables that are not referenced by foreign keys. In fact, data dictionary information is used to visualize relational schemas in data modeling and metadata management tools. In [10], useful queries to explore schemas in several popular databases can be found. In Sections 5.1 and 5.2, we will show how these kinds of SQL queries on data dictionaries can be expressed with SkiQL in a more concise and simple way.

In the case of NoSQL systems, a schema native query facility is only provided in systems in which a schema may or must be declared, such as OrientDB² or Cassandra.³ OrientDB is a multi-database system (graph and document) that allows to work schemaless or with a declared schema. When developers declare the database schema, they can issue SQL queries on the schema, indexes, or storage. These queries return information in form of tables [11]. Cassandra is a popular columnar store that offers a schema query support similar to OrientDB. In both systems, queries are issued on a physical schema.

To our knowledge, the definition of a schema query language for NoSQL systems has only been discussed in [4]. In that work, the authors observed that well-known datasets have entities with tens of thousands of variations, which largely complicates the extraction and visualization of schemas. Their work focused on document databases, in particular MongoDB,⁴ and a document schema management framework is presented to tackle the problem. This framework includes a set of utilities aimed to extract, persist, and query schemas. Extracted schemas are recorded in a data structure defined as part of the work to facilitate queries on schemas: *eSiBuTree* trees. A SQL-like language is proposed to express queries, but the authors only show a couple of examples: (i) checking if a particular variation, which is specified by a list of properties, exists for a given entity, and (ii) finding which variations of a given entity have a concrete property. A limitation of this proposal is that queries are issued only on entities because relationships between entities are not inferred: references and entities for embedded objects are not considered. The query language suggested, as far we know, has not been completely defined and implemented yet. Our proposal differs from the approach of [4] in the following aspects:

- We present a full-fledged query language, with its corresponding implementation.
- Our approach is multi-model: it supports the four most popular NoSQL systems, as well as relational systems.
- It has been devised keeping in mind the existence of relationships both between entities and between entity variations.
- Queries can return information on entities, variations, or relationships.

Other schema query solutions are available, but they do not support relationships or entity variations. Variety⁵ is a database tool developed for MongoDB, which provides support to analyze schemas. The queries are expressed in Javascript code, instead of using a language tailored to query schemas. Apache Drill⁶ is a SQL-based query engine that supports access to any kind of database (relational, NoSQL, Hadoop, etc.) Drill represents the extracted schema in form of relational schema, so that SQL queries can be issued on it.

Before creating SkiQL, we experimented with the Cypher language to query NoSQL schemas in [12]. For this, we loaded schemas inferred from MongoDB databases into Neo4j⁷ databases and used Cypher to write queries on graph schemas. The resulting graphs were visualized with the Neo4j Browser tool. In our experiment, we observed that the queries were usually large and difficult to write. We estimated that the average number of Cypher LoC for simple queries was around 8. This size is mainly due to the need of expressing the path to be traversed, and storing the visited nodes in variables. It should be noted that the size estimation was performed for simple queries. We then decided to build a domain-specific language (DSL) tailored to query schemas represented with the U-Schema unified metamodel. The SkiQL implementation is publicly available on the GitHub repository.⁸ In Section 7.2, two examples of schema queries are expressed in Cypher and in our DSL to evidence the greater length and complexity of the Cypher queries (listings 1 and 2).

To conclude this section, it is worth noting that several generic models have been defined for NoSQL databases, but none of the published works has tackled the creation of a language dedicated for querying schemas. Some of the most relevant proposed generic models are: (i) SOS [13], designed to uniform access to NoSQL stores, (ii) NOAM [14] that is part of a method for designing NoSQL schemas, (iii) Typhon [15], aimed to develop and evolve polyglot persistence architectures, (iv) PartiQL [16,17] by Amazon, developed to create a SQL-like language able to query the different kinds of storage (relational, NoSQL, and data-lake) in the company, and (v) additionally, some data modeling tools such as Hackolade [18] and Erwin [19] have announced the definition of generic models. How U-Schema differs from these models is elaborated upon in [9]. The main differences lie in its support for both

² OrientDB Community Webpage: <http://orientdb.com/orientdb>.

³ Cassandra Webpage: <http://cassandra.apache.org>.

⁴ MongoDB Webpage: <http://www.mongodb.com>.

⁵ Variety repository: <http://www.github.com/variety/variety>.

⁶ Apache Drill Webpage: <http://drill.apache.org>.

⁷ Neo4j Webpage: <http://www.neo4j.com>.

⁸ Modelum GitHub: <https://github.com/modelum/uschema-engineering>.

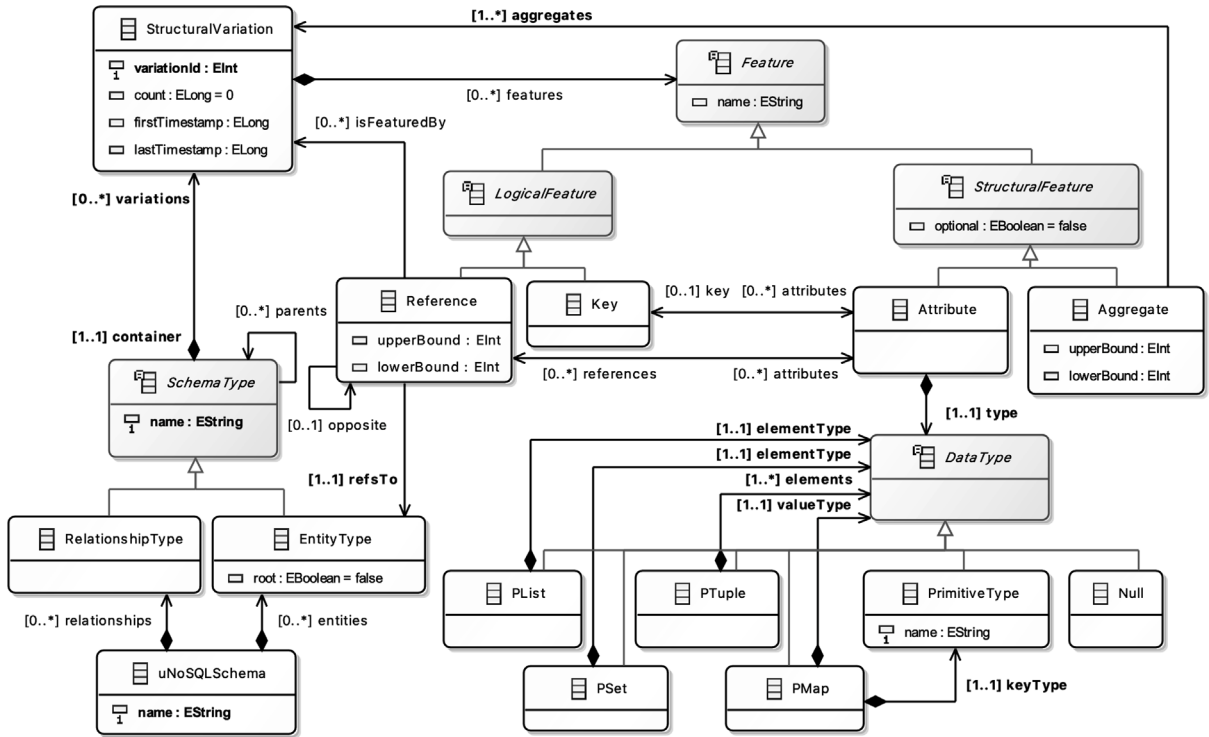


Fig. 1. U-Schema data model.

relational and the predominant NoSQL data models (columnar, document, key-value, and graph), its inclusion of relationship types as defined in graph models, its capability to represent both aggregate and reference relationships between entities, and the ability to express structural variation. These characteristics will be explained in depth in the following section.

3. The U-Schema unified data model

SkiQL aims to query logical database schemas represented as instances of the U-Schema unified data model presented in [9]. This data model provides a uniform representation for schemas extracted from relational databases and the four more popular NoSQL stores: columnar, document, key-value, and graph. Building SkiQL on top of U-Schema, we allowed us to have a query language independent of the data model. In this section, we will describe the U-Schema data model in sufficient detail to understand the rest of the paper.

U-Schema has been defined as a metamodel whose instances (i.e., models) are schemas. Fig. 1 shows the U-Schema metamodel. To understand the metamodel, it is convenient to consider that the four categories of NoSQL stores are classified in two groups depending on the kind of relationship that is prevalent to organize data. In “aggregate-based data models”, databases store semi-structured data which form aggregation hierarchies, and references are established by using object identifiers. Columnar, document, and key-value systems are based on aggregation. Instead, graph-based systems are organized as a graph of objects connected through arcs denoting a binary relationship between the entity types to which connected objects belong, and aggregation is not supported. In aggregate-based systems, objects stored are instances of entity types, while both entity and relationship types can be instantiated in graph-based systems.

A U-Schema model (i.e., a schema) is formed by a set of entity types and relationship types. *Entity types* represent real-world entities whose data are stored, and *Relationship types* specify relationships between entities. Relationship types only exist in schemas coming from graph stores. We will use the term “schema type” to refer to both entity type and relationship type.

Entity types can be root or aggregated. The root entity types are those whose instances are not embedded into other objects, while the instances of aggregated entity types are embedded into a root object or another embedded object. Aggregated entity types allow hierarchies of aggregation proper of semi-structured objects, and they are not supported in graph systems.

Types in U-Schema have a name and a set of *structural variations*. These variations are characterized by a set of *features* that can be of two kinds: logical, and structural. Variations can be identified by a numeric value which range from 1 to the number total of variations.

On the one hand, *Structural features* determine the structure of the database objects, and they can be *attributes* or *aggregates*. *Attributes* and *Aggregates* are specified as name-type pairs. For attributes, the type can be either simple (*Number*, *String*, *Boolean*) or

```

1 // User Collection
2 {
3   _id: 178,
4   name: "Brian",
5   surname: "Caldwell",
6   email: "brian_caldwell@gmail.com",
7   address: {
8     city: "Aylesbury",
9     street: "Fairfax Cres",
10    number: 6,
11    postCode: 30760
12  },
13  watchedMovies: [
14    {
15      stars: 4,
16      movie_id: 202
17    }
18  ],
19  favoriteMovies: [
20    202,
21    267,
22    378
23  ]
24 }

```

```

1 // Movie Collection
2 {
3   _id: 202,
4   name: "The Matrix",
5   year: 1999,
6   genre: "Science Fiction"
7 }

```

```

25 // User Collection (cont'd)
26 {
27   _id: 156,
28   name: "Allison",
29   email: "allison@gmail.com",
30   address: {
31     city: "Aylesbury",
32     street: "Lott Meadow",
33     number: 8
34   },
35   "watchedMovies": [{
36     stars: 3,
37     movie_id: 202
38   }, {
39     stars: 5,
40     movie_id: 295
41   }]
42 }

```

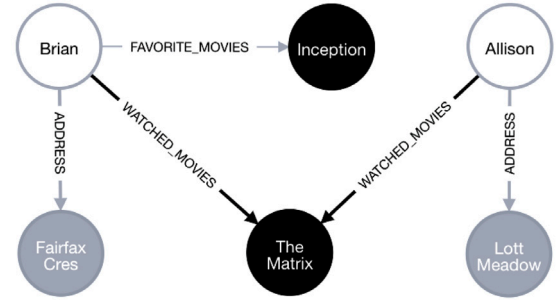


Fig. 2. Running example for aggregate and graph stores.

structured (*Set*, *List*, *Map*, and *Tuple*). In the case of aggregates, the type is a variation of an aggregated entity type, or a collection of variations of the same aggregated entity type. In graph schemas, *Relationship types* have attributes but not aggregates. This is not represented in the class diagram of the metamodel because this would complicate the definition of the metamodel, but it is expressed by means of separated constraints.

On the other hand, *Logical features* are those that have not to do with the structure of the objects, but determine the object identification (*Key*) and the connections or links (*References*) between objects. Depending on the data model, the keys and references are formed by one or more attributes, or they are declared independently of attributes. For example, Foreign Keys (*References*) are formed by one or more columns (*Attributes*) in the Relational model, but the graph model provides the notion of “Relationship type” to establish references (i.e., arcs) between objects (i.e., nodes). This distinction is reflected on the U-Schema metamodel, where the *attributes* relationships going from *Key* and *Reference* to *Attribute* have zero-to-many cardinality. In U-Schema, the existence of the attribute is therefore independent to the key or references using it, that is, supposing a key formed by only one attribute, the schema would include an *Attribute* instance and a *Key* instance. In the case of graph models, *Relationship types* can have attributes (structure), so the *isFeaturedBy* relationship is used to establish which structural variation describes the structure of a *Reference*. A *Reference* always refers to a given *EntityType* (*refsTo* in the diagram in Fig. 1.)

Given a Schema Type t with n variations, its properties can be classified into: *common*, if they belong to all the variations of t ; *shared*, if they belong to some, but not all the variations of t ; and *specific of a variation v* , if they belong only to the variation v .

In next section, we will introduce a visual notation to represent U-Schema schemas, and some examples will be shown. For instance, Fig. 3 shows a U-Schema model obtained for a document store, which includes entity types, variations, attributes, aggregates, and references.

4. Visualization of SkiQL query results

Before explaining the syntax and semantics of SkiQL, we will present the graphical notation devised to show the query results. The notation will be described showing how various NoSQL schema types and very simple query results are represented.

4.1. Kinds of NoSQL schemas

Most NoSQL schema inference approaches [4,20] do not extract variations or relationships between entities. Thus, the schema notion considered is the set of *union of entity types*, where each type is formed by the union of all the features that are present in its variations. Instead, a U-Schema schema contains a set of schema types, with their variations, and the relationships (aggregation and references) between variations or types. Next, we define some sub-schemas and schema views that can be obtained from a U-Schema

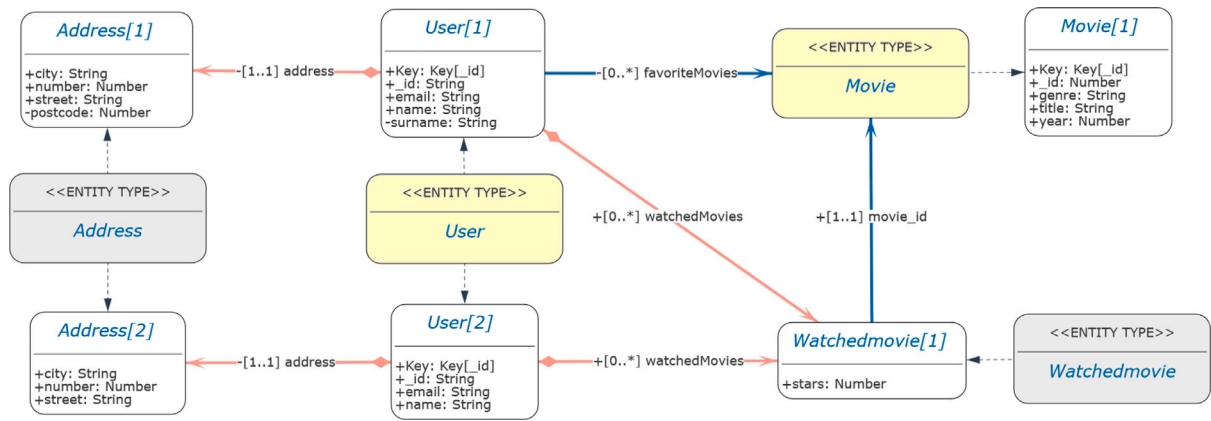


Fig. 3. U-Schema complete schema for "UP-aggregate".

model, which provide information on a particular aspect of the stored data structure. For each kind of schema, we will indicate a figure in which an example is shown by using the notation described in the following Section 4.2.

Type-variations sub-schema. It contains a schema type and all its variations. All the properties of a variation are considered pairs formed by its name and type, and the cardinality is also included for aggregations and references. Figs. 6 and 7 show a type-variation sub-schema for an entity type and a relationship type, respectively, as discussed in the following section.

Union type. It is a reduced view of a type-variations sub-schema that results of gathering all the variations of the type into a single variation. The set of features of such a variation is the union of the set of features of the gathered variations. Obtaining the union of features requires making a decision to resolve feature name collisions: the same feature name is associated to different types in different variations of the same entity type. We decided to use union data types, i.e., a feature can have multiple types.

Simple schema of union types. Joins all the union types of a schema. As mentioned above, this kind of schema is the result commonly obtained in the extraction approaches for document stores, such as [4,20]. In fact, it is not a schema, but a reduced view of a NoSQL complete schema.

Complete schema of union types. It also joins all the union types, but relationships between entity types are also added. It is also a view of the complete U-Schema schema. This kind of schema corresponds to the logical schema typically used for relational databases. An example is shown in Fig. 5, which will be commented in the following section. Note that this example includes four union types: *Address*, *Movie*, *User*, and *WatchedMovie*, and removing the relationships connecting the union types, a simple schema of union types is obtained.

4.2. Visualization of complete schemas

A *User Profile* database will be used as a running example throughout this paper. We used this example to validate U-Schema earlier in [9] because it contains all U-Schema elements. This database was stored both in an aggregate-based system (e.g., MongoDB or Cassandra) and in a graph system (e.g., Neo4j), that will be called "UP-aggregate" and "UP-graph", respectively. This example exercises all possible queries to all U-Schema elements, including: entity types, relationship types, reference and aggregation relationships, and variations. The database records data on users subscribed to a streaming service, including: personal data, watched movies, and favorite movies. Fig. 2 shows the running example for the two stores: two *User* objects and one *Movie* object of "UP-aggregate" are shown in form of JSON documents stored in MongoDB. A *User* aggregates an *Address* object and an array of *WatchedMovies* objects, and also holds an array of references to *Movie* objects that records the user's favorite movies. Each *WatchedMovies* holds a reference to the *Movie* watched by the user and the number of stars of the user's score. In the case of "UP-graph", *Addresses* and *WatchedMovies* are also connected to *Users* through reference relationships, as shown in Fig. 2.

User and *Address* have two variations, while *Movie* and *WatchedMovies* have only one, i.e., there is not structural variability for these two entities. *User* and *Address* variations will be commented below when explaining the schema diagrams.

Table 1 shows the mapping between U-Schema and graphical notation elements. Query results are visualized as diagrams in which there are two kinds of nodes:

- Schema types are represented as boxes with two compartments: «entity type» or «relationship type» stereotypes appear on the upper one, and the type name on the lower one; different colors are used to make it easier to identify the types of nodes: light yellow for root entity types, light gray for aggregate entity types, and light blue for relationship types.

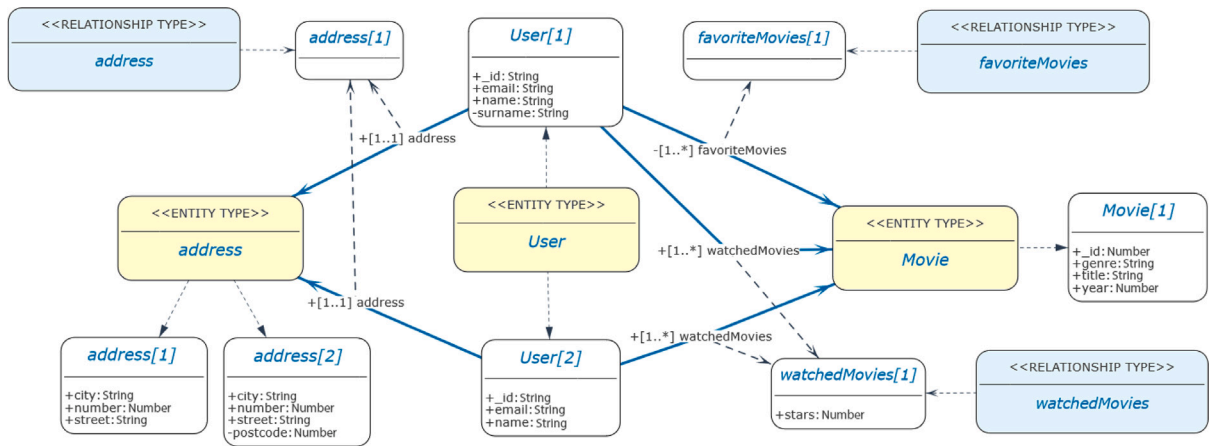


Fig. 4. U-Schema complete schema for "UP-graph".

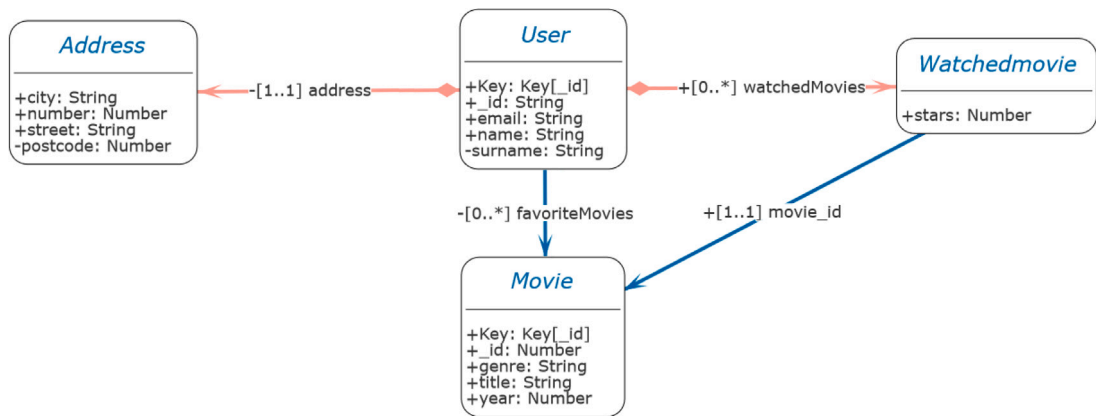


Fig. 5. The complete schema of union types for "UP-aggregate" schema.

- Variations are represented as white boxes with two compartments: the variation name and identifier appear in the upper one, and the list of features in the lower one.

These nodes are connected by means of four kinds of arrows as indicated in

Table 1: (i) schema type to variation, (ii) variation to aggregated variation, (iii) variation to referenced entity, and (iv) reference to the relationship type that specifies it.

Features are prefixed with "+", "?", and "-" symbols to indicate if they are common, shared, or specific. In the case of aggregation and reference arrows, this prefix is followed for the cardinality specification before the property name: "[0..1]" (zero to one), "[1..1]" (exactly one), "[0..*]" (zero to many), and "[1..*]" (one to many). It is worth noting that references and aggregations that belong to variations present in the query result but are not part of the set of relationships returned, will be shown in the lower compartment of its variation. They will appear in the same way as features, but indicating the kind of relationship (".." or "<..") and the cardinality.

Figs. 3 and 4 show the U-Schema complete schemas extracted for "UP-aggregate" and "UP-graph", respectively. Both schemas can be obtained with the query "FROM * TO *", as discussed later in Section 5.2.

In Fig. 3, the schema includes two root entity types: User and Movie, and two aggregated entity types: Address and WatchedMovies which are embedded into User.

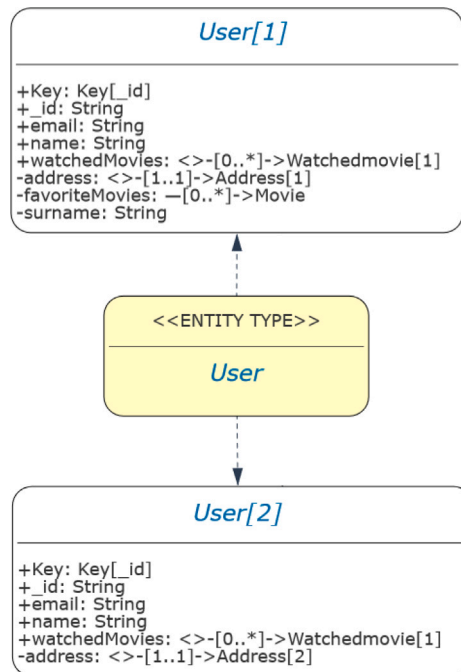
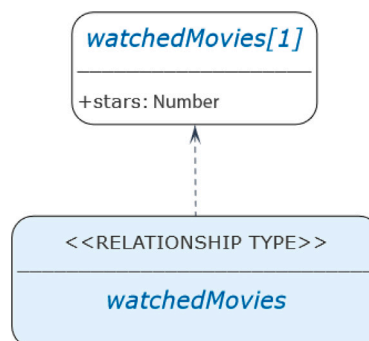
User has two variations: User[1] only includes the common attributes (email, name, and _id), while User[2] has the surname specific attribute and the favoriteMovies specific reference. Both variations aggregate Address, but each of them a different Address's variation. Address has three common properties: city, number, and street. Depending on whether the postCode optional property is present or not, two variations exist for Address.

In Fig. 4, the schema includes three relationship types: address, watchedMovies, and favoriteMovies, and three entity types: the User, Address, and Movie. Relationship types address and watchedMovies result from the aggregated entity types with the same name in the previous schema. As observed, each reference arrow is connected to the relationship type that features it, e.g., the two existing watchedMovies references are connected to the only variation of the watchedMovies relationship type. Note that this type includes the attribute stars.

Table 1

Mapping between U-Schema and graphical notation.

U-Schema elements	Graphical notation elements
Entity Type	Box stereotyped with «Entity Type»
Relationship Type	Box stereotyped with «Relationship Type»
Structural Variation	Box with two compartments, one to specify the variation and another to include its list of feature specifications
Variation belongs to a schema type	Dashed arrow from an Entity box to a variation box
Attribute	Name and type separated by colon inside a variation box
Key	Prefix “Key” followed by the key’s name and type inside a Variation box
Reference	Blue arrow directed from referencing entity to referenced entity, and labeled with the cardinality and reference name
Aggregation	Red arrow directed from aggregate entity to aggregated entity, and labeled with the cardinality and aggregation name, and decorated with a filled diamond at the aggregate class end
Variation featuring a reference	Dashed arrow from the middle of a reference arrow to a variation box of a relationship type

**Fig. 6.** The User entity type variation subschema for “UP-aggregate”.**Fig. 7.** The Watchedmovies relationship type variation subschema for “UP-graph”.

Finally, Fig. 5 shows the complete schema of union types for “UP-aggregate”, which would be obtained with the query UNION FROM * TO *.

5. SkiQL query language: Syntax and semantics

SkiQL was designed to be easy to learn, understand, and write. To achieve these characteristics, our choice was to create a command language and visualize the result of the queries in form of a schema graph. Users should interactively write queries in a console with the results returned immediately. Being a command language encompasses other advantages, such as easily extending it with new query commands. SkiQL is intended for any stakeholder involved into the development of NoSQL database applications, such as database administrators, developers, and testers. We considered that these users could be interested in two kinds of queries: (i) recovering information on properties and variations of a particular entity type (and relationship type in the case of graph schemas), and (ii) checking the existing relationships (aggregations and references) among entity types. Both kinds of queries should return a sub-graph of the database schema. Also, the language should allow each previously defined schema and sub-schema type to be obtained. It is important to note that SkiQL is a DSL aimed to help database stakeholders to explore large database logical schemas, but it is not intended to express every possible query on a database schema.

To support the desired queries, SkiQL provides two kinds of declarative query statements: “Schema type query” (QT) to query on one schema type, and “Relationship query” (QR) to query on the path between schema types. Next, these query statements are described, and examples of queries on the User Profile schema will be shown to illustrate the application and usefulness of SkiQL.

5.1. Querying on schema types

A “Schema type query” (QT statement) allows the user to express a predicate on a schema type in order to extract information from its *type variations sub-schema*. More formally said: Given a schema S , a *Schema type query* qt expresses an entity or relationship type specification $spec$ that conveys a predicate $P(t)$ to be satisfied by the schema type t of S . Such specification consists of a partial intensional definition of t (a partial list of their features expressed with its name and optionally its data type), e.g., User[name:string, favoriteMovies]. If such a schema type t exists, the query returns the subgraph of the type variations sub-schema that satisfies the predicate. In this case, the relationships are enclosed in the lower compartment of the variations, as indicated above, and as can be observed in Fig. 6 that is commented below.

Regarding the syntax, a QT query statement consists of three parts. First, a keyword indicating the schema type on which the query is applied: ENTITY for an entity type, REL for a relationship type, and ANY for both schema types. Next, the name of the schema type, which can be followed of an optional *variation filter* clause. The type name can be expressed in different ways: the exact name to be matched, * to get all entities, use the symbol “*” to establish a prefix, suffix or both, e.g., *Movie to express an entity type name ending in “Movie”, or Java-like regex expressions.

An excerpt of the EBNF grammar of this kind of query is the following:

```

<type-query> ::= [‘UNION’] (‘ENTITY’ | ‘REL’ | ‘ANY’) <TypeSpec> [<variation-filter>] | [<operations>]

<TypeSpec> ::= [*]<typeName>[*]|[*]‘r’ <regex> ‘r’

<variation-filter> ::= [‘<feature>’ (‘,’ <feature>)* ‘>’]

<feature> ::= [<presenceQualifier>] <nameFeature> [‘:’ <featureType>]

<presenceQualifier> ::= ‘common’ | ‘shared’ | ‘specific’

<featureType> ::= <AttributeDataType> | <AggregatedType> | <ReferenceType> | ‘?’

<AttributeDataType> ::= <BasicType> | <CollectionType>

<BasicType> ::= ‘number’ | ‘string’ | ‘boolean’

<CollectionType> ::= <BasicType>[‘[’ ‘]’] | ‘Set’<‘<BasicType>’> | ‘List’<‘<BasicType>’> | ‘Tuple’<‘<BasicType>’ (‘,’ <BasicType>)*>’
| ‘Map’<‘<BasicType>’ ‘,’ <BasicType>’>

<AggregatedType> ::= ‘AGGR’ ‘<’ <typeName> ‘>’

<ReferenceType> ::= ‘REF’ ‘<’ <typeName> ‘>’

<operations> ::= <operation> (‘,’ <operation>)*

<operation> ::= ‘keys’ | <date-interval>

<date-interval> ::= ‘history’ (‘before’ <date> | ‘after’ <date> | ‘between’ (‘<date>’ ‘,’ <date>))

```

An *entity type variations subschema* or a *relationship type variation subschema* is returned when the ENTITY or REL keywords are followed by the name of an entity or relationship type, respectively. Fig. 6 shows the results obtained for the query “ENTITY User” and Fig. 7 for “REL watchedMovies” query. Note that two relationship type variation subschemas would be obtained for the query “REL Movie”, those that corresponds to the watchedMovies and favoriteMovies relationship types. ANY is used to express that the name can refer to either an entity type and a relationship type, e.g. this would occur if “ANY Address” is issued on the *User Profile* graph database. These three forms of query could be used to check if a schema type is present or not in the schema.

A *variation filter* enumerates the list of features that a variation must have in order to be selected, i.e. a QT query predicate. Each feature is specified by indicating its name and type separated by a colon, and features are separated by commas. The data types allowed for attribute features are number, string, boolean, as well as *collections* of values of these data types. The collections are those included in the U-Schema metamodel: Arrays, Sets, Lists, Tuples, and Maps. An array contains values of the same type, and the array type is specified by adding square bracket after the type name, for example string[]. The rest of collections are specified with the collection type name followed by the base type between angle brackets, for example Set<string> and Map<string, number>. A question mark can be used to indicate that the property type is unknown or either can be omitted. The types for relationship features are expressed with the prefix “AGGR” for aggregates or “REF” for references.

Query Q1 shows a variation filter example: “find all User variations with the name: string attribute, and another feature named favoriteMovies whose type is unknown.” The result returned would be the same as Fig. 6 but not including the variation User[2] that does not meet the filter.

Q1

ENTITY User [name: string, favoriteMovies]

A QT statement can also be used to retrieve useful information on schema types or variations. These operations follow the type name or filter. At this moment, two operations have been defined: “keys” returns the keys of the specified entity types, and “history” returns a graph that shows the timeline of appearance of variations in a given date interval.

In a variation filter, the common, shared, and specific keywords can be used when specifying a feature. For example the query “ENTITY * [common id]” would return all the entity types having a common property named “id” of unknown data type, and “ENTITY User [specific surname: string]” would return all User variations having a specific property named surname of data type string. In the previous section, we showed the use of QT queries to obtain complete entity and relationship schemas: “ENTITY *” and “REL *”.

5.2. Querying on the path between schema types

As explained in Section 3, two kinds of relationships can be found in NoSQL stores: *aggregations* from a origin variation to another target variation (only in aggregate-based systems), and *references* from a origin variation to a target entity type. A *Relationship query* (QR statement) selects the sub-schema that includes the specified relationships in the query. This kind of query can be formally defined as follows. Given a schema S , a *relationship query* qr expresses a specification oe of a entity type t belonging to S , and one or more relationship specifications $r_i, i = 1 \dots n$, each of them indicating a relationship kind k_i and a specification of a target entity type tt_i . Thus, qr formulates a predicate $P(t, r)$ that is formed by a conjunction of logical operands, and each operand expresses that the relationship of kind k_i exists from t to tt_i . If this predicate is satisfied, the query returns the subgraph of S that contains the set of relationships r_i . While a QT query retrieves a subgraph of a type variations sub-schema, a QR query may return any subgraph of a complete schema.

Regarding the syntax, a QR query consists of a FROM clause followed by a TO clause. The former specifies the source type of the relationship, and the latter the target type and the kind of relationship. Depending on whether the prefix UNION is present or not, variations or union schema types are returned as source and target of the relationship returned.

The syntax is expressed below in form of an EBNF grammar.

```

<schema-query> ::= ['UNION'] <from-clause> <to-clause>

<from-clause> ::= 'FROM' (<entitySpec> [<variation-filter>] | '_')

<to-clause> ::= 'TO' <rel-spec> (',' <rel-spec>)*

<rel-spec> ::= ([>] <entitySpec> [<variation-filter>] [(‘REF’ [<featureName>] [<variation-filter>] |
  (‘AGGR’|‘ANY’ [<featureName>]))] | ‘_’

<entitySpec> ::= [*]<typeName>[*]|[*]<regex>

```

A *from clause* is formed by the FROM keyword followed by an entity type name, and an optional variation filter that is expressed with the syntax exposed for QT queries. An empty FROM clause (with the underscore symbol, “FROM _”) denotes that no entity type or variation could have a relationship to the target entity type.

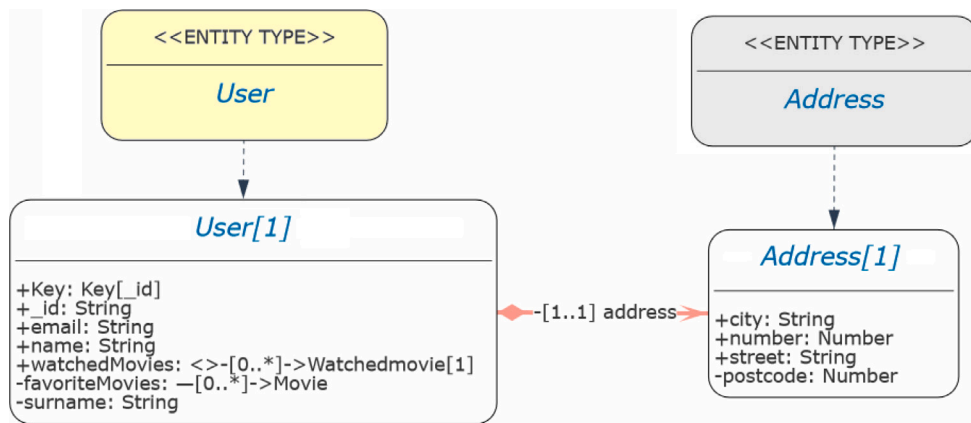


Fig. 8. Subschema returned for queries Q2 and Q5 on “UP-aggregate” schema.

Table 2

QR query examples.

Q3	Q4
<pre>FROM _ TO User</pre>	<pre>FROM User TO Movie REF, Address AGGR</pre>
Q5	Q6
<pre>FROM User [favoriteMovies] TO Address [postcode] AGGR</pre>	<pre>FROM User TO >> Movie</pre>

A *to clause* is formed by a list of relationship specifications which are formed by an entity type and an optional keyword denoting the kind of relationship: “REF”, “AGGR”, or “ANY”. This latter keyword is used to indicate that the relationship can be aggregation or reference. A variation filter can only be used with “REF”. A star can be used to refer to “any entity type” and an underscore to “no entity type.” Likewise, the QT statement allows some operations to be executed, “empty FROM” and “empty TO” negative queries can be considered two boolean operations for the QR statement, which perform two useful queries.

Q2 is a QR query specifying the condition “aggregation between User variations including the attribute surname of type string and an Address variation.” As shown in Fig. 8, if the query is applied on the “UP-aggregate” database schema, the result is the User variation “User[1]”, which appears connected to the Address variation “Address[1]” through an aggregation relationship. Note that the watchedMovies aggregation or the favoriteMovies reference are not shown in form of edges as they are not part of the set of relationships satisfying the query predicate, so they appear in the variation box as features.

Q2

```
FROM User[surname:string]
TO Address AGGR
```

Table 2 shows more QR query examples for the User Profile schema. Q3 checks if the User entity type has incoming relationships, and would return a message indicating that User is not target type of any relationship. Q4 checks if User has references to Movie and aggregations to Address, and would return the User[1] variation connected to Movie and Address through the favoriteMovies reference and the address aggregation, respectively, as shown in Fig. 9. Just like for query Q2, the watchedMovies aggregation is not shown in form of an edge, but it appears as an attribute of User[1].

Q5 query retrieves relationships whose origin are User variations having favoriteMovies feature of unknown type, and the target is an Address variation containing the attribute postcode through aggregation. The returned diagram is the same as for query Q2, which is shown in Fig. 8.

In the query execution, relationships specified are direct by default, but a path of any length can be indicated by using the » prefix, as illustrated in query Q6. This query checks if the User entity is connected to Movie by means of a path that can include any number of aggregations and references. Fig. 10 shows the subschema returned where the User[1] variation is directly connected to Movie (favoriteMovies reference), and User[2] variation is indirectly connected to Movie through the WatchedMovies aggregate entity type that references Movie.

All the relationships directly or indirectly incoming/outgoing to/from a given entity type can be obtained by using “*” to specify the schema type name, as shown below for the User entity type.

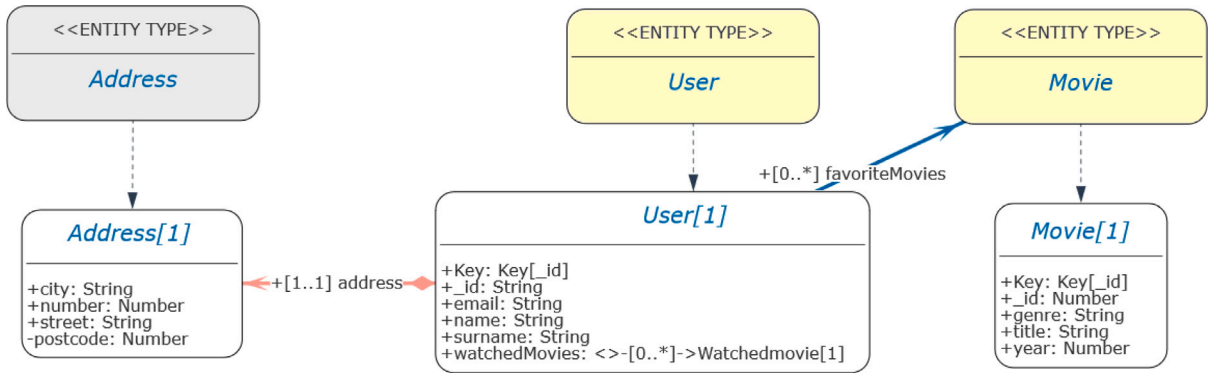


Fig. 9. Subschema returned for query Q4 on "UP-aggregate" schema.

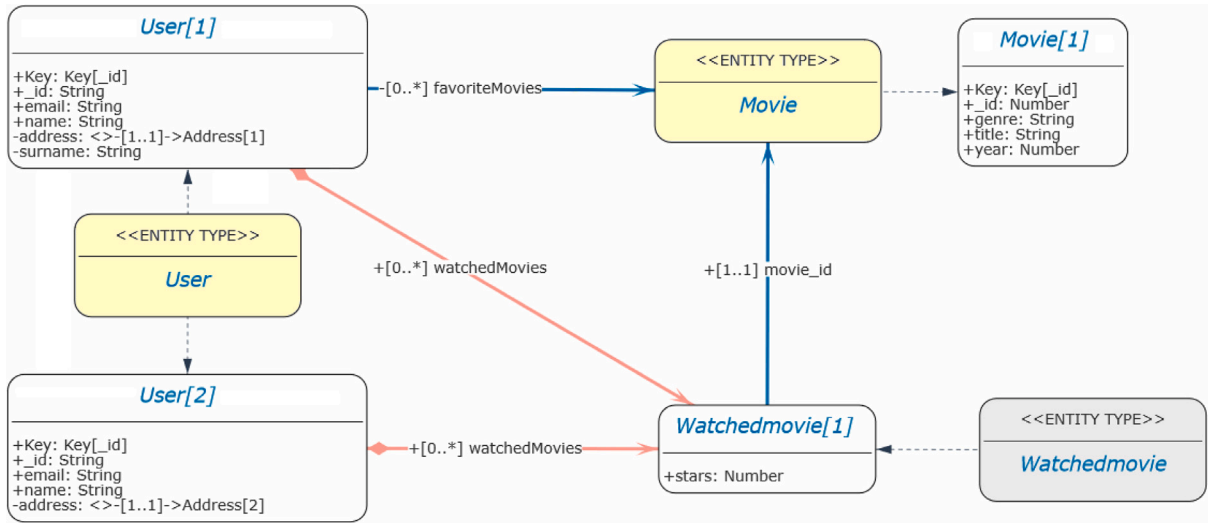


Fig. 10. Subschema returned for query Q6 on "UP-aggregate" schema.

- FROM User TO * returns all relationships outgoing from User,
- FROM * TO User returns all relationships incoming to User.
- FROM User TO * » returns all relationships outgoing from User to any entity type connected directly or indirectly.
- FROM * » TO User returns all direct or indirect relationships incoming to User.

These four queries return union types instead variations if the UNION prefix is present.

In the TO clause, the keyword indicating the kind of relationship can be optionally followed by the name of a property, so that the query would only return relationships with that name. As references can have attributes in graph systems, they are instances of relationship types, SkiQL allows variation filters to be used to specify relationship attributes. Query Q7 would check if User is connected to Movie through a reference which has a stars attribute of type number. The result of this query issued on "UP-graph" schema is shown in Fig. 11.

Q7

```
FROM User
TO Movie REF [stars: number]
```

Finally, Q8 shows a QR query issued on "UP-graph" to find if the schema contains User entity type variations with the surname attribute, which are connected both to Address variations with postcode and to Movie through only favoriteMovies references. Fig. 12 shows the result obtained for Q8.

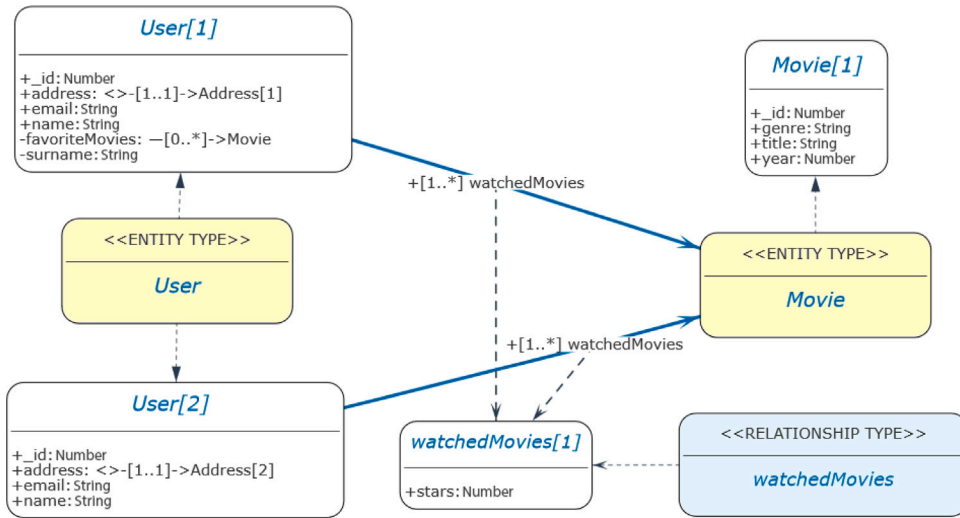


Fig. 11. Subschema returned for query Q7 on “UP-graph” schema.

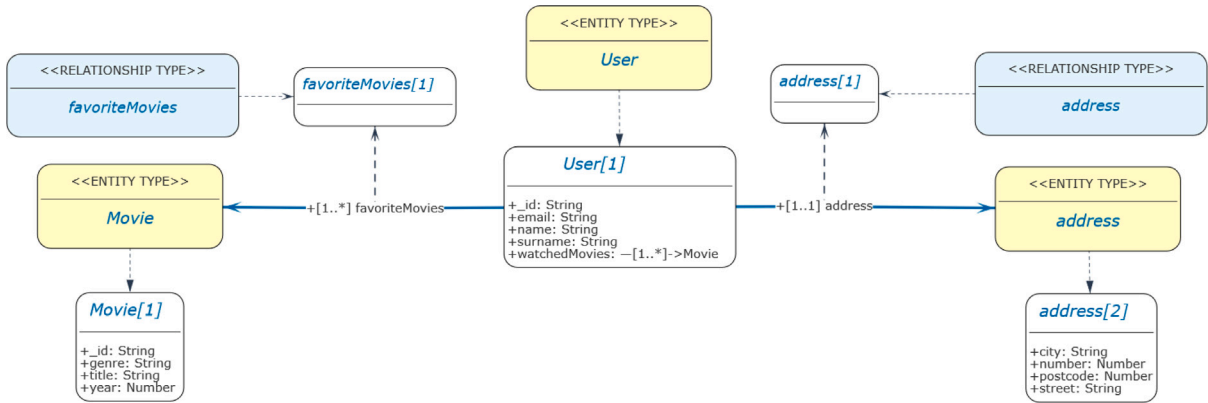


Fig. 12. Subschema returned for query Q8 on “UP-graph” schema.

Q8

```

FROM User [surname:string]
TO Address [postcode],
   Movie REF favoriteMovies

```

In addition to the graphical notation, the results can be also displayed as a set of tables, one for each returned schema type. Each table has a row for each variation, and rows have four columns: schema type name, variation identifier, number of instances, and a listing of features expressed in the format used in the diagrams. This textual notation can be useful if the number of variations returned is high.

6. Implementation of SkiQL

SkiQL was created with a metamodel-based language workbench, Xtext [21]. As it is well-known [22], these tools automate the building of DSLs by automatically generating an editor, a parser, and a model injector from the EBNF-like grammar or metamodel of the language.

Once the syntax of SkiQL was determined, a metamodel-based approach [23] was applied to implement the language. We first defined the metamodel (i.e., its abstract syntax) and then wrote the grammar in form of Xtext syntax rules. A translational approach [23] was applied to define the SkiQL semantics: SkiQL queries are written with the generated editor, and the model injector automatically produces SkiQL models in Ecore/EMF format [24]. Then, a query interpreter has as input these query models along with the U-Schema model that represents the NoSQL schema on which queries are issued.

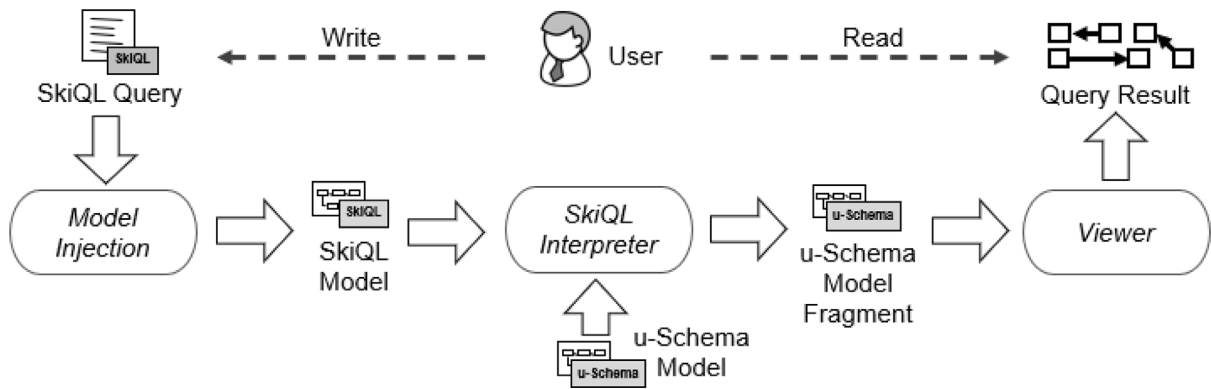


Fig. 13. An overview of the visualization process and its implementation.

Every time a QT or QR query is issued, the interpreter launches the injector execution to convert the query script into a SkiQL model. Then, the interpreter performs the following two-step process. Firstly, the query model is analyzed to identify the conditions to be satisfied. In that analysis, the interpreter captures the information necessary to execute the query, which includes: the query type, the schema types (entity and relationship types) involved in the query, and its variation filters if any. In the second step, the information obtained is used to search on the U-Schema model (i.e. the schema) what elements will be part of the result graph. In the case of QT queries, each schema type of the query is searched on the U-Schema model, and its structural variations are filtered to select those that satisfy the variation filter, if present. For the QR queries, the algorithm is similar but is separately applied for the FROM and TO clauses. The entity types specified in the FROM are firstly obtained, and they are filtered as in the case of QT queries. Then, for each entity type selected, its structural variations are filtered by *References* and *Aggregations* using the information provided by the query, as relationship type, relationship name or *Entity Type* target.

Next, once the *Structural Variations* related to the FROM clause are found, the targets specified in the TO clause are processed. The target *Entity Types* and its *Structural Variations* are filtered in the same way as it is done for QT queries. This process is repeated for any embedded QR query. In both kind of queries, all the *Schema Types* and *Structural Variations* along with its *Features* found are stored in a new U-Schema model ready for the second step. This second step is a model-to-model transformation that extracts the part of the U-Schema model that constitutes the desired result. Note that the U-Schema model is both the source and target metamodel in this transformation. The interpreter has been implemented with the language Xtend [21].

As shown in Fig. 13, the interpreter has been integrated with a SkiQL schema viewer to graphically show the result of the SkiQL queries that are written in the console (i.e., the generated web editor). This viewer receives as input the U-Schema model produced by the interpreter, and then creates the corresponding graph by applying the mapping exposed in Table 1 between U-Schema elements and graphical notation elements.

The viewer has been implemented by using VisJS⁹ as a graphical visualization API. Our tool (query interpreter and schema viewer) is a Web application that allows queries to be entered through an editor and also visualized in the browser. The browser offers various features to handle large results effectively. Users can zoom in and out, drag individual elements, or navigate to different sections of the resulting graph. Additionally, there is an option to display the results in a table view, presenting all elements in text format.

7. Evaluation

In this section, we will present the evaluation of SkiQL, which has been carried out in two forms. First, we measured some language metrics for SkiQL and compared the results with those of other query languages. Secondly, we surveyed some experienced NoSQL researchers on SkiQL features.

7.1. Calculating language metrics

In order to assess to what extent SkiQL is a simple and easy to learn language, we calculated some of the metrics proposed in [25], and compared the results obtained to those of other three query languages, in particular: Cypher, SPARQL, and GraphQL. The choice of these languages is motivated by the possibility of using them to query database schemas, if they are represented in the appropriate form: Neo4J graph database, RDF graph, or GraphQL types. In fact, queries were translated into Cypher in the first version of SkiQL. GraphQL is increasingly used to query APIs in web and mobile applications. The structure of GraphQL types is

⁹ VisJS Webpage: <http://visjs.org>.

Table 3
SkiQL, GraphQL, Cypher, and SPARQL metrics.

Language	TERM	VAR	HAL	AVS	LRS	LAT/LRS
SkiQL	29	39	12.81	3.40	310	0.09
GraphQL	44	71	43.03	4.21	603	0.16
Cypher	115	99	141.16	6.99	15,756	0.14
SPARQL	158	123	116.55	3.94	15,172	0.16

similar to U-Schema entity types but structural variations or relationship types are not allowed. SQL was not considered because it is a large language whose specification has a large number of statements that are not used to query data.

Table 3 shows the result metrics for these three languages and SkiQL.¹⁰ The considered metrics are the following:

- *TERM* and *VAR* denote the number of terminal and non-terminal symbols.
- *HAL* (Halstead effort) measures the designer's effort to understand the grammar. This metric was defined for measuring the mental effort to develop programs. It is applied to grammars by considering grammar operations (e.g., alternation and optional) and terminal and non-terminal symbols to calculate the HAL metric [26].
- *AVS* (Average Size of RHS) is related to readability (the lower the value, the more readable the language is). This metric calculates the average size of the right hand side (RHS) of the production rules of the grammar. For each rule, the number of terminal and non-terminal symbols is added, and the total of these sizes is divided by the number of non-terminals [26].
- *LRS* and *LAT* are metrics based on the LR automaton used to build a bottom-up parser. *LRS* is the number of states of the LR automaton, and *LAT* is calculated for each terminal by adding the number of states not leading to an error. *LRS* is used to measure the complexity of the language independent of its size, and *LAT/LRS* the ease of understanding the language [25].

Analyzing the results obtained for each language, we found the following:

- Cypher and SPARQL are larger languages than GraphQL and SkiQL, as they are intended to query more complex data structures. This is shown by the *TERM* and *VAR* values in Table 3. The *TERM* values are very close for SkiQL (29) and GraphQL (44), while Cypher (115) and SPARQL (158) have higher values. With non-terminals, the *VAR* value for SkiQL is significantly lower than the other three values.
- The metric *HAL* shows that Cypher is the more complex (141.16), followed by SPARQL (116.55), while GraphQL (43.03) and SkiQL (12.81) are much simpler languages. SkiQL is appreciably the least complex of the four. It is convenient to remark that Cypher is about ten times more complex than SkiQL.
- SkiQL has the lowest *AVS* value (3.40), half the value obtained for Cypher (6.99) which has the highest value. These values corroborate the greater readability of SkiQL compared to Cypher, evidenced in listings 1 and 2 (and the listings in the Appendix). SPARQL (3.94) and GraphQL (4.21) have similar *AVS* values.
- *LRS* is other metric that measures the language complexity, and its values are consistent with those obtained for *HAL*. Regarding *LAT/LRS*, Table 3 shows that GraphQL (0.16) and SPARQL (0.16) are somewhat more difficult to learn than Cypher (0.14), and the SkiQL value is half of that of Cypher. This difference in the easiness to learn a language is similar to those calculated for other DSLs defined as alternative to general purpose languages, such as [27].

Listings 1 and 2 show Cypher queries for *Q1* and *Q4* SkiQL queries (the rest of queries expressed in Cypher are included in the Appendix). As indicated in Section 2, we estimated that the average number of LoC for simple schema queries expressed in Cypher is about 8. Queries *Q2* and *Q8* are challenging to write in Cypher due to the difficulty of implementing variation filters (see Appendix). However these two queries are very easy to write in SkiQL. Therefore, Cypher queries are longer and more complex than SkiQL queries. In addition, the developer should learn Cypher and know how schemas are represented as Neo4J graphs in the database. With SkiQL, developers save time writing queries with a simpler and both easier to understand and to learn language than Cypher.

Listing 1: Cypher query for *Q1*: ENTITY User [name:string, favoriteMovies].

```

1 WITH ["name:string", "favoriteMovies"] AS properties
2 MATCH (p:Property) WHERE p.nameType IN properties
3 WITH collect(p) AS ps, properties
4 MATCH (ev:EntityVariation {entity:"Users"})-->(:Property)
5 WHERE ALL (p IN ps WHERE (ev) -->(p))
6 RETURN ev

```

¹⁰ The *cfgMetrics* program was used calculate language metrics.

Table 4
Questionnaire results.

Question	AVG	SD
Is SkiQL easy to learn?	4.19	0.38
Is SkiQL easy to read?	4.84	0.35
Is SkiQL easy to write?	4.23	0.68
Is SkiQL expressiveness appropriate?	4.26	0.79
Could SkiQL be useful to developers?	3.81	0.72
Is the visualization understandable?	4.36	0.81

Listing 2: Chyper query for Q4: FROM User TO Movie REF, Address AGGR.

```

1 MATCH c = allShortestPaths(
2   (:ENTITY {name: "Users"}) - [: ENTITY_VARIATION | PROPERTY | REFS_TO*1..3] ->
3   (:ENTITY {name: "Movies"}) )
4 MATCH c2 = allShortestPaths(
5   (:ENTITY {name: "Users"}) - [: ENTITY_VARIATION | PROPERTY | AGGREGATES*1..4] -
6   (:ENTITY {name: "Address"}) )
7 RETURN c, c2

```

7.2. Survey on SkiQL features

We surveyed a total number of 31 participants, which had no knowledge on SkiQL: 7 researchers from other research groups, 8 Spanish developers experienced in MongoDB, 6 members of our research group, and 10 students of a Big Data Master's Degree.

We provided to the participants a document with three parts: a SkiQL tutorial with examples of queries and the result graph, several query exercises to be solved by respondents, and a questionnaire of six items to evaluate SkiQL. The questionnaire is shown in Table 4. Each question had to be assessed with a mark from 1 to 5 in the *Likert* scale.

The participants were provided with a virtual machine with all the necessary tools to write and execute SkiQL queries. Therefore, they all used the same environment with the same assistance from the editor. They completed the questionnaire once they solved the exercises. The six questions asked were about the following features: legibility of result graphs, ease to learn, ease to understand queries, adequate expressiveness, usability of the environment, and usefulness of the language.

Results and discussion. Table 4 shows the average and the standard deviation of the participant's scores for each of the six questions.

Easy to learn None of the respondents considered the language difficult to learn, the average obtained for this question is 4.19 with a standard deviation of 0.38, supporting SkiQL is easy to learn. In their comments, the participants indicated that the documentation provided had been very useful.

Usability This feature includes the ease of reading and understanding queries (second question of the survey) as well as the ease of writing queries (third question). The former is the best evaluated in the survey, with an average of 4.84, and the participants strongly agreed that SkiQL is a simple and concise language. On the other hand, writing is well evaluated (4.23) but not so well as reading (4.84), although none of the participants scored negatively. Their scores divided equally between the two positive positions.

Expressiveness The expressiveness of the language refers to whether the language offers all the needed features. This characteristic is usually considered with the preciseness feature to measure the effectiveness: its ability to perform complex queries with the least number of elements. In our case, we only considered expressiveness because SkiQL is a command language, and a single query is executed each time. Most of the participants positively positioned on expressiveness with an average of 4.26.

Usefulness of language In the usefulness of the language, their scores divided equally between the neutral and positive answers (average is 3.81). More than half of respondents claimed to agree or strongly agree, and the other remaining took a neutral position. Some of them pointed out that the language had a great similarity in simplicity to the SQL language.

Legibility of the result graph The legibility of the graph returned refers to aspects such as the proper understanding of the schema in form of a graph, the ability to know the kind of each shown property as well as the variation which it belongs to, and understanding the relationships between different entities, among others. None of the participants considered that the visualization representation is illegible, and their scores divided equally between the neutral and positive positions. Thus most respondents are positively positioned regarding to the understanding of the graph that represent result schemas with an average of 4.36.

Limitations of the validation Among the limitations of the validation is that large schemas were not used, in an attempt to reduce the effort to learn SkiQL. The survey included a limited number of exercises. We included very simple exercises to familiarize respondents with SkiQL, and then we wanted to assess the expressiveness of the language, and also to cover most of its features, so we included more complex queries. This may have lead some participants to consider using the language to be slightly difficult. In the documentation given to respondents, we included a brief explanation on the metamodel used to represent schemas, and some of them had problems to solve exercises because they had not clear notions of structural variation of an schema type.

8. Conclusions and further work

In this paper, we presented the SkiQL generic language capable of querying logical schemas of NoSQL and relational databases. In addition to the common elements of logical schemas (entities, properties, aggregation, references, and keys), the notion of structural variation has also been taken into account in its design. When extracting NoSQL schemas, variations of entity types can be represented as union types, or either the proper variations can be added to the discovered schema. Our query language allows for both possibilities. On the other hand, when designing schemas, variations could be useful, for instance, if a hierarchy of entity types is part of the conceptual schema [28]. We have also considered relationship types for graph schemas.

Although the focus of our work is schema querying, a graphical visualization has also been devised for query results. The U-Schema unified metamodel has been used to represent logical schemas, but the SkiQL language and the visualization are independent of the kind of schema representation.

SkiQL is easy to learn and usable as performed evaluation showed, and it allows schemas to be easily explored. A possible strategy for exploring an unknown schema might be to first obtain the complete schema of union types. Then, each schema type could be consulted to know its variations. Once that knowledge is acquired, queries on relationships could be issued to find more specific information.

It is convenient to note that SkiQL queries are expressed at a more abstract level than SQL queries on the data dictionary. In this regard, really complex queries cannot be expressed in SkiQL. For example, those that include both positive and negative specification of features. We prioritized ease of usage over completeness to maintain the language balance between expressiveness and complexity.

We would like to remark that as far as we know, SkiQL is the first language proposed to query NoSQL logical schemas, an utility widely available for relational schemas. SkiQL is part of a data modeling tool we are building on the U-Schema unified metamodel: a kit of tools providing solutions for some common database tasks in NoSQL and relational systems. At this moment, we also have developed a schema evolution language [29].

We plan extending SkiQL to allow queries on elements that are specific to physical schemas, such as indexes, deployment, and sharding information. The statements to be added to the language should be based on an extension of U-Schema. Instead of adding elements to U-Schema, the definition of a separated generic physical metamodel could be convenient, and both metamodels should be linked.

Finally, because the SkiQL interpreter and viewer are separated components, we will explore the integration of the SkiQL language with dataset exploration graphical tools such as jHound [30].

CRedit authorship contribution statement

Carlos J. Fernández Candel: Conceptualization, Investigation, Software, Validation, Writing – original draft, Writing – review & editing, Visualization. **Jesús J. García-Molina:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. **Diego Sevilla Ruiz:** Investigation, Software, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix. Example queries written in Cypher

This appendix includes eight Cypher queries that return the same result than the SkiQL queries shown in the article to illustrate the use of SkiQL. Queries *Q1* and *Q4* were already shown in Section 7 (listings 1 and 2).

Listing 3: Cypher query for Q2: FROM User[surname:string] TO Address AGGR.

```

1  WITH ["surname:String"] AS attributeNamese1
2  MATCH ipe1 = (e1:Entity {name: "User"})
3      -[:COMMON|SHARED|SPECIFIC|VARIATION*1..2]->
4      (ae1:Feature {entity: "User"})
5  WHERE ae1.name IN attributeNamese1 OR ae1.nameType IN attributeNamese1
6      OR ae1.relationNameTypeTarget IN attributeNamese1
7      OR ae1.relationNameType IN attributeNamese1
8  MATCH pe11 = (e2:Entity {name: "Address"})
9  MATCH innerPathe11 =
10     (e1)-[:VARIATION|COMMON|SHARED|SPECIFIC|AGGREGATES_TO*2..3]->
11     (:Variation)<-[:VARIATION]-(e2)
12  RETURN ipe1, innerPathe11

```

Listing 4: Chyper query for Q3: FROM _ TO User.

```

1  MATCH (e1:Entity {name: "User"})
2  WHERE NOT EXISTS ((e1)<-[:HAS_REFERENCE_TO|HAS_AGGREGATION_TO]-())
3  RETURN e1

```

Listing 5: Chyper query for Q5: FROM User [favoriteMovies] TO Address [postcode] AGGR.

```

1  WITH ["favoriteMovies"] AS attributeNamese1,
2     ["postcode"] AS attributeNamese2
3  MATCH ipe1 = (e1:Entity {name: "User"})
4     -[:COMMON|SHARED|SPECIFIC|VARIATION*1..2]->
5     (ae1:Feature {entity: "User"})
6  WHERE ae1.name IN attributeNamese1
7     OR ae1.nameType IN attributeNamese1
8     OR ae1.relationNameTypeTarget IN attributeNamese1
9     OR ae1.relationNameType IN attributeNamese1
10 MATCH ipe2 = (e2:Entity {name: "Address"})
11    -[:COMMON|SHARED|SPECIFIC|VARIATION*1..2]
12    ->(ae2:Feature {entity: "Address"})
13 WHERE ae2.name IN attributeNamese2 OR ae2.nameType IN attributeNamese2
14    OR ae2.relationNameTypeTarget IN attributeNamese2
15    OR ae2.relationNameType IN attributeNamese2
16 MATCH innerPathe11 = (e1)-
17    [:VARIATION|COMMON|SHARED|SPECIFIC|AGGREGATES_TO*2..3]->
18    (:Variation)<-[:VARIATION]-(e2)
19 RETURN ipe1, ipe2, innerPathe11

```

Listing 6: Cypher query for Q6: User TO » Movie.

```

1  MATCH (e1:Entity {name: "User"})
2  MATCH p11 = (e1)-[:HAS_REFERENCE_TO|HAS_AGGREGATION_TO*]->
3     (e21:Entity {name: "Movie"})
4  RETURN p11

```

Listing 7: Cypher query for Q7: FROM User TO Movie REF [stars: number].

```

1  WITH ["stars:_number"] AS attributeNamese1
2  MATCH (e1:Entity {name: "User"})
3     -[r1:COMMON|SHARED|SPECIFIC|VARIATION*1..2]
4     ->(re1:Reference {entity: "User"})-[:REFS_TO]->
5     (e2:Entity {name: "Movie"})
6  MATCH ip12 = (re1)-[:COMMON|SHARED|SPECIFIC|VARIATION*1..2]->
7     (ae1:Feature)
8  WHERE ae1.name IN attributeNamese1 OR
9     ae1.nameType IN attributeNamese1 OR
10    ae1.relationNameTypeTarget IN attributeNamese1 OR
11    ae1.relationNameType IN attributeNamese1
12 RETURN e1, e2, ip12

```

Listing 8: Cypher query for Q8: User [surname:string] TO Address [postcode], Movie REF favoriteMovies.

```

1  WITH ["surname:String"] AS attributeNamese1, ["postcode"] AS
     attributeNamese2
2  MATCH ipe1 = (e1:Entity {name: "User"})
3     -[:COMMON|SHARED|SPECIFIC|VARIATION*1..2]
4     ->(ae1:Feature {entity: "User"})
5  WHERE ae1.name IN attributeNamese1 OR ae1.nameType IN attributeNamese1
6     OR ae1.relationNameTypeTarget IN attributeNamese1
7     OR ae1.relationNameType IN attributeNamese1

```

```

8  MATCH ipe2 = (e2:Entity {name: "Address"})
9    -[:COMMON|SHARED|SPECIFIC|VARIATION*1..2]->
10    (ae2:Feature {entity: "Address"})
11  WHERE ae2.name IN attributeNamese2 OR ae2.nameType IN attributeNamese2
12    OR ae2.relationNameTypeTarget IN attributeNamese2
13    OR ae2.relationNameType IN attributeNamese2
14  MATCH pe11 = (e3:Entity {name: "Movie"})
15  MATCH innerPathe11 = (e1)-
16    [:VARIATION|COMMON|SHARED|SPECIFIC|REFS_TO
17    |AGGREGATES_TO*2..4]->(e2)
18  MATCH innerPathe212 = (e1)-[:VARIATION|COMMON|SHARED|SPECIFIC*2]->
19    (ae2:Reference {entity: "Address", name: "favoriteMovies"})
20    -[:REFS_TO]->(e3)
21  RETURN ipe1, innerPathe11, innerPathe212

```

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Carlos Javier Fernández Candel He received his Computer science Ph.D from the University of Murcia (Spain). He was a member of the ModelUM research group at the Department of Informatics and Systems. His research interests include data engineering, model-driven development and databases.



Jesús J. García Molina Full Professor in the Department of Informatics and Systems at the University of Murcia, Spain, where he leads the ModelUM group, an R&D group focused on Model-Driven Engineering with a close partnership with industry. His research interests include model-driven development, domain-specific languages and model-driven modernization. He obtained a Ph.D. degree from the University of Murcia in 1987.



Diego Sevilla Ruiz Associate professor in the Department of Computer Engineering (DITEC) of the University of Murcia, Spain. His body of research publications include journal and conference articles in his main research interests, mainly NoSQL databases, Distributed Systems, Functional Programming and Model-Driven Engineering and Testing. He received the M.Sc. and Ph.D. degrees in Computer Science from the University of Murcia. He has published several journal articles and conference papers on these topics.