Under consideration for publication in Knowledge and Information
Systems

A Graph-based Meta Model for Heterogeneous Data Management

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Abstract. The wave of interest in data-centric applications has spawned a high variety of data models, making it extremely difficult to evaluate, integrate or access them in a uniform way. Moreover, many recent models are too specific to allow immediate comparison with the others, and do not easily support incremental model design. In this paper we introduce GSMM, a meta-model based on the use of a generic graph that can be instantiated to a concrete data model by simply providing values for a restricted set of parameters and some high-level constraints, themselves represented as graphs. In GSMM, the concept of data schema is replaced by that of constraint, which allows the designer to impose structural restrictions on data in a very flexible way. GSMM includes GSL, a graph-based language for expressing queries and constraints that besides being applicable to data represented in GSMM, in principle, can be specialised and used for existing models where no language was defined. We show some sample applications of GSMM for deriving and comparing classical data models like the relational model, plain XML data, XML Schema, and time-varying semistructured data. We also show how GSMM can represent more recent modelling proposals: the triple stores, the BigTable model and Neo4j, a graph-based model for NoSQL data. A prototype showing the potential of the approach is also described.

Keywords: Meta-modelling; Heterogeneous data; Graph-based Data Model; Graph-based Constraints

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Received xxx
Revised xxx
Accepted xxx

1. Introduction

The mass of digital data made available to applications has exploded in the last few years, and a rich panoply of flexible data modelling techniques, both structured and semistructured[1], have been proposed. Even more than volume, data diversity makes it difficult to access data in a uniform way and to integrate the heterogeneous results obtained from queries. Nevertheless, simultaneous use of differently prescriptive data representations has become the norm, and structured data models are often used side-by-side with semi-structured ones. The result is a plethora of data sources with no unique schema and, consequently, a possibly irregular, incomplete or even totally absent structure.

The current wave of interest in flexible data modelling has been largely driven by applications; in particular, the XML data model (W3C, 1998) has become widespread since the late Nineties because its hierarchical nature made it suitable to catalog-style applications, including large bioinformatics repertoires of proteins, genomes and DNA (Chen, Oughtred, Berman and Westbrook, 2004). Later, attention has shifted to analytics applications (e.g. Web clickstream analysis) where data needs to be translated from the data model used for their collection to others more suitable for analysis; this model shifting, often called *model management*, was initially envisaged by Bernstein et al. (Bernstein, Halevy and Pottinger, 2000) and has been later investigated for service interoperability (Zang, Calinescu and Kwiatkowska, 2011).

Today, flexible data modelling is playing a major role in the design of NoSQL databases for Big Data applications (Cattell, 2011). All NoSQL databases claim to be schema-less, which means there is no schema enforced by the database management systems. However, during data integration or data exchange, schema-less databases still need a supervised migration, due to the schema implicitly assumed when accessing the data. For example, migrating the schema of the data from a document datasource to a target relational database requires that a domain expert determines an appropriate schema that accurately describes the data, avoiding duplication and sparsity. Although NoSQL databases have been investigated from a number of viewpoints, above all scalability and performance, not much has been done in the way of effective comparison between two different NoSQL systems from the data modelling point of view, and even less to foster cross-system reuse of semi-structured modelling choices. Individual comparisons have been attempted in some vertical domains (Vicknair, Macias, Zhao, Nan, Chen and Wilkins, 2010), but a general methodology and formalism for comparing and translating data models, though important during data integration processes, is still lacking.

We believe that being able to assess and compare data models using precise criteria, like run-time model revision, has acquired even more importance in the face of the large-scale storage systems needed for Big Data management. Unfortunately, structured and semistructured data models are often too specific to allow immediate comparison with each other, and do not easily support incremental model design; as a consegquence, a unified framework to represent them is mandatory.

In this paper we describe the General Semistructured Meta-Model (GSMM) (Damiani,

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[1] We say that data are *semi-structured* when, although some structure is present, it is not as strict, regular, or complete as the one required by the traditional database management systems (Abiteboul, 1997).

Oliboni, Quintarelli and Tanca, 2003). A simple meta-model which accommodates both structured and semistructured information, GSMM leverages the use of *constraints* to accommodate all kinds of structures in a truly flexible way. Thanks to this distinctive feature, GSMM can be applied for the translation of any data model proposed in the literature into a common formalism, and is useful for easy *a priori* comparison and discussion of the features of concrete models, such as allowed sets of values, handling of object identifiers, relationship representation, and support for run-time model revisions, e.g. to adapt to new query and access patterns; moreover, it supports effective inter-model translation and design.

GSMM includes a graph-based language, named *General Semistructured Language* (GSL), used to express the queries and the constraints in a concise and unambiguous way, as suggested by Bekiropoulos et al. (Bekiropoulos, Keramopoulos, Beza and Mouratidis, 2010), and more recently by Fan and Lu (Fan and Lu, 2017). Rather than being a formal representation of schema-based semistructured data using tree grammars as formal framework (Makoto, Lee, Mani and Kawaguchi, 2005), in the wake of the proposals of Atzeni et al., and Bernstein et al. (Atzeni, Cappellari, Torlone, Bernstein and Gianforme, 2008; Bernstein et al., 2000) our highly expressive meta-model and language accommodate semi- or fully structured data, allowing the representation of intensional information where a rigid schema is not possible.

Indeed, to deal with data that are “schema-less” and “self-describing”, we allow the modeller to impose restrictions on the structure of data by means of *constraints* graphically expressed in GSL. In the line of widely accepted standards like XML Schematron (Benda, Klímek and Nečaský, 2013), our constraints are not expressed as a part of the schema, but stand by themselves and are directly applied to the data. In this way, our meta-model provides the data designer with a powerful tool for enforcing the desired degree of precision of the structure, supporting flexibility at the data representation level.

Differently from XML Schematron and in line with the most recent Data Modeling trends, we choose the graph paradigm because it is readily understood and widely accepted by data modellers. Indeed, graphs are a natural formalism to express relationships between concepts and are enjoying huge popularity among non-specialists, for instance, as a way to represent social network information (e.g. Twitter, Facebook, and LinkedIn). Also, graph-theoretical algorithms, such as procedures to compute sub-graph matching, are well understood and studied in the literature.

GSMM is based on a *generic* graph that can be instantiated into a number of *concrete* models by providing a) values for a restricted set of parameters (labels) and b) some high-level constraints, themselves represented as graphs. Although our meta-model is entirely implementation-agnostic, we discuss in detail its application to a number of practical data models, including the relational model and the graph-based model used by NoSQL databases like Neo4j (Kaur and Rani, 2013). Of course, we cannot show how to apply our meta-model to all possible data models, but our worked-out examples aim to provide designers with the necessary intuition of carry out their own meta-model-based comparisons between any two of the many available NoSQL models, including *column-family* models like BigTable[2].

The structure of the paper is as follows: in Section 2 we introduce the GSMM meta-model, and in Section 2.2 we describe GSL, the graph-based formalism to express queries and constraints on GSMM data. In Section 2.3 we describe different types of constraints, while in Section 3 we apply them in order to represent and compare some well-known semistructured data models with our unified formalism. In Section 3.8 we classify the set of parameters for inter-model comparison, and in Section 4 we report an example of inter-model translation. In Section 5 we describe related work, and in Section 6 we sketch some conclusions and possible lines for future work.

2. The meta-model and the graph-based constraints

Our self-contained, graph-based meta-model can represent various aspects of (semi)structured data, such as static or dynamic information, crisp or fuzzy data; furthermore, it is general enough that most data models proposed in the literature can be derived from it, including the relational model, OEM (Papakonstantinou, Garcia-Molina and Widom, 1995), DOEM (Chawathe, Abiteboul and Widom, 1998; Chawathe, Abiteboul and Widom, 1999), XML (W3C, 1998), WG-Log (Damiani and Tanca, 1997), and PSTDM (Combi, Oliboni and Quintarelli, 2012), just to name a few.

We will apply GSMM also to represent recent data models inspired by OEM, like Neo4j (Section 3.7), which is graph-based and has proven exceptionally suitable to express (and explore) local relationships between nodes. Also, we will handle *BigTable* models, also called *soft schemata* (Chang et al., 2008), which can be seen as a semistructured version of standard relational schemata. BigTable defines a variable set of columns to be chosen at instantiation time within a *column family* and - consequently - allows choosing among multiple structures for each table entry.

Definition 1. A *GSMM graph* is a directed labeled graph $\langle N, E\rangle$, where $N = \{n_1, \ldots, n_k\}$ is a (finite) set of nodes n_i, each associated to a tuple of labels L_{n_i}, with $|L_{n_i}| \geq 0$ and $|L_{n_i}| = |L_{n_j}| \forall i, j \in \{1, \ldots, k\}$ and $E = \{e_1, \ldots, e_p\}$ is a set of edges $e_j = \langle (n_h, n_k), R_{e_j}\rangle$, with n_h and n_k in N, and R_{e_j} a tuple of labels such that $|R_{e_j}| \geq 0$ and $|R_{e_i}| = |R_{e_j}| \forall i, j \in \{1, \ldots, p\}$.

In order to represent the data, we must associate graph nodes with *content* (i.e,. a *value*) by means of node labels. *Simple nodes* are nodes whose content label is a value, such as an integer or a string. *Complex nodes* have a $\perp$ (undefined) value for the content label, showing that they represent abstract objects. The content of a complex node n is actually the sub-graph rooted in n.

2.1. Instantiation GSMM Parameters

In order to obtain a specific *concrete model* suitable to represent data in a given context, all one has to provide is a set of *instantiation parameters*, which are

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[2] Big Table is the model shared by popular NoSQL databases like Apache HBase and Cassandra (Chang, Dean, Ghemawat, Hsieh, Wallach, Burrows, Chandra, Fikes and Gruber, 2008).

the *node and edge label cardinalities*, and *the domains of node and edge labels.* In other words, the cardinalities and domains of the sets of node and edge labels are model-dependent, and fixed: once a concrete model has been instantiated, all its nodes have the same number of labels, and the same happens for all its edges. Among the meta-model instantiation parameters are *the sets of base types*, used as domains of the content labels of simple nodes. By delegating all the specific model features to the choice of the instantiation parameters, the comparison between different concrete models becomes straightforward, since they exactly express the concrete models. The comparison criteria are listed below:

1. *Cardinality of the tuple of node labels.* The higher is cardinality, the wider is the set of properties that can be associated with each node in the concrete model.
2. *Cardinality of the tuple of edge labels.* The tuple of labels that can be associated to edges shows the granularity of the concrete model's representation of semantic relationships between objects. For example, the OEM model represents only the containment relationship because a single edge label is actually used to represent the name of the edge endpoint, whereas the WG-Log model includes an edge label to specify the semantics of a relationship between two objects, which in turn have their own labels. So the cardinality of WG-Log edge labels is higher than the one of OEM.
3. *Domains of node and edge labels.* The sets of node and edge labels, together with their domains, allow to compare the application contexts of concrete models. In particular, labels may range over:
   - *time intervals*, allowing the representation of time by associating a temporal label to the attached item (node or edge);
   - *the singleton set* $\{isa\}$, for the representation of specialization/generalization relationships;
   - *object identifiers*, hence the *OID label* associated to nodes allows explicit *OID representation*;
   - *simple values* (i.e., *base types*) admitted in the concrete model, e.g. natural numbers, to be used to represent ordering between the set of children of a chosen node. Thus, we can compare models with respect to the set of allowed base types;
   - *simple values/OID pairs*, i.e., simple values that are replicas of objects represented elsewhere. Checking whether this type is supported, we can assess the concrete model's degree of capability for de-normalisation, an important flexibility feature.

For example, in temporal applications (Oliboni, Quintarelli and Tanca, 2001) the node labels in L_n are the object identifier, the node name (i.e., a string), the node type (Complex or Simple), the content (an elementary value, e.g. a number, a string), and the temporal element ranging on union of time intervals, thus $|L_n| = 5$. The edge labels in R_e are the edge name, the edge type (Temporal or Relational) and the temporal element, so $|R_e| = 3$. In Figure 1 we report a simple GSMM graph representing temporal information related to *Mega Book Store* about the book *Harry Potter and the Prisoner of Azkaban.*

Some or all the instances of a particular concrete model will share some additional properties that depend on the real-world objects they represent or on the semantics of objects and relations taken into account by the model. In our

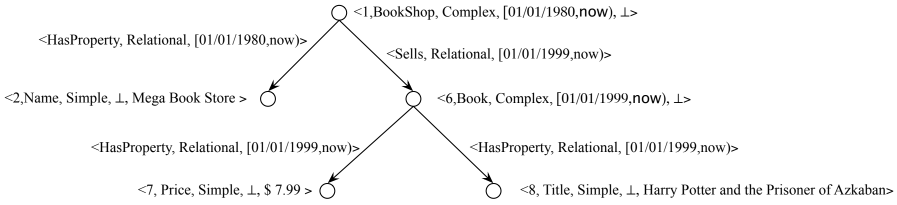

Fig. 1. A simple example of GSMM graph for a temporal database.

approach, these properties are represented by means of GSL *constraints*, added to the concrete model.

2.2. The GSL Language

Classical database constraints are used to impose (semantic) restrictions on data; typically, they are expressed with reference to a schema of which themselves become a part. In the case of flexible data models, however, often there is no a-priori, and thus a different notion of constraint is required. GSL is capable of expressing constraints in ways that schema languages cannot. For example, by means of GLS we can require that the content of an element be controlled by one of its siblings, or impose that the root element of a tree, regardless of what type it belongs to, must have specific attributes. More importantly, besides being used to constrain specific values, GSL constraints can be stated for the entire data model we want to represent, becoming part of the description of what that model can or cannot express. We start by introducing the general notion of *rule*, which is either a query or a constraint, to be applied to instances of GSMM data graphs. In general, our rules are composed by (i) a *graph*, which is used to identify the sub-graphs (i.e., the portions of a database where the rule is to be applied), and (ii) a set of *formulae*, which dictate the restrictions imposed on those subgraphs.

For the graph part of a rule we use a variant of G-Log (Paredaens, Peelman and Tanca, 1995), a Turing complete complex object query language. GSL queries are composed of *colored patterns*, i.e., graphs whose nodes and edges are colored. A GSL rule has three colors: *red solid* (RS) and *red dashed* (RD) indicate respectively information that must and must not be present in the instance where the rule is applied, while *green* (G) indicates a desired situation in the resulting instance.

Unlike G-Log (Paredaens et al., 1995), in GSL we express forbidden situations by means of negated formulae. This does not increase the expressive power of GLS, yet it makes rules and rule sets much more readable; it is easy to prove that the two formalisms are equivalent.

In GSL, the specification of logical formulae associated with rules allows to predicate on the variable labels that appear in the graph part. In particular, we introduce two sets of variables $\mathcal{V}_\mathcal{L}$ and $\mathcal{V}_\mathcal{R}$, used as node labels and edge labels in GSL rules. In general, variables in $\mathcal{V}_\mathcal{L}$ and $\mathcal{V}_\mathcal{R}$ may range over domains of node and edge labels of the considered concrete model, or may assume an undefined value (i.e., $\perp$) when the label itself does not have a specific value.

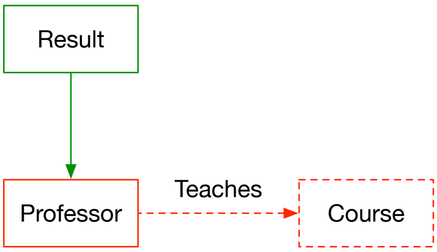

Fig. 2. A GSL graph representing a query for finding all professors who do not teach any course.

Definition 2. A *colored directed labeled graph* is an ordered pair $\langle G, Col \rangle$, where $G = \langle N, E \rangle$ is a GSMM data graph and $Col : N \cup E \rightarrow \{RS, RD, G\}$ is a total function. For each subset C of $\{RS, RD, G\}$, CG_C denotes the part of the colored graph CG containing only the colors of C.

For example, $CG_{\{RS\}}$ represents the red solid part of CG. Now we introduce the construct we use to specify rules:

Definition 3. A *GSL graph* $\mathcal{G}$ is a pair $\langle G, \mathcal{F} \rangle$ where G is a *colored* directed labeled graph $\langle \langle N, E \rangle, Col \rangle$ and $\mathcal{F}$ is a set of formulae. Moreover, the following properties hold:

- node labels can be either constants or variables in $\mathcal{V}_{\mathcal{L}}$;
- edge labels can be either constants or variables in $\mathcal{V}_{\mathcal{R}}$;
- $\mathcal{F}$ is a set of Conjunctive Normal Form formulae on the constants and variables of $\mathcal{G}$.

We remark that GSL graphs are not necessarily connected. Examples of GSL graphs are shown in Figures 2, 3.(c), 4, and 5[3], because the constraint applies to any pair of nodes connected by an edge, independently of their actual labels; the difference between GSL graphs used to express queries and those representing constraints is in the semantics of their application on a given instance (see Definition 9).

Indeed, when we use GSL graphs to express queries, the graph itself is applied to an instance (that in general does not satisfy it), and its application consists in modifying the instance, so that the obtained graph is satisfied by the result. In other words, query semantics is given as a set of pairs of instances (I, I'), where $I' \supseteq I$ is the result of applying the query to I.

For example, the query in Figure 2 requires to find all professors who do not teach any course (note the use of a RD sub-graph for expressing the negation). Its application adds to the original instance a node labeled “Result” with some outgoing edges pointing to all the Professor nodes satisfying the requirements specified in the query.

When a GSL graph is used to express a constraint, again, *an instance satisfies the rule iff, whenever the red part is satisfied, also the green part is satisfied.*

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[3] In the remainder of the paper we denote constants by means of lowercase words, whereas words denoting variables start with a capital letter.

However, in this case we do not require the input instance I to be *modified* to satisfy the rule, but only check whether the rule is satisfied by I itself.

Applying queries or constraints is a morphism between graphs representing rules and graphs representing database instances. We formalise this morphism as *embedding* (Paredaens et al., 1995):

Definition 4. An *embedding* i of a labeled graph $G_0 = \langle N_0, E_0 \rangle$ into another labeled graph $G_1 = \langle N_1, E_1 \rangle$, is a total mapping $i : N_0 \rightarrow N_1$ such that:

1. $\forall n \in N_0,\ L_{i(n)} \doteq L_n$ (where $\doteq$ means that if both labels in the same position are constants they must be equal, or if in a given position one of the labels is a variable then it is mapped on the corresponding constant), and
2. $\forall \langle\langle n_1, n_2 \rangle, L \rangle \in E_0 : \langle\langle i(n_1), i(n_2) \rangle, L \rangle \in E_1$.

An embedding i is also extended to edges by defining the mapping $i(\langle\langle n_1, n_2 \rangle, R \rangle)$ as $\langle\langle i(n_1), i(n_2) \rangle, R \rangle$.

Thus, a graph is embeddable into another one if they share the same paths and if the relation between the first and the second graph is a function.

The following two definitions specify the concept of graph matching with respect to the positive or negative requests represented in coloured graphs.

Definition 5. Let G be a graph, $C = \langle\langle N, E \rangle, Col \rangle$ a colored graph, and $C' = \langle\langle N', E' \rangle, Col' \rangle$ a subgraph of C. Let b_1 be an embedding between C' and G and b_2 be an embedding between C and G. The embedding b_2 is an *extension* of b_1 if $b_1 = b_2 \mid N'$[4].

Definition 6. Let G be a graph, $C = \langle\langle N, E \rangle, Col \rangle$ a colored graph, and $C' = \langle\langle N', E' \rangle, Col' \rangle$ a subgraph of C. An embedding b between C' and G is *constrained* by C if either $C = C'$, or there is no possible extension of b to an embedding between C and G.

In other words, we may informally say that in GSL (like in G-log) a semi-structured instance *satisfies* the graph part of a rule, if every embedding of the red solid part of the rule in the instance that is constrained by the red dashed part, can be extended to an embedding of the whole solid part (red and green).

Definition 7. Let G be a graph and $\mathcal{C} = \langle C, \mathcal{F} \rangle$ a rule. $\mathcal{C}$ *is applicable in* G if there is an embedding of $C_{\{RS\}}$ in G.

Definition 8. Let G be a graph and $\mathcal{C} = \langle C, \mathcal{F} \rangle$ a rule. G *satisfies* $\mathcal{C}$ ($G \models \mathcal{C}$) if either $\mathcal{C}$ is not applicable in G, or, for all embedding b of $C_{\{RS\}}$ in G that are constrained by $C_{\{RS,RD\}}$, b can be extended to an embedding b' of $C_{\{RS,G\}}$ in such a way that the set of formulae $\mathcal{F}$ is true w.r.t. the variable substitution obtained from b'.

Consider, for example, the graphs G_T and G_F and the constraint R in Figure 3, requiring that, whenever a b node has a “child”, that child is labeled c. G_T satisfies the constraint R, whereas G_F does not satisfy the same constraint because of the subgraph in the dashed region.

Definition 9. Let $\mathcal{G} = \langle G, \mathcal{F} \rangle$ be a GSL graph. $Sem(\mathcal{G})$ is a set of pairs $\{\langle I, v \rangle\}$, where:

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[4] The notation $b_2 \mid N'$ stands for the restriction of mapping b_2 to the nodes in N'.

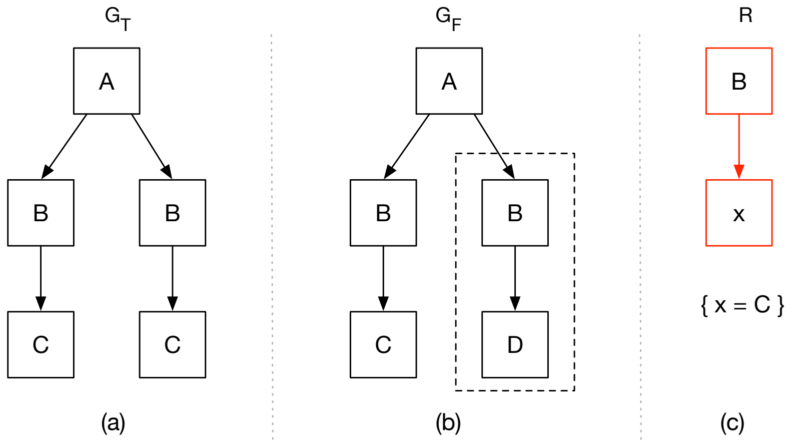


Fig. 3. Constraint satisfaction: only the graph G_T satisfies the constraint R.

- I is an instance, and
- each v is a labeled graph $I' \supseteq I$, such that $I' \models G$ and I' is minimal, **if $\mathcal{G}$ is a query**;
- $v \in \{0, 1\}$, and $v = 1$ if $I \models G$, $v = 0$ otherwise, **if $\mathcal{G}$ is a constraint**.

We remark that, in order to reduce constraint checking time, one can check violation instead of constraint satisfaction. Intuitively, there is a constraint violation if there is at least a subgraph G_1 of G matching (with respect to embedding notion) the graph part of the constraint that does not satisfy the formulae in $\mathcal{F}$. The set $\mathcal{F}$ is the conjunction of its formulae, and thus, there is a violation if at least one is false.

2.3. Constraints

In the next section we describe the use of GSL for the representation of the constraints that express restrictions on the structure and types of the data entities supported by a concrete data model. By comparing the constraints of two different concrete models, we obtain a qualitative assessment, or even a quantification, of their flexibility.

To start with, however, we shall familiarise with the notation by observing some simple constraints that hold for a specific database instance, representing information about Professors, Students and Courses, rather than for an entire data model (Bunemann, Fan, Siméon and Weinstein, 2001), (Bunemann, Fan and Weinstein, 1998).

We consider a database whose model is expressed according to GSMM and represent some simple constraints in Figure 4. The constraint of Figure 4.(b) contains a formula that imposes restrictions on the possible values of a label. In Figure 5 we show some **cardinality constraints**. The application of both Figure 5.(a) and Figure 5.(b) expresses the constraint stating that every Professor Teaches *exactly one* Course.

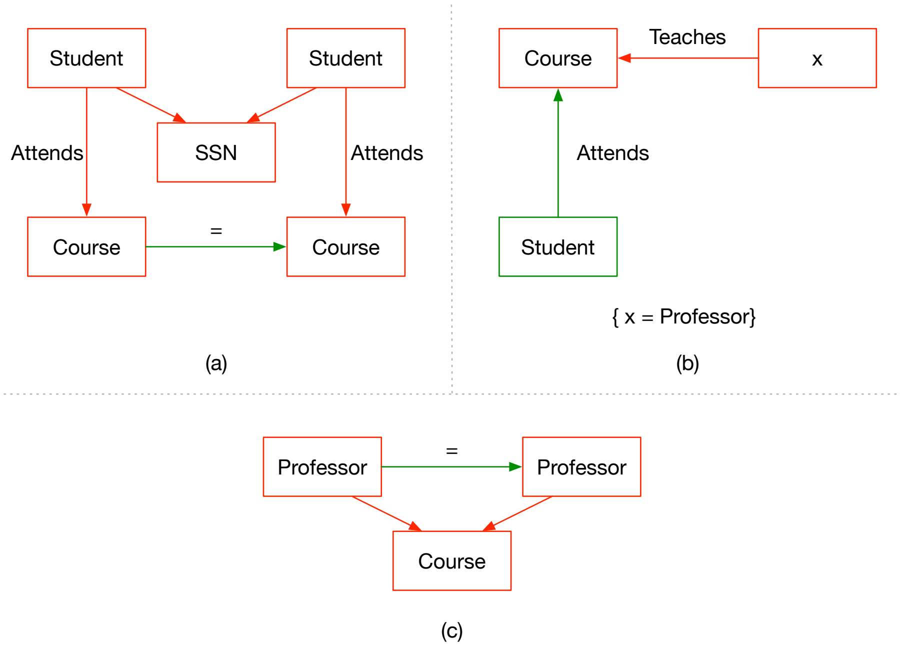


Fig. 4. (a) A constraint asserting that the SSN of a student functionally determines the courses the student is taking; (b) a constraint stating that courses are only taught by professors and requiring (green part) that for each course there is at least one student attending it; (c) the constraint forbids two different professors to teach the same course.

3. Constraints and concrete models

In this section we describe the two types of constraints supported by our meta-model.

- **High level, or "concretisation", constraints.**
  Concretisation constraints hold *for all instances of a given concrete data model.* They provide a concise representation of the data model's expressive power. For example, to characterise the XML data model we can use a concretisation constraint stating that each attribute must be connected to its parent element by means of an "*attribute-of*" edge. For all concrete models supporting a "content" label, we should also specify the constraint that abstract (i.e., non-terminal) nodes content is undefined (as anticipated in natural language after Definition 1).
  Figure 6 shows this constraint in the XML context. We remark that in this case labels are composed by variables.
- **Low level, or "domain related", constraints.**
  These constraints are defined on instances of concrete models. The introductory examples shown in Section 2.3 belong to this category. While all the instances of a particular concrete model must satisfy all the high level constraints specified for that model, only some of the instances satisfy a particular low level constraint.

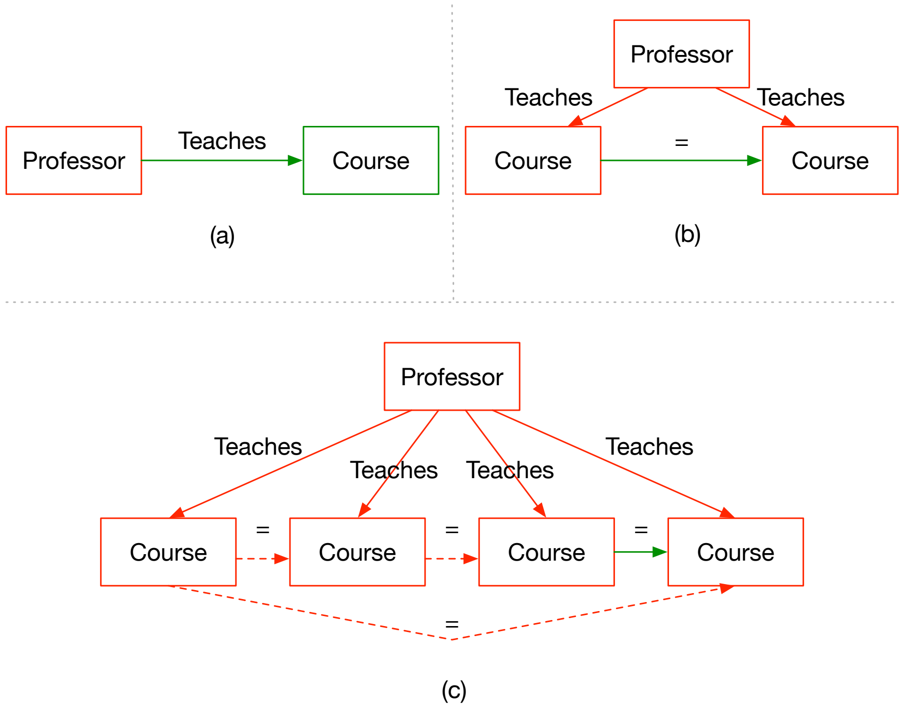


Fig. 5. (a) Every Professor Teaches *at least* one Course; (b) every Professor Teaches *at most* one Course; (c) each Professor must teach exactly three courses.

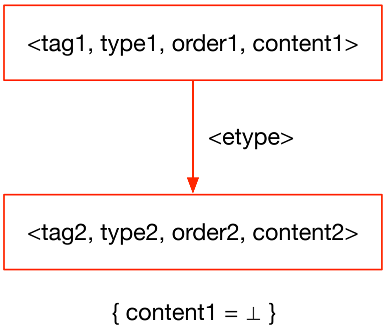


Fig. 6. Content label of non-terminal nodes must be undefined.

For example, the low-level constraint of Figure 11.(g) (on the GSMM temporal instance of Figure 11.(b)) dictates that the time interval of a Book must start after the time interval of its Author.
This constraint makes sense in all the instances representing bookshops information, and actually contributes to the semantics of the "Author_of" relationship. Depending on the particular concrete model, we may need to represent also *dynamic* low-level constraints, defined on temporal semistructured data to impose restrictions on data evolution. For example, the constraint of Figure 11.(g) is a dynamic low level constraint.

We remark that, given two models M_1 and M_2 the way to translate M_1 into M_2 may not be unique. For instance, the data designer might be called to make choices about how to translate a model where order is supported into an unordered model (e.g. XML versus relational).

We do not provide guidelines to the designers except for the recommendation to be coherent in the choices made within the same system.

Next, we show the use of our meta-model to specify some classic flexible data models. This exercise will help us to:

1. Show how the features of GSMM allow the expression of many different constraints;
2. Show how to perform an inter-model comparison w.r.t. the modelling constructs provided by the different models (Section 3.8 and Figure 15);
3. Show our meta-model capability of supporting inter-model translation (Section 4).

3.1. The Relational Data Model

Mappings between graph-based and relational data models have been deeply investigated (Virgilio, Maccioni and Torlone, 2014). No wonder that we can represent both a relational schema and its instance by using a *semistructured data graph* $\langle N, E \rangle$, where:

- the cardinality $|L_n|$ of the sets of node labels is 3. Each node $n_i = \langle oid_i, name_i, type_i \rangle$ has an object identifier $oid_i \in \mathcal{UID}$, and the node type $type_i \in \{$ *DBname, RelationName, Att, KeyAtt, SetOfAtt, AttValue* $\}$.
- the cardinality $|R_e|$ of the tuple of edge labels is 0, and each edge $e_j = \langle (n_h, n_k) \rangle$ with n_h and n_k in N.

An example of a relational database schema, a possible graph-based representation for the schema and an instance (similar to the one proposed by Virgilio et al. (Virgilio et al., 2014)), is reported in Figure 7. We also represent the related GSMM graphs.

In Figure 7.(e) and 7.(f) we represent a primary key and a foreign key constraint.

Representing instances of a relational schema by using our graph-based data model is a straightforward application of the same technique, as shown in Figure 7(d).

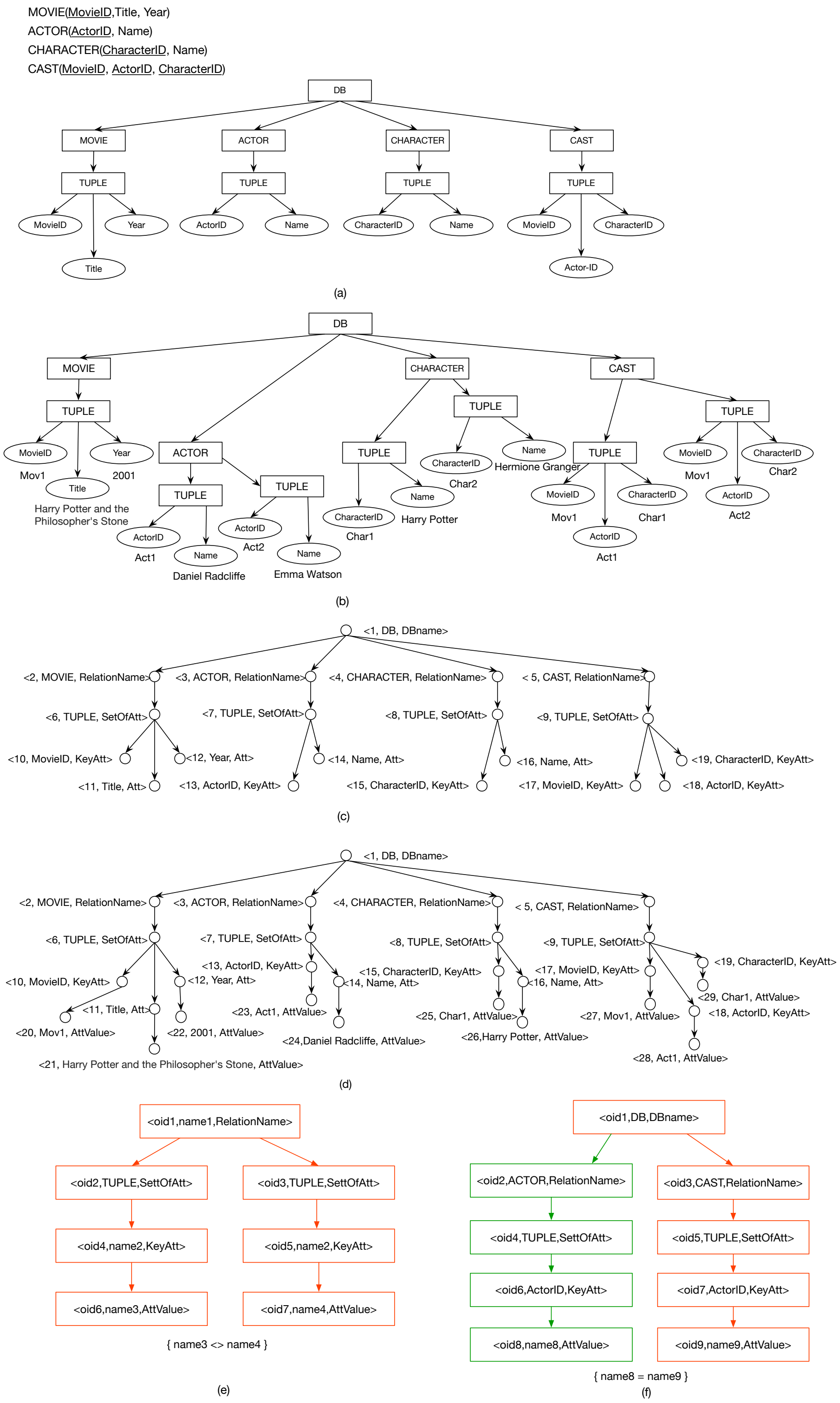


Fig. 7. (a) A relational database schema and its graph-based representation; (b) graph-based representation of a relational instance; (c) the GSMM graph for the relational schema and (d) corresponding instance; (e) a primary key constraint (with the key composed by a unique attribute); (f) one of the foreign key constraint on the MOVIE relation.

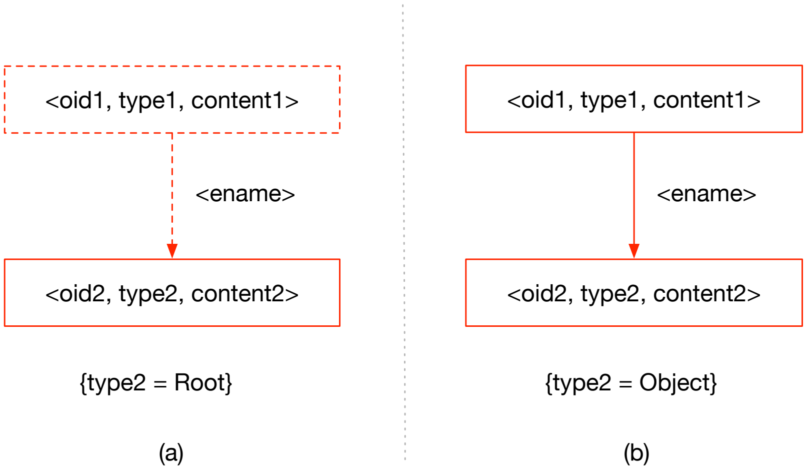


Fig. 8. (a) A node without incoming edges must have type *Root*; (b) each node with an incoming edge has as type *Object*.

3.2. The Object Exchange Model

The Object Exchange Model (OEM) (Papakonstantinou et al., 1995) has been introduced in the context of the seminal TSIMMIS project carried out at Stanford University, one of the first attempts to support fast integration of heterogeneous information sources.

OEM is a graph-based data model where the basic idea is that each object has a label that describes its meaning. The label is used to extract information about objects that represent the underlying data.

The information that can be extracted is limited to the inclusion/containment relationship; indeed OEM does not actually represent the semantics of relationships between objects.

An *OEM graph* is a *GSMM rooted graph* $\langle N, E, r\rangle$, where:

- the cardinality $|L_n|$ of the sets of node labels is 3. Each node $n_i = \langle oid_i, type_i, content_i\rangle$ has an object identifier $oid_i \in \mathcal{UID}$, and the node type $type_i \in \{\ Root,\ Object\ \}$.
- the cardinality $|R_e|$ of the tuple of edge labels is 1, and each edge $e_j = \langle (n_h, n_k), R_{e_j}\rangle$ with n_h and n_k in N, has a label $R_{e_j} = \langle ename_j\rangle$, where $ename_j$ is actually the name of the pointed node n_k.

Again, $r \in N$ is the root of the graph, and the root node has type “Root”. Consequently, an OEM graph must satisfy the high level constraints in Figure 8.(a) and 8.(b).

3.3. XML and XML Schema

In this section we apply our meta-model to derive a simple concrete model supporting XML information and XML Schema. XML datasets are often called

```
<?xml version="1.0" encoding="UTF-8"?>
<computer>
  <maker> Toshiba </maker>
  <model >
    <modelname serialcode = “12303B” > Satellite Pro 4200 </modelname>
    <year> 2001 </year>
    <description>
      A versatile laptop computer product.
    </description>
  </model>
  <plant>
    <address> Osaka, Japan</address>
  </plant>
</computer>
```

Fig. 9. A well-formed XML document

documents because they can be serialised as plain text. However, unlike generic text documents, XML documents are not completely unstructured.

A XML document is a sequence of nested elements, each delimited by a pair of start and end tags (e.g., `<tag>` and `</tag>`). The sequence is itself enclosed by a *root element.* Figure 9 shows a well-formed XML document.

3.3.1. Plain XML

Plain XML documents like the one in Figure 9 can be represented quite straightforwardly in our framework: a *Plain XML graph* is a *GSMM rooted graph* $\langle N, E, r\rangle$, where:

- the cardinality $|L_n|$ of the sets of node labels is 4. Each node n_i has as tuple of labels $L_{n_i} = \langle tag_i, type_i, order_i, content_i\rangle$; the type label $type_i$ indicates whether the node is the Root, an Element, Text, Attribute, Processing Instruction or Comment[5], whereas the label $order_i$ assumes as value a natural number representing the relative order of the node w.r.t. other children of its parent node, or $\perp$ for root, text and attribute nodes. Moreover, the label $content_i$ can assume `PCDATA` or $\perp$ (undefined) as value.
- The cardinality $|R_e|$ of the tuple of edge labels is fixed to 1, where the unique label represents the edge type. Each edge $e_j = \langle(n_h, n_k), R_j\rangle$, with n_h and n_k in N, has a label $R_j = \langle etype_j\rangle$, where the label $etype_j \in \{AttributeOf, SubElementOf\}$. Note that edges simply represent the “containment” relationship between different items of an XML document and do not have names.

For Plain XML the following high level constraints hold: (i) in an XML document the root node has type label “Root”, (ii) the *content* label of element nodes is undefined (as shown in Figure 6), and (iii) the *tag* label for text nodes is not explicitly specified.

---

[5] Plain XML documents may also contain `ENTITY` nodes, not unlike macro calls that must be expanded before parsing. We do not consider `ENTITY` expansion in this paper.

3.3.2. XML Schema

Although XML information can be treated as schema-less data, the notion of *XML Schema* has been introduced to represent sets of instances sharing the same structure. An XML Schema is an XML document complying to a standard structure, itself expressed as a schema; for example a schema's root node has always the label "schema" and may have a child of type *namespace* (W3C, 2001).

Our representation of XML schemata is twofold:

- An XML schema is a *low-level constraint* that identifies a set of instances.
- An XML schema is itself an XML document; as such, it is represented as in Section 3.3, and must satisfy a suitable set of low level constraints.

An *XML Schema graph* is a *GSMM rooted graph* $\langle N, E, r\rangle$, obtained as an extension of a *Plain XML graph.* In particular:

- the cardinality $|L_n|$ of the tuples of node labels is 6. Each node n_i has as tuple of labels L_{n_i} the corresponding labels of the Plain XML representation plus the two labels uri_i, representing the resource identifier attached to that node, and $namespace_i$, representing the node namespace.
- the cardinality $|R_e|$ of the tuples of edge labels is 1, where the unique label represents the edge type as in Plain XML.

This approach is a simple and effective way to characterise XML schemata and all their instances a-priori. Specifically, an XML graph representing a schema must satisfy, among others, the low-level constraints shown in Figure 10.

3.4. Time

In this section we apply our high level data model to the context of temporal applications (see for example TGM (Oliboni et al., 2001)) for representing semistructured data dynamics. In this case we use a time interval to represent when an object exists in the outside world or in the database.

A *semistructured temporal graph* is a *GSMM rooted graph* $\langle N, E, r\rangle$, where:

- the cardinality $|L_n|$ of the sets of node labels is 5, where each node $n_i = \langle oid_i, name_i, type_i, content_i, time_i\rangle$ has an object identifier $oid_i \in \mathcal{UID}$, the node name, the node type in $\{Complex, Simple\}$, a time interval $time_i \in V \cup \{\perp\}$, where V is a set of time intervals, and the node content.
- The cardinality $|R_e|$ of the sets of edge labels is fixed to 3, where each edge $e_j = \langle (n_h, n_k), R_j\rangle$, with n_h and n_k in N, has three labels $R_j = \langle ename_j, etype_j, Et_j\rangle$, where $etype_j \in \{Relational, Temporal\}$ is the type of the edge, and the last one $Et_i \in V$ is the time interval representing the valid time. Edges the $Relational$ type are used to represent classical relationships between two nodes, $Temporal$ edges are used to store represent the update of the content of a given node (it allows the representation of historical values).

Among others, instances of semistructured temporal graphs must satisfy the high level constraints in Figures from 11.(c) to 11.(f).

In Figure 11.(b) we show a portion of a *semistructured temporal graph* containing information about books and authors. Note that this labeled graph satisfies the high level constraints described above. Once an instance of a semistructured temporal graph has been constructed, low level constraints may be applied

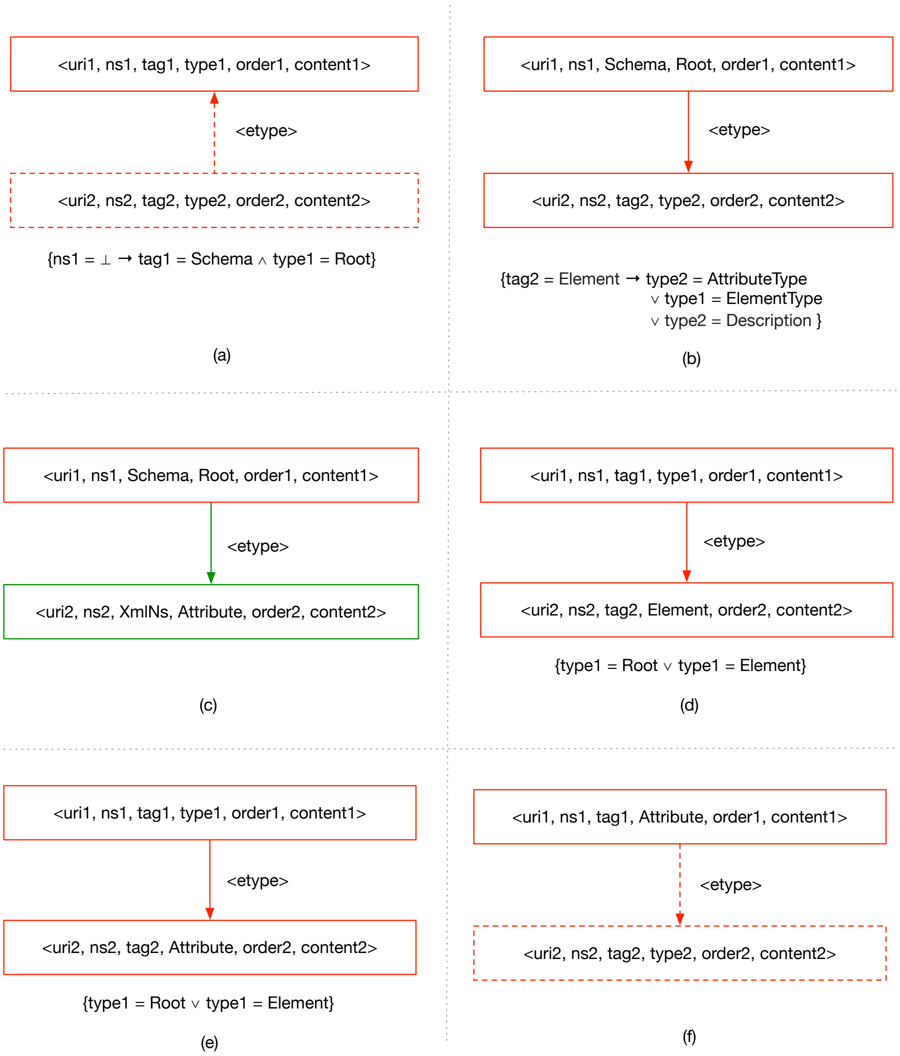


Fig. 10. (a) The root of the graph has as type *root* and as tag *Schema*; (b) Each element node must be a root child and its label must be *ElementType*, *attribute Type*, or *Description*; (c) Root must have an attribute with tag *XmlNs* as child; (d) Each *Element* node is a child of either the root, or another *Element* node; (e) each *Attribute* node is a child of either the root, or an *Element* node; (f) Each *attribute Type* node is a leaf.

to enforce static or dynamic properties. For example, with the constraint of Figure 11.(g) on the instance of Figure 11.(b) we could enforce that the time interval of a Book starts after the time interval of its Author.

Note that, in general, the time interval of a relationship is not connected to the time interval of the related objects. If we represent *valid time* in the real world, the constraint above must be added because it gives semantics to the "Writes" relation: a book can become valid only after its author was born!

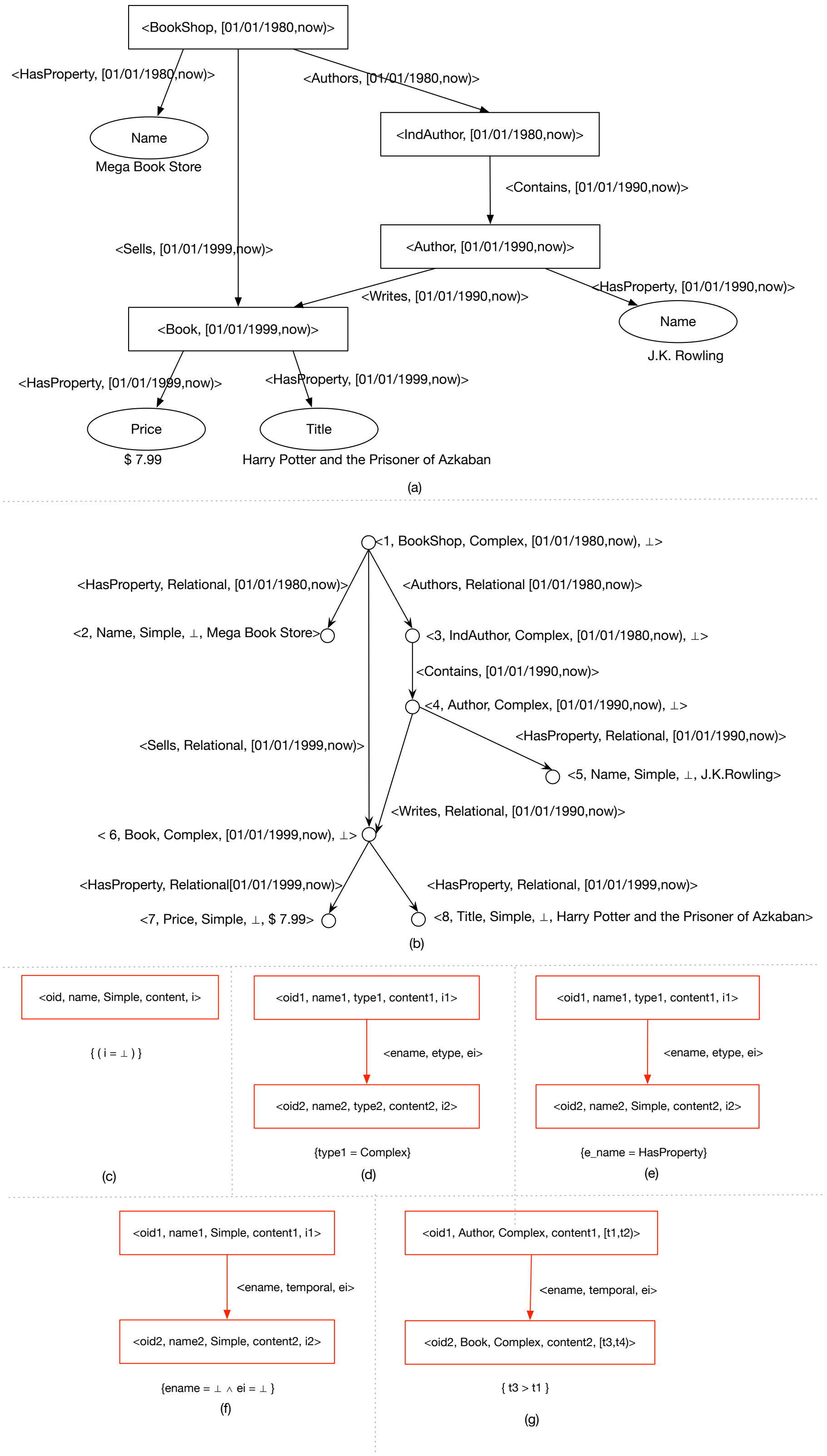


Fig. 11. (a) A simple TGM instance representing Bookshop temporal database; and (b) the corresponding GSMM graph. Some examples of high level constraints: (c) simple nodes do not have a time interval; (d) simple nodes are leaves; (e) edges pointing to simple nodes are named "HasProperty"; (f) temporal edges do not have a name, neither they have a time interval. A low level constraint on time: (g) the time interval of a Book starts after the time interval of its Author.

3.5. The Triplestore database

A Triplestore dataset allows the storage and retrieval of triples. A triple is a data entity in the form subject-predicate-object. Example of triples are "Peter is 40" or "The t-shirt is white". Triples can be easily managed by using the Resource Description Framework (RDF). The RDF data model uses triples for expressing statements about resources (in particular web resources) and supports reification, i.e., the possibility to add properties (e.g. provenance properties) of a relation/predicate.

We can represent a triple-based database by using a *GSMM graph* $\langle N, E\rangle$, where:

- the cardinality $|L_n|$ of the sets of node labels is 2. Each node $n_i = \langle oid_i, name_i\rangle$ has an object identifier $oid_i \in \mathcal{UID}$, which can be an URI for the RDF model, and a string representing the node label $name_i$. In case we need to represent the RDF Blank Node, we suppose to have $\perp$ as value of $name_i$.
- the cardinality $|R_e|$ of the set of edge labels is 1, and each edge $e_j = \langle (n_h, n_k), R_j\rangle$ with n_h and n_k in N, has a label $R_j = \langle epredicate_j\rangle$, where $epredicate_j \in \{TO, FROM\}$.

A triplestore dataset, is translated into GSMM by introducing nodes for subjects, predicates and objects (see Figure 12.(b) for an example), and must satisfy the high level constraint in Figure 12.(c) each node having an incoming edge labeled $< TO >$ (i.e., representing a predicate) must also have a not dangling incoming edge labeled $< FROM >$. Predicates are modeled as nodes to support the RDF reification.

3.6. BigTable

Under the BigTable data model, each table is a collection of rows composed of an arbitrary number of cells, and uniquely identified by a key. BigTable rows are often called *wide rows*, because the columns cells belong to are not pre-defined as in relational databases.

GSSM can represent a BigTable database by defining a graph node per cell. The property ID and the property value of each cell are stored in the value of the corresponding GSSM node. Each GSSM node gets its set of outgoing edges via the BigTable row containing the corresponding cell's adjacency list (often called *adjacency row*). We remark that according to this construction each outgoing edge is represented individually, expressing the fact that in BigTable each element of the adjacency list has its own cell in the adjacency row. The GSSM representation (see Figure 13(a)) shows us that, compared to other concrete data models, BigTable supports efficient insertions and deletions. The maximum number n of cells allowed per row in a concrete BigTable model can be represented by specifying a GSSL concretisation constraint over the maximum degree of nodes in the GSSM graph that represents it. As an example, in Figure 13.(b), we report the constraint specifying that the maximum cells per row must be $n = 3$.

We can represent a triple-based data model by using a *GSMM rooted graph* $\langle N, E, r\rangle$, where:

- the cardinality $|L_n|$ of the sets of node labels is 3. Each node $n_i = \langle oid_i, name_i,$

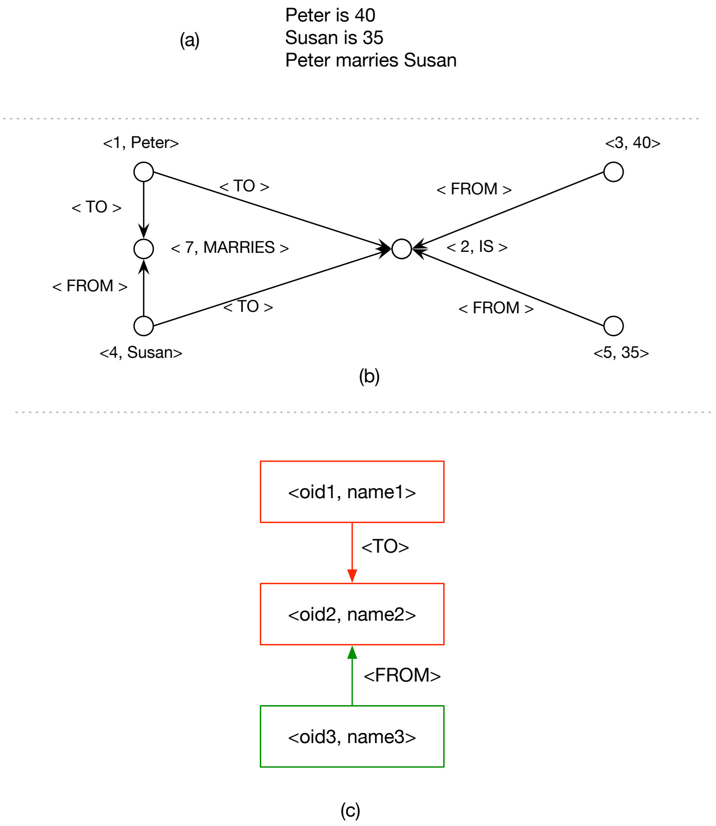


Fig. 12. (a) A triplestore database and (b) its GSMM graph. The high level constraint: (c) each node representing a predicate, i.e., having an incoming edge labeled $< TO >$, must have also an incoming edge labeled $< FROM >$.

$content_i\rangle$ has an object identifier $oid_i \in \mathcal{UID}$, a string as $name_i$ and a content $content_i$ that could be $\perp$.

- the cardinality $|R_e|$ of the tuple of edge labels is 0.

If a given BigTable model backend supports key-order, the outgoing edges will be ordered by the ID of their endpoint. Again, the GSSM representation allows one to assess the concrete model's runtime flexibility: ease of updating node IDs means that nodes which are frequently co-accessed can easily be assigned IDs with small absolute difference at run-time.

3.7. The Neo4j Graph Database

Neo4j is an open-source and graph-based database that stores data structured in graphs rather than in tables (Kaur and Rani, 2013).

Graph-based data models allow the representation of connections and make available information by using navigation operations. This issue is becoming very

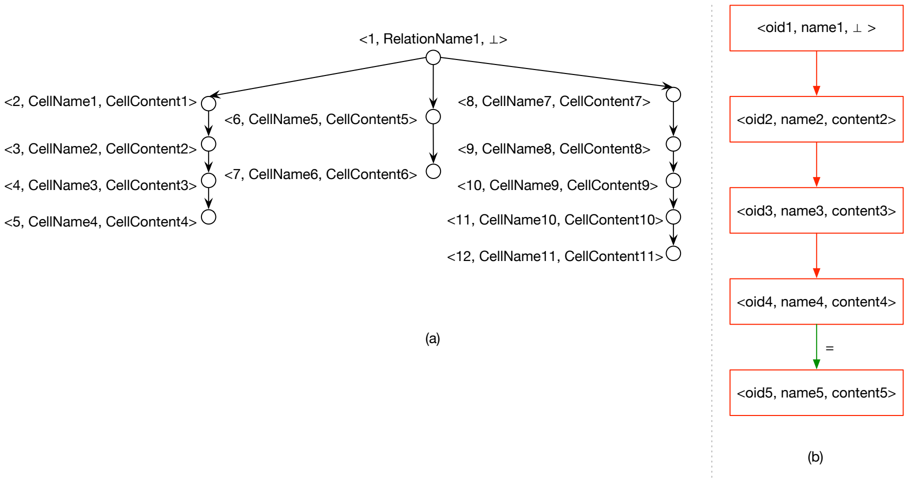


Fig. 13. (a) The GSMM graph of a table in the BigTable data model; (b) the maximum cells per row constraint for $n = 3$.

important in the information management context, since nowadays there are no isolated pieces of information: as an example we can consider the Internet of Things (IoT) where every data source is connected and huge amounts of data correspond to even larger amounts of links expressing relations among them. For this reason, graph-based models are often used as a general description of Big Data.

In Neo4j data are stored in form of nodes and relationships (edges). Nodes and edges can have zero or multiple properties, each associated with a value. Moreover, a given node can also be labelled with multiple labels: each node label indicates a name of the node itself; each edge can be labelled with a type label (see Figure 14.(a) for an example). Differently from the other data models we have dealt with, Neo4j allows one to use multiple (and not predefined) labels, thus, in our translation into GSMM each label or property will be considered a node.

A *Neo4j graph* is a *GSMM graph* $\langle N, E\rangle$, where:

- the cardinality $|L_n|$ of the sets of node labels is 3. Each node $n_i = \langle oid_i, label/property_i, propertyvalue_i\rangle$ has an object identifier $oid_i \in \mathcal{UID}$, the node name $label/property_i$ which assumes values in the string domain and represents the name (label) or the property of the node, and the $propertyvalue_i$, which indicates either the value of the property or can assume as value $\perp$ in case the $label/property_i$ represents a property.
- the cardinality $|R_e|$ of the tuple of edge labels is 1. Each edge $e_j = \langle (n_h, n_k), R_{e_j}\rangle$ with n_h and n_k in N, has a label $R_{e_j} =< etype_j >$ with $etype_j \in \{TO, FROM, has\_property, has\_label\}$.

Similarly to the high level constraint specified for the Triplestore model (see Figure 12.(c)), also in the translation of Neo4j, each node having an incoming edge labeled $< TO >$ (i.e., representing an edge in the original Neo4j graph) must also have a not dangling incoming edge labeled $< FROM >$.

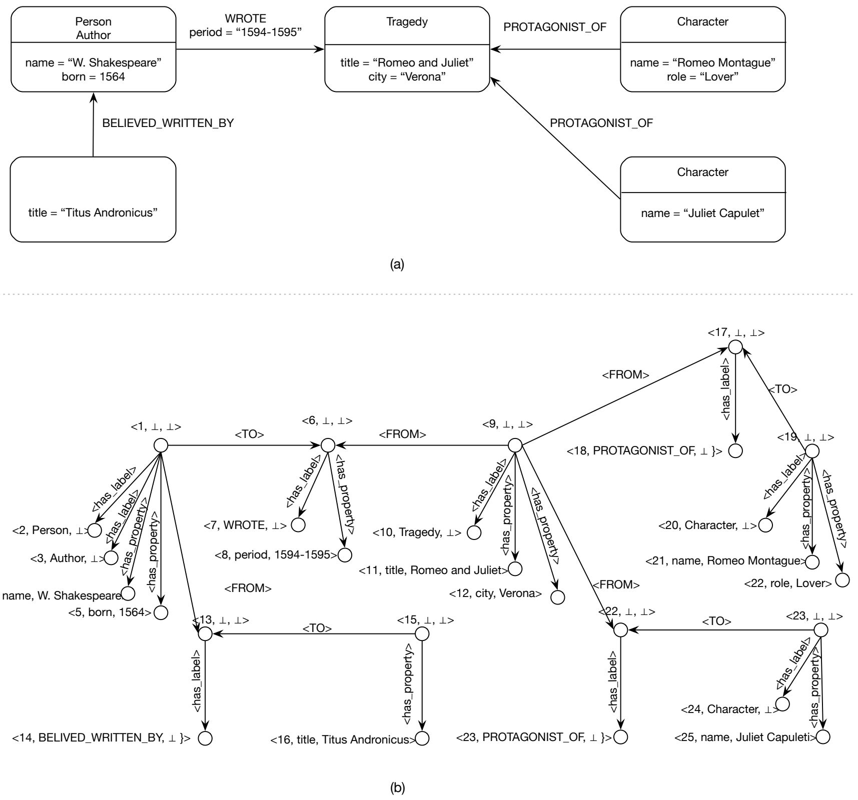


Fig. 14. (a) A Neo4j graph and (b) its corresponding GSMM graph.

3.8. Parameters

Instantiation parameters shown in the table in Fig. 15 are the *cardinality of node labels* (named $|L_n|$), the *cardinality of edge labels* (named $|R_e|$), the *domain of node labels* (named Node Label Domain), and the *domain of edge labels* (named Edge Label Domain), for the six concrete models described above[6]. By inspecting Table 15, we can carry out fast "a-priori" comparison of the models. For example, OEM only distinguishes two kinds of nodes, while OEM edges are labeled with a single label (actually, this label corresponds to the name of the pointed node, and edges represent the containment relation). The XML Infoset is quite similar to OEM, though it has a wider repertoire of node types and uses an enumeration type rather than a generic string for the edge label value. Intuitively, a model that uses enumeration values as edge labels can support *design rules*, saying when attribute rather than element containment should be used. Note that all the XML-based models represent order between node children, while OEM and TGM do not. Plain XML is the one model that does not provide object identifiers.

---

[6] For the sake of conciseness Table 15 does not explicitly consider Base Types, because they may be very large.

Concrete Model	$\lvert L_n \rvert$	$\lvert R_e \rvert$	Node Label Domain	Edge Label Domain
Relational	3	0	$OIDSet \times NodeNameSet \times \{DBname, RelationName, Att, KeyAtt, SetOfAtt, AttValue\}$	
OEM	3	1	$OIDSet \times \{Root, Object\} \times (OEMBaseTypes \cup \{\perp\})$	$NodeNameSet$
Plain XML	4	1	$TagSet \times \{Root, Attribute \cdots\} \times \mathbb{N} \cup \{\perp\} \times (PCDATA \cup \{\perp\})$	$\{SubelementOf, AttributeOf\}$
XML Schema	6	1	$URI \times NameSpaceSet \times TagSet \times \{Root, Element, Text, Attribute \cdots\} \times \mathbb{N} \cup \{\perp\} \times (XMLBaseTypes \cup \{\perp\})$	$\{SubelementOf, AttributeOf\}$
TGM	5	3	$OIDSet \times NodeNameSet \times \{Complex, Simple\} \times (TGMBaseTypes \cup \{\perp\}) \times V$	$EdgeNameSet \times \{Relational, Temporal\} \times V$
Triplestore	2	1	$OIDSet \times (NodeNameSet \cup \{\perp\})$	$\{TO, FROM\}$
BigTable	3	0	$OIDSet \times NodeNameSet \times (BigTableBaseTypes \cup \{\perp\})$	
Neo4j	3	1	$OIDSet \times NodeNameSet \times (Neo4jBaseTypes \cup \{\perp\})$	$\{TO, FROM, has\_property, has\_label\}$

Fig. 15. Instantiation of meta-model parameters for some concrete models

4. Inter-model translation

Our meta-model can be used for inter-model comparisons and translation as well. In particular, given two or more concrete models expressed by means of the GSMM formalism, we would like to be able to translate instances from one model to another one.

The translation task is mainly based on the following steps:

- for each node and edge label of the source model, try to find a corresponding label in the destination model. Whenever this basic translation is not possible, try to express each node or edge label of the source model, which does not have a corresponding label into the destination model, with a construct (e.g. a label, an additional node or edge) available in the destination model.
- to each label of the destination model that is not useful to express components of the instances of the source model assign an undefined value.

Next, we show how our technique can facilitate the inter-model translation process by considering TGM and plain XML as examples of concrete models.

4.1. Translating TGM into XML

We start from a TGM instance $\mathcal{G}$ translated into the corresponding GSMM graph $G = \langle N, E, r \rangle$.

In order to obtain another GSMM graph $G' = \langle N', E', r' \rangle$ related to an XML document, which represents the information originally contained in $\mathcal{G}$, we have to apply the primitives represented in Figure 16:

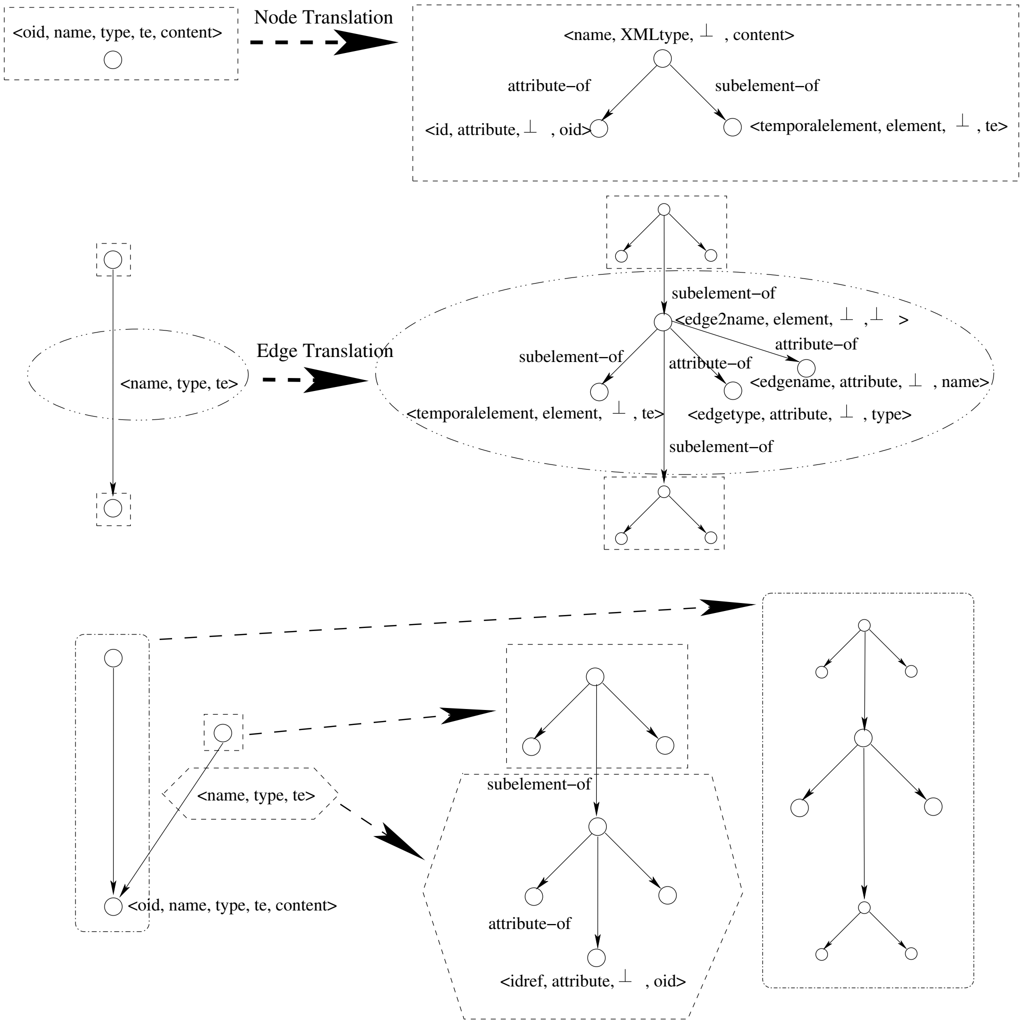


Fig. 16. Translating TGM into Plain XML.

1. for each $n \in N$, with $n = \langle oid, name, type, te, content \rangle$, transform it in a subtree of G' composed by three nodes n_1, n_2, and n_3.
   The first node n_1 has as tag label *name*, as type label *root* if $n = r$, *element* otherwise, an undefined order label, and *content* as content label (note that *content* is a defined value only for simple nodes of the TGM graph).
   The two children of n_1, named n_2 and n_3 have the labels $\langle id, attribute, \perp, oid \rangle$ and $\langle temporalelement, element, \perp, te \rangle$, respectively.
   Note that the edge connecting n_1 to n_2 is labeled $attribute - of$, whereas the edge from n_1 to n_3 is labeled $subelement - of$. Moreover, we do not use the order label of Plain XML because TGM does not consider an order relation between the children of a given node.

2. For each edge $e = \langle (m_1, m_2), R_e \rangle \in E$, with $R_e = \langle name, type, te \rangle$, we transform it into a subtree of four nodes n_1, n_2, n_3, and n_4.
   The node n_1 is an element with tag $edge2m_2$[7] (and undefined order and content labels) which has three children: n_2 is an element which has as tag *temporalelement* and as content te, n_3 is an attribute with tag *edgetype* and value *type*, n_4 is an attribute with tag *edgename* and value *name*.

3. TGM instances are modeled as DAGs whereas XML documents can be represented in a graphical way by means of trees.
   The third primitive of Figure 16 is introduced in order to solve this distinction between the two concrete models we are considering.
   If the original graph G contains a node n with more than one incoming edge, we translate one path to n as explained in the previous two steps, and we consider all the other edges to n as elements with an $idref$ attribute whose value is the object identifier of the pointed node.

4.1.1. An algorithm for translating TGM into XML

The above considerations allow us to formalise a depth-first algorithm for translating a TGM graph represented with the GSMM formalism into plain XML code.

```
TGM2XML(set of nodes N, set of edges E, node r)
{
  for all nodes n in N
    paint n white
  TGM2XMLCODE(N,E,r)
}

TGM2XMLCODE(set of nodes N, set of edges E, node n)
{
  paint n grey
  if (n = <oid,nodename,type,contentvalue,t> is a complex node)
  {
     write:``<nodename id=``oid''>
               <temporalelement> t </temporalelement>''
     for all outgoing edges e_i=((n,x_i),<Ename_i,relational,Et_i>)
    pointing to a white node x_i
     {
       write:``<edge2x_i edgename=``Ename_i'' type=``relational''>
                 <temporalelement> Et_i </temporalelement>''
       TGM2XMLCODE(N,E,x_i)
       write:``</edge2x_i>''
     }
     for all outgoing edges e_i=((n,x_i),<Ename_i,relational,Et_i>)
        pointing to a black node x_i
     {
```

---

[7] An edge pointing to m_2.

```
      write:‘‘<edge2x_i edgename=‘‘Ename_i’’
               type=‘‘relational’’ idref=‘‘objx_i’’>
                <temporalelement> Et_i </temporalelement>’’
      write:‘‘</edge2x_i>’’
    }
    paint n black
    write:‘‘</nodename>’’
  }
  else
  {
    write:‘‘<nodename id=‘‘oid’’> contentvalue ’’
    if (n has a temporal outgoing edge to x_j)
      write:‘‘<edge2x_j edgename=‘‘Temporal’’ type=‘‘temporal’’>
              </edge2x_j>’’
    write:‘‘</nodename>’’
    paint n black
  }
}
```

Consider the TGM instance reported in Figure 11.(a) and its translation into GSMM of Figure 11.(b). The XML code produced by `TGM2XML` is the following:

```
<BookShop id = 1>
  <TimeInterval> [01/01/1980,now) </TimeInterval>
  <Edge2Name edgename = HasProperty type = relational>
    <TimeInterval> [01/01/1980,now) </TimeInterval>
    <Name id = 2> Mega Book Store </Name>
  </Edge2Name>
  <Edge2IndAuthors edgename = Authors type = relational>
    <TimeInterval> [01/01/1980,now) </TimeInterval>
    <IndAuthors id = 3>
      <TimeInterval> [01/01/1980,now) </TimeInterval>
      <Edge2Author edgename = Contains type = relational>
        <TimeInterval> [01/01/1990,now) </TimeInterval>
        <Author id = 4>
          <TimeInterval> [01/01/1990,now) </TimeInterval>
          <Edge2Name edgename = HasProperty type = relational>
            <TimeInterval> [01/01/1990,now) </TimeInterval>
            <Name id = 5> J.K. Rowling </Name>
          </Edge2Name>
          <Edge2Book edgename = Writes type = relational>
            <TimeInterval> [01/01/1999,now) </TimeInterval>
            <Book id = 6>
              <Edge2Price edgename = HasProperty type = relational>
                <TimeInterval> [01/01/1999,now) </TimeInterval>
                <Price id = 7> 7.99 </Price>
              </Edge2Price>
              <Edge2Title edgename = HasProperty type = relational>
                <TimeInterval> [01/01/1999,now) </TimeInterval>
                <Title id = 8>
                   Harry Potter and the Prisoner of Azkaban
```

```
                </Title>
              </Edge2Price>
           </Book>
          </Edge2Book>
        </Author>
      </Edge2Author>
    </IndAuthors>
  </Edge2IndAuthors>
  <Edge2Book edgename = Sells type = relational idref = 6>
    <TimeInterval> [01/01/1999,now) </TimeInterval>
  </Edge2Book>
</BookShop>
```

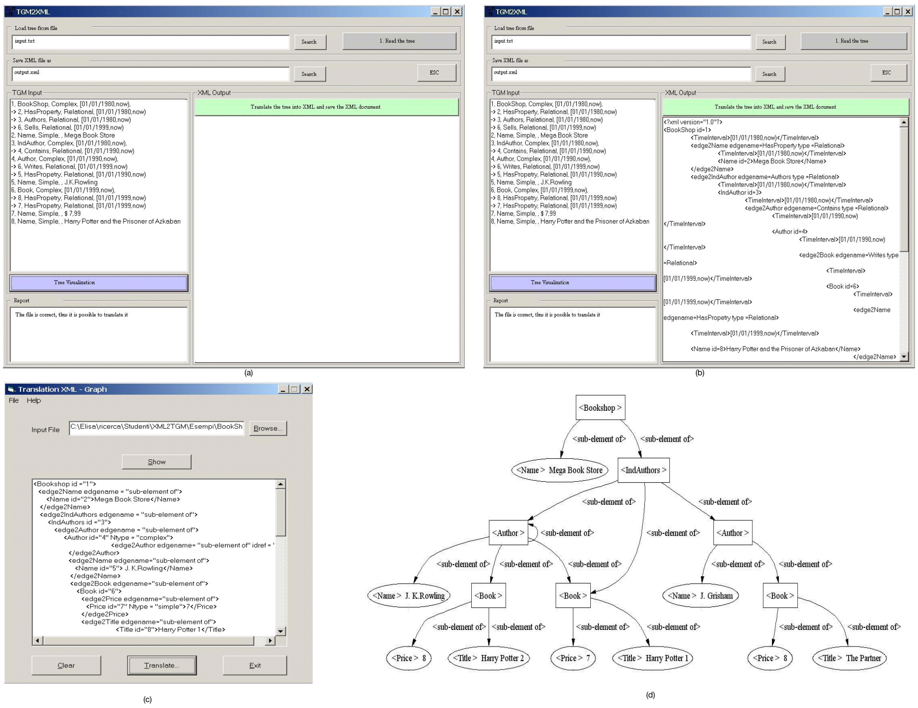
4.2. A software translator

Note that the element `Edge2Book` has an `idref` attribute, because the node labeled Book in the graph of Figure 11.(b) has two ingoing edges.

We have developed a software tool for translating TGM graphs into XML documents and viceversa. Figures 17.(a) and 17.(b) show how the textual representation of a TGM graph reporting information about Books is translated into an XML document. In the bottom part of Figure 17, we show the reverse step: the XML document about Books which is produced by the previous translation (Figure 17.(c)) is coded into the TGM graph depicted in Figure 17.(d).

5. Related work

Our meta-model's main goal is the uniform representation of flexible data models; it can be applied to inter-model comparison and translation, aimed at mediation between heterogeneous data sources. An early approach to this problem was a unified framework for the management and the exchange of semistructured data (Atzeni and Torlone, 2001), described according to a variety of formats and models. In particular they consider various schema definition languages for XML, OEM and a model to store Web data, and show that the primitives adopted by all of them can be classified into a rather limited set of basic types. On these basic types, they define a notion of "meta-formalism" that can be used to describe, in a uniform way, heterogeneous representations of data, and give the definition of an effective method for the translation between heterogeneous data representations. The main difference between this early proposal and our meta-model is related to schemata: Atzeni et al. (Atzeni and Torlone, 2001) assumes that a schema is available for each data source, whereas we do not require to have the schema in advance, but rather consider schemata as constraints that can be specified if needed. Another early effort is the Hypergraph Data Model (HDM) (McBrien and Poulovassilis, 1999), a simple low level modelling language based on a hypergraph data structure together with a set of associated constraints. Here the constraint specification language is not formalised; the authors define a small set of transformations as schemata expressed in HDM, which are used for inter-model transformation. Again, the main difference between this proposal and our meta-model is related to schemata translation. Our work focuses on flexible



(a)

input.txt

output.xml

```
1, BookShop, Complex, [01/01/1980,now),
-> 2, HasProperty, Relational, [01/01/1980,now)
-> 3, Authors, Relational, [01/01/1980,now)
-> 6, Sells, Relational, [01/01/1999,now)
2, Name, Simple, , Mega Book Store
3, IndAuthor, Complex, [01/01/1980,now),
-> 4, Contains, Relational, [01/01/1990,now)
4, Author, Complex, [01/01/1990,now),
-> 6, Writes, Relational, [01/01/1999,now)
-> 5, HasPropetry, Relational, [01/01/1990,now)
5, Name, Simple, , J.K.Rowling
6, Book, Complex, [01/01/1999,now),
-> 8, HasPropetry, Relational, [01/01/1999,now)
-> 7, HasPropetry, Relational, [01/01/1999,now)
7, Name, Simple, , $ 7,99
8, Name, Simple, , Harry Potter and the Prisoner of Azkaban
```

The file is correct, thus it is possible to translate it

(b)

input.txt

output.xml

```
1, BookShop, Complex, [01/01/1980,now),
-> 2, HasProperty, Relational, [01/01/1980,now)
-> 3, Authors, Relational, [01/01/1980,now)
-> 6, Sells, Relational, [01/01/1999,now)
2, Name, Simple, , Mega Book Store
3, IndAuthor, Complex, [01/01/1980,now),
-> 4, Contains, Relational, [01/01/1990,now)
4, Author, Complex, [01/01/1990,now),
-> 6, Writes, Relational, [01/01/1999,now)
-> 5, HasPropetry, Relational, [01/01/1990,now)
5, Name, Simple, , J.K.Rowling
6, Book, Complex, [01/01/1999,now),
-> 8, HasPropetry, Relational, [01/01/1999,now)
-> 7, HasPropetry, Relational, [01/01/1999,now)
7, Name, Simple, , $ 7,99
8, Name, Simple, , Harry Potter and the Prisoner of Azkaban
```

```
<?xml version="1.0"?>
<BookShop id=1>
        <TimeInterval>[01/01/1980,now)</TimeInterval>
        <edge2Name edgename=HasProperty type =Relational>
                <TimeInterval>[01/01/1980,now)</TimeInterval>
                <Name id=2>Mega Book Store</Name>
        </edge2Name>
        <edge2IndAuthor edgename=Authors type =Relational>
                <TimeInterval>[01/01/1980,now)</TimeInterval>
                <IndAuthor id=3>
                        <TimeInterval>[01/01/1980,now)</TimeInterval>
                        <edge2Author edgename=Contains type =Relational>
                                <TimeInterval>[01/01/1990,now)
</TimeInterval>
                                <Author id=4>
                                        <TimeInterval>[01/01/1990,now)
</TimeInterval>
                                        <edge2Book edgename=Writes type
=Relational>
                                                <TimeInterval>
[01/01/1999,now)</TimeInterval>
                                                <Book id=6>
                                                        <TimeInterval>
[01/01/1999,now)</TimeInterval>
                                                        <edge2Name
edgename=HasPropetry type =Relational>

        <TimeInterval>[01/01/1999,now)</TimeInterval>

        <Name id=8>Harry Potter and the Prisoner of Azkaban</Name>
                                                        </edge2Name>
```

The file is correct, thus it is possible to translate it

(c)

C:\Elisa\ricerca\Studenti\XML2TGM\Esempi\BookSh

```
<Bookshop id ="1">
  <edge2Name edgename = "sub-element of">
     <Name id="2">Mega Book Store</Name>
  </edge2Name>
  <edge2IndAuthors edgename = "sub-element of">
     <IndAuthors id ="3">
       <edge2Author edgename = "sub-element of">
          <Author id="4" Ntype = "complex">
                         <edge2Author edgename= "sub-element of" idref = '
            </edge2Author>
            <edge2Name edgename="sub-element of">
              <Name id="5"> J. K.Rowling</Name>
            </edge2Name>
            <edge2Book edgename="sub-element of">
              <Book id="6">
                <edge2Price edgename="sub-element of">
                  <Price id="7" Ntype = "simple">7</Price>
                </edge2Price>
                <edge2Title edgename="sub-element of">
                          <Title id="8">Harry Potter 1</Title>
```

(d)

Fig. 17. (a) A tool for translating TGM graphs into XML document; (b) the XML translation of a TGM graph; (c) a tool for translating an XML document into a TGM graph; (d) the visualization of the resulting TGM graph.

models which may be schemaless thus, we do not target schemata translation, but provide a very general graph-based formalism allowing the representation of different aspects of data. Our inter-model translation, as shown by example in Section 4, relies on the generality of nodes and edge labels, which can be specialised to the labels allowed by the source and destination models. Moreover, while the meta-model by McBrien et al. (McBrien and Poulovassilis, 1999) provides some basic primitives whereof the basic constructs of models can be *built*, ours provides a high level, general formalism whose *specializations* are the models themselves. Other early proposals ((Bernstein and Pottinger, 2003), (Bowers and Delcambre, 2000), and (Levy, Rajaraman and Ordille, 1996)) dealing with inter-model translation do not propose a unifying meta-model but focus on the possibility to translate information from a model to another. Bernstein et al. provide a generic framework that can be used to merge models in different contexts (Bernstein and Pottinger, 2003). Bowers et al. proposed an approach to represent, in a uniform way, information coming from different models (Bowers and Delcambre, 2000). They use RDF and provide a mapping formalism for inter-model translation. With the advent of NoSQL data models and systems, some researchers pointed out the need of analyzing these new systems for a data modelling point of view (Indrawan-Santiago, 2012), while others noticed that small differences in data modelling features may have a huge impact on performance of NoSQL systems (Angles, 2012) However, we are not aware of any attempt to provide a comprehensive meta-model and a comparison framework like our own. Rather, recent research has focused on one-on-one data model comparison in vertical domains. Lee et al. identify a set of informal expressive power criteria that lead to choosing the XML Infoset over the relational model as a concrete data representation for patient data (Lee, Tang and Choi, 2013). Unfortunately, lack of formalisation of their criteria prevents them for providing a rigorous assessment methodology.

When choosing a NoSQL data model, the computer scientist is faced with the contrasting requirements of dealing with data whose structure is not easily captured by traditional approaches, and allowing for fast revisions of representational choices at run-time. The use of GSMM and GSL marks a step forward toward a rigorous treatment of the fundamental issues of flexible data modeling and querying. For example, GSMM provides a way for *a posteriori schema derivation*: intuitively, a schema *represents* an instance if it contains its skeleton while disregarding multiplicities and values. Given a data-base instance, we can obtain a schema by drawing a constraint that defines the structure of the document (Cortesi, Dovier, Quintarelli and Tanca, 2002). In particular the constraint specifies, by means of first-order formulae, all the possible paths starting from the root node, and sets also the admitted labels of nodes and edges. We claim that such schemata may play an important role in assessing similarity and differences between individual data representations.

6. Conclusions and Future work

We have presented a graph based meta-model (GSMM) and a language (GSL) aimed at bringing flexible data model properties into a unified framework. In our future work we will define flexibility metrics on concrete data models based on their GSSM representations. We expect to be able to establish benchmarks supporting a priori assessment of data models, guiding adoption decisions. Another line of investigation concerns the use of GSL as a language for those models where no language is defined. As an example, consider the Unified Modeling Language (UML), where schemata (models, in UML notation) may be specified by means of different notations, at different levels of detail (e.g. class diagrams). A specification based on GSMM could allow the expression of constraints to be associated to a UML class diagram or to any UML diagram. Moreover, constraints expressed in GSL may easily be transformed from more general to more specific representations of the same information by means of different UML notations.

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