

From XML Schema to Relations: A Cost-Based Approach to XML Storage

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Abstract

XML has become an important medium for data representation, particularly when that data is exchanged over or browsed on the Internet. As the volume of XML data increases, there is a growing interest in storing XML in relational databases so that the well-developed features of these systems (*e.g.*, concurrency control, crash recovery, query processors) can be re-used. However, given the wide variety of XML applications and the mismatch between XML's nested-tree structure and the flat tuples of the relational model, storing XML documents in relational databases presents interesting challenges.

LegoDB is a *cost-based* XML-to-relational mapping engine that addresses this problem. It explores a space of possible mappings and selects the best mapping for a given application (defined by an XML Schema, XML data statistics, and an XML query workload). LegoDB leverages existing XML and relational technologies: it represents the target application using XML standards and constructs the space of configurations using XML-specific operations, and it uses a traditional relational optimizer to obtain accurate cost estimates of the derived configurations. In this paper, we describe the LegoDB mapping engine and provide experimental results that demonstrate the effectiveness of this approach.

1 Introduction

As XML is now an important medium for representing, exchanging and accessing data over the Internet, applications are processing an increasing amount of XML data. Not surprisingly, there is a growing interest in storing XML in relational databases so that these applications can use a complete set of data management services (including concurrency control, crash recovery, scalability, etc) and benefit from the highly optimized relational query processors. A number of strategies have been proposed [7, 11, 14, 18, 19] to address the XML-to-relational mapping problem. An important limitation of most of these proposals is that they rely on a fixed XML-to-relational mapping. A given mapping is unlikely to work well for more than a few of the wide variety of access patterns an application may present. For example, a web site may perform a large volume of simple lookup queries, whereas a catalog printing application may require large and complex queries with deeply nested results. Modern commercial databases (see *e.g.*, [24]), on the other hand, provide a more flexible approach to storing XML data, by allowing the developer to specify the storage mapping.

However, this approach has drawbacks, most notably: it requires the developer to master two quite distinct technologies (XML and RDBMS); and it might be hard, even for an expert, to determine a good mapping for a complex application.

In this paper, we introduce a novel cost-based framework for XML-to-relational storage mapping, and describe the design of LegoDB, a tool based on this framework that automatically finds an efficient XML-to-relational mapping for a target application. The three main design principles behind LegoDB are cost-based search, logical/physical independence, and re-use of existing technology. Since the effectiveness of one-size-fits-all mapping is improbable given the wide variety of XML applications (with data ranging from flat to nested, schemas ranging from structured to semistructured, access patterns ranging from traditional SPJ queries to full-text or recursive queries), our first principle is to take application parameters into account. More precisely, given a schema describing the XML data to be processed, a query workload, and data statistics, the LegoDB engine explores various relational configurations in order to find the most efficient for the application.

Our second principle is to support logical/physical independence. Developers of XML applications should deal with XML structures and operations and they should not be concerned with the underlying physical storage in a relational database. Hence, the LegoDB interface is purely XML-based—it takes as input XML queries, schemas and statistics.

Our third principle is to leverage existing XML and relational technology whenever possible. LegoDB relies on: 1) existing XML standards to represent the target application, 2) XML-specific operations over a schema to generate a space of possible mappings, and 3) a traditional relational optimizer to obtain accurate cost estimates for the derived mappings. On the first point, queries which make up the application workload are given in XQuery [5], and the user data is described with XML Schema [21].

Our main contributions are summarized below.

- We introduce the notion of physical XML Schemas (*p-schemas*), which are XML Schemas extended with statistics about the underlying XML data. We define a fixed mapping from a particular *p-schema* to a relational schema and a corresponding mapping from XML documents to databases.
- We define XML Schema transformations that when applied to a *p-schema* and followed by the fixed mapping, lead to a space of alternative storage configurations. The idea is that one may define many alternate XML Schemas which are equivalent in terms of the documents which are *valid* under each schema, but yield different configurations. For instance, types can be introduced or elided, and regular expressions can be rewritten without affecting the semantics of the schema. Because the proposed rewritings are specific to XML Schema, this search space contains many configurations not exploited by relational storage design tools (see, for example, [1, 23]).
- Through the fixed mapping, XML-specific statistics are translated into the corresponding relational statistics, and XQuery workloads are converted into the corresponding SQL workloads. As a result, we can exploit a traditional relational optimizer to obtain cost estimates for the various configurations, and select the best among them. One potential problem with this approach is search space explosion. Due to the nature

of XML Schema, the schema transformations may lead to a large (possibly infinite) search space. In this paper we use a greedy evaluation strategy to explore an interesting subset of this space.

- We give experimental results which show that LegoDB is able to find efficient storage designs for a variety of workloads in a reasonable time. Our results indicate that our cost-based exploration selects storage designs which would not be arrived at by previously-proposed heuristics, and that in most cases, these designs have significantly lower costs.

Organization of the Paper The rest of the paper is organized as follows. In Section 2, we present a motivating example along with some background information. In Section 3, we present the LegoDB framework for mapping XML Schemas, queries, and documents into relational configurations, queries, and databases. In Section 4, we present the rewriting rules defining the search space and our search algorithm. In Section 5, we present preliminary experimental results. We review related work in Section 6, and discuss directions for future work in Section 7.

2 Background and Motivating Example

In this section, we motivate our approach, notably the use of XML Schema and the cost-based evaluation of storage mappings, with an example XML storage mapping scenario inspired from the Internet Movie Database [13].

XML documents and DTDs Figure 1 gives an example XML fragment in which the `show` element is used to represent movies and TV shows. This element contains information that is shared between movies and TV shows, such as `title` and `year` as well as information specific to movies (*e.g.*, `box_office` and `video_sales`) and to TV shows (*e.g.*, `seasons`). Figure 2(a) shows a Document Type Definition (DTD) [2] for the example document of Figure 1. The DTD contains declarations for all elements and attributes in the document. The contents of each element may be text (*e.g.*, `#PCDATA`, `CDATA`), or a regular expression over other elements (*e.g.*, `(show* ,director* ,actor*)`).

Using XML Schema for storage Figure 2(b) shows an alternative schema described using the notation for types from the XML Query Algebra [9]. This notation captures the core semantics of XML Schema, abstracting away some of the complex features of XML Schema which are not relevant for our purposes (*e.g.*, the distinction between groups and complexTypes, local vs. global declarations, etc). The XML Schema and the XML Query Algebra notation for our sample schema can be found in Appendix B.

Like DTDs, XML Schema describes elements (*e.g.*, `show`) and attributes (*e.g.*, `@type`) and uses regular expressions to describe allowed subelements (*e.g.*, `imdb` contains **Show***, **Director***, **Actor***). But Figure 2(b) also illustrates a number of distinguishing features that are useful for storage. First, one can specify precise data types (*e.g.*, `String`, `Integer`) instead of text, an essential feature for generating an efficient storage configuration. Also, regular expressions are extended with more precise cardinality annotations for collections (*e.g.*, `{1,10}` indicates that there can be between 1 to 10 aka elements for `show`),

```

<imdb>
  <show type="Movie">
    <title>Fugitive, The</title>
    <year>1993</year>
    <aka>Auf der Flucht</aka>
    <aka>Fuggitivo, Il</aka>
    <review>
      <suntimes>
        <reviewer>Roger Ebert</reviewer>
        <rating>Two thumbs up!</rating>
        <comment>
          This is a fun action movie,
          Harrison Ford at his best.
        </comment>
      </suntimes>
    </review>
    <review>
      <nyt>
        The standard Hollywood summer
        movie strikes back.
      </nyt>
    </review>
    <box_office>183,752,965</box_office>
    <video_sales>72,450,220</video_sales>
  </show>

  <show type="TV series">
    <title>X Files, The</title>
    <year>1994</year>
    <aka>Akte X - Die unheimlichen
      Fälle des FBI</aka>
    <aka>Aux frontieres du Reel</aka>
    <seasons>
      <number>10</number>
      <years>1993 1994 1995 1996 1997
        1998 1999 2000 2001</years>
    </seasons>
    <description>
      A paranoid FBI agent teams up with
      a frustrated female scientist to chase
      DNA modified aliens financed by the NSA.
    </description>
    <episode>
      <name>Ghost in the Machine</name>
      <guest_director>
        Jerrold Freedman
      </guest_director>
    </episode>
    <episode>
      <name>Fallen Angel</name>
      <guest_director>
        Larry Shaw
      </guest_director>
    </episode>
  </show>
  ....
</imdb>

```

Figure 1: XML data sample for a subset of the IMDB

<pre> <!DOCTYPE imdb [<!ELEMENT imdb (show*, director*, actor*)> <!ELEMENT show (title, year, aka+, reviews*, ((box_office, video_sales) (seasons, description, episode*)))> <!ATTLIST show type CDATA #REQUIRED> <!ELEMENT title (#PCDATA)> <!ELEMENT year (#PCDATA)> <!ELEMENT aka (#PCDATA)> <!ELEMENT review (#PCDATA)> <!ELEMENT box_office (#PCDATA)> <!ELEMENT video_sales (#PCDATA)> <!ELEMENT seasons (#PCDATA)> <!ELEMENT description (#PCDATA)> <!ELEMENT episode (name,guest_director)> <!ELEMENT name (#PCDATA)> <!ELEMENT guest_director (#PCDATA)>]> </pre> <p style="text-align: center;">(a)</p>	<pre> type IMDB = imdb [Show*, Director*, Actor*] type Show = show [@type[String], title[String], Year, Aka{1,10}, Review*, (Movie TV)] type Year = year[Integer] type Aka = aka[String] type Review = review[~[String]] type Movie = box_office[Integer], video_sales[Integer] type TV = seasons[Integer], description[String], episode[name[String], guest_director[String]]* type Director = ... </pre> <p style="text-align: center;">(b)</p>
--	---

Figure 2: Schema samples for the IMDB documents

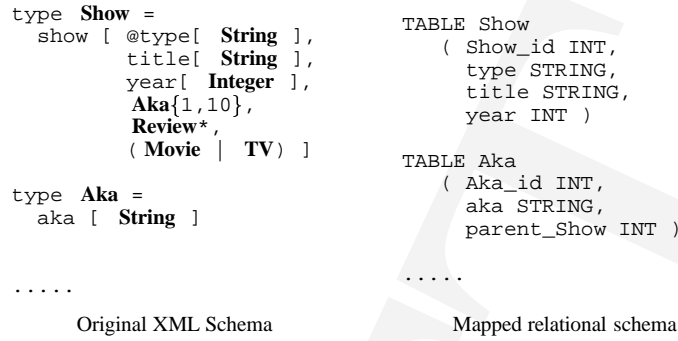


Figure 3: Mapping XML Schema to relations

which enables the specification of more constrained collections. Finally, XML Schema can describe so-called *wildcards*: for instance, the `~ [AnyType]` notation specifies that the `review` element can contain an element with an arbitrary name and content. This allows XML Schema to describe parts of the schema for which no precise structural information is available.

Storage mappings In addition to the features described above, a very important difference between XML Schema and DTDs is that the former distinguishes between elements (*e.g.*, a `show` element) and their type (*e.g.*, the `Show` type). The type name never appears in the document, and one element may have different allowed content when it appears in different types. A key feature of the LegoDB approach is that it uses the classification of elements to type names as the basis for creating storage mappings. As an example, Figure 3 shows a sample mapping for a fragment of the schema in Figure 2(b). Each type (*e.g.*, `Show`) can be used to group a set of elements together. The LegoDB mapping engine creates a table for each such type (*e.g.*, `Show`) and maps the contents of the elements (*e.g.*, `type`, `title`, etc.) to columns of that table. Finally, the mapping also generates a key column that contains the `id` of the corresponding element (*e.g.*, `Aka_id` column), and a foreign key that keeps track of the parent-child relationship (*e.g.*, `parent_Show` column).

Clearly, it is not always possible to map types into relations. For instance, since there can be many `episode` elements in the type `TV`, these elements cannot be mapped into columns of that table. In Section 3, we introduce a restricted form of XML Schemas, which we refer to as *physical schemas*, which have the property that they are easily mapped to relations by creating one relation for each type name.

Schema transformations An important observation is that there are many different XML schemas that validate the exact same set of documents. For instance, different but equivalent regular expressions (*e.g.*, $(a(b|c^*))((a,b)|(a,c^*))$) can describe the contents of a given element. In addition, the allowed subelements of an element can be referred to *directly* (*e.g.*, the element `title` in `Show`), or can be referred to by a type name (*e.g.*, see the type `Year`). Although the presence of a type name does not change the semantics of the XML Schema, it affects the derived relational schema, as our mapping generates one relation for each type. Hence, by performing a sequence of transformations (also called rewritings) which preserve the semantics of the schema and then generating the implied the storage mapping, a space of storage

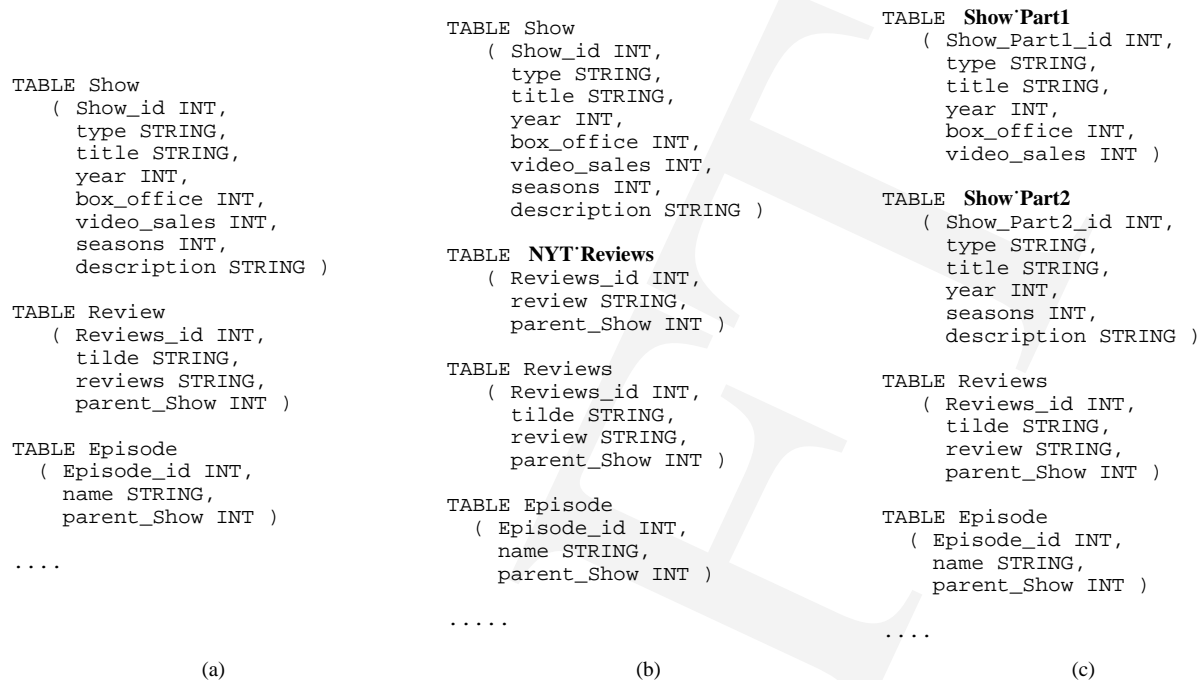


Figure 4: Three storage mappings for the Show element

mappings can be explored.

Cost-based evaluation of XML storage Figure 4 shows three possible relational storage mappings that are generated by some of our transformations. For instance, configuration (a) results from inlining as many elements as possible in a given table, roughly corresponding to the strategy advocated by [19]. Configuration (b) is obtained from configuration (a) by partitioning the reviews table into two tables (one that contains New York Times reviews, and another for reviews from other sources). Finally, configuration (c) is obtained from configuration (a) by splitting the Show table into Movies or TV shows.

Even though each of these configurations can be the best for a given application, there may be cases where they perform poorly. An important question is then how to select a particular configuration. In LegoDB, this decision is based on query workloads and data statistics. Consider the queries of Figure 5 described in XQuery [4]. The first query returns the title, year and the New York Times reviews for all shows from 1999. Query 2 publishes all the information available for all shows in the database. Query 3 retrieves the description of a show based on the title, and Query 4 retrieves episodes of shows directed by a particular guest director. Whereas queries 1 and 2 are typical of a publishing scenario (*i.e.*, to send a movie catalog to an interested partner), queries 3 and 4 contain specific selection criteria and are typical of interactive lookup queries. We then define two workloads, $W1$ and $W2$, where $W1 = \{Q1 : 0.4, Q2 : 0.4, Q3 : 0.1, Q4 : 0.1\}$ and $W2 = \{Q1 : 0.1, Q2 : 0.1, Q3 : 0.4, Q4 : 0.4\}$, where each workload contains a set of queries and an associated weight that could reflect the relative importance of each query for the application. From an application perspective, workload $W1$ might be representative of the workload generated by a cable company which routinely publishes large parts of the database for download to intelligent set-top boxes,

```

Q1:
FOR $v in imdb/show
WHERE $v/year = 1999
RETURN $v/title, $v/year, $v/nyt_reviews

Q2:
FOR $v in imdb/show
RETURN $v

Q3:
FOR $v in imdb/show
WHERE $v/title = c2
RETURN $v/description

Query 4:
FOR $v in imdb/show
RETURN
<result>
  $v/title
  $v/year
  FOR $v/episode $e
  WHERE $e/guest_director = c4
  RETURN $e
</result>

```

Figure 5: Queries for the Show element

	Storage Map 1 (Fig 4(a))	Storage Map 2 (Fig 4(b))	Storage Map 3 (Fig 4(c))
Q1	1.00	0.83	1.27
Q2	1.00	0.50	0.48
Q3	1.00	1.00	0.17
Q4	1.00	1.19	0.40
W1	1.00	0.75	0.75
W2	1.00	1.01	0.40

Figure 6: Estimated Costs for Queries and Workloads

while while *W2* might represent the lookup queries issued to a movie-information web site, like the IMDB itself.

Figure 6 shows the estimated costs for the queries and workloads returned by the LegoDB storage mapping tool for each configuration in Figure 4. These costs are normalized by the costs of Storage Map 1.

It is important to remark that only the first one of the three storage mappings shown in Figure 4 can be generated by previous heuristic approaches of which we are aware. However, this mapping has significant disadvantages for either workload we consider. First, due to its treatment of union, it inlines several fields which are not present in all the data, making the Show relation wider than necessary. Second, when the entire Show relation is exported as a single document, the records corresponding to movies need not be joined with the Episode tables, but this join is required by mapping 4(a) and (b). Finally, the large Description element need not be inlined unless it is frequently queried.

3 From XML Schema to Relations

The architecture of the LegoDB mapping engine is depicted in Figure 7. Given an XML Schema and statistics extracted from an example XML dataset, we first generate an initial physical schema (PS0). The physical schema and the XQuery workload are then input into the Query/Schema Translation module, which in turn generates the corresponding relational catalog (schema and statistics) and SQL queries that are input

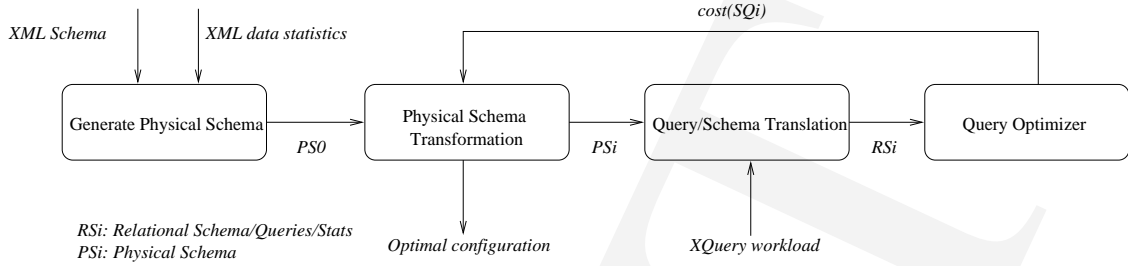


Figure 7: Architecture of the Mapping Engine

into a relational optimizer for cost estimation. Schema transformation operations are then repeatedly applied to PS_0 , and the process of Schema/Query translation and cost estimation is repeated for each transformed PS until a *good* configuration is found. In this section we focus on physical schemas and on the Query/Schema Translation module.

3.1 Physical XML Schemas

As pointed out in [19], mapping DTDs to relational configurations is a hard problem. There are several reasons for that: (1) the presence of regular expressions, nested elements and recursive types results in a mismatch with flat relations; (2) DTDs do not differentiate between elements that correspond to entities (*e.g.*, a person) and elements that correspond to some attribute of that entity (*e.g.*, the name of a person) — hence it is not clear whether one should map an element to a relation or to an attribute of a relation; (3) DTDs define no explicit data types for elements (*e.g.*, integer, date), and as a result all values must be stored as strings which can lead to inefficiencies.

As we have seen in Section 2, XML Schema differs from DTDs in a number of ways. Notably, because XML Schema distinguishes between type names and element description, a straightforward mapping strategy is to create a relation for each type in XML Schema. In addition, XML Schema provides explicit data types which lead to more natural (and efficient) storage mappings. However, a number of difficulties remain:

- the mismatch between the structure of XML Schema types and relations, due to the presence of nested tree regular expressions, and
- the lack of information about the data to be stored, *e.g.*, cardinality of collections and number of distinct values for an attribute, which is necessary for designing an efficient storage mapping.

In order to address these problems, we introduce the notion of physical XML schemas (*p-schemas*). *P-schemas* have the following properties: (i) they are as expressive as XML Schemas, (ii) they contain useful statistics about the data to be stored, and (iii) there exists a fixed, simple mapping from *p-schemas* into relational schemas. Before we give a precise definition of *p-schemas*, we illustrate the construction of a *p-schema* from an XML Schema through an example.

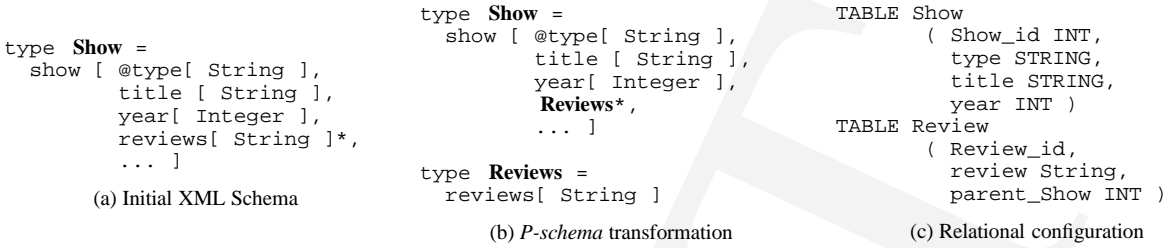


Figure 8: P-schema creation

Transforming an XML Schema into a *P-schema* By inserting appropriate type names for certain elements, one can satisfy (iii) above while preserving the semantics of the original schema. For instance, in order to guarantee that there exists a simple and unique mapping into a relational configuration, the XML Schema is rewritten so that all multi-valued elements have an associated type name. For example, the Show type of Figure 8(a) cannot be stored directly into a relational schema because there might be multiple `reviews` elements in the data. However, the equivalent schema in Figure 8(b), in which this element is described by a separate type name, can be easily mapped into the relational schema shown in 8(c). The foreign key from the Review table, `parent_Show` is present since the type name **Reviews** appears within the definition of the **Show** type.

Data Statistics The *p-schema* also needs to store data statistics. These statistics are extracted from the data and inserted in the original physical schema PS0 during its creation. A sample *p-schema* with statistics for the type Show is given below:

```

type Show =
  show [ @type[ String<#8,#2> ],
         year[ Integer<#4,#1800,#2100,#300> ],
         title[ String<#50,#34798> ],
         Review* <#10> ]

type Review =
  review[ String<#800> ]

```

where `Scalar<#size, #min, #max, #distincts>` indicates for each scalar datatype the corresponding size (e.g., 4 bytes for an integer), minimum and maximum values, and the number of distinct values; and `String<#size, #distincts>` which specifies the length of a string as well as the number of distinct values. The notation `* <#count>` indicates the *relative* number of `Reviews` elements within each element of type Show (e.g., in this example, there are 10 reviews per show).

Stratified physical types We are now ready to define *p-schemas*. As we have discussed, it is essential that each type name contains a structure that can be directly mapped to a relation. Accordingly, we adapt the original syntax for types of [9] to enforce the appropriate structure¹. The resulting grammar is shown in Figure 9.

Because this new grammar is *stratified* (i.e., instead of the types defined in the original XML Schema, there are three different layers of types), it ensures that type names are always used within collections or

¹Note that for space reasons, we do not enclose here the original grammar, but encourage the reader to consult the original XML Query Algebra document.

scalar type	s	::=	Integer String Boolean	
physical scalar	ps	::=	$ps < \#size, \#min, \#max, \#distincts >$	
named type	nt	::=	X	type name
			$nt \mid nt$	choice
			\emptyset	empty choice
			$nt\{n, m\} < \#count >$	repetition
optional type	ot	::=	nt	named type
			s	optional scalar
			$l[ot]$	optional element
			ot, ot	optional sequence
			$()$	empty sequence
physical type	pt	::=	nt	named type
			$ot\{0, 1\}$	optional type
			s	scalar
			$l[pt]$	element
			pt, pt	sequence
			$()$	empty sequence
schema item	si	::=	type $X = pt$	type declaration
schema		::=	schema $Sn = si, si, \dots$ end	schema

Figure 9: Stratified Physical Types

unions in the schema. The first layer, *physical types*, contains only singleton elements, nested singleton elements, and optional types. The second layer, *optional types*, is used to represent element structures that are tagged with a question mark. Finally *named types* can only contain type names and are used to enforce that complex regular expressions (such as union and repetition) do not contain nested elements.

An important property of physical schemas is that any XML Schema has an equivalent physical schema. As a proof sketch of that statement, one just needs to realize that each schema can be rewritten by having a type name for each element, and that the resulting schema is a *p-schema* equivalent to the original schema.

3.2 Mapping p-schemas into relations

The reason for the above stratification of physical types is to make sure there is a straightforward mapping from these types into relations. The mapping is as follows:

- Create one relation R_T for each type name T .
- For each relation R_T , create a key that will store the node id of the corresponding element.
- For each relation R_T , create a foreign key $T_{\circ_PT_Key}$ to all relations R_{PT} such that PT is a parent type of T
- A column is created in R_T for each subelement of T that is a physical type.
- If the data type is contained within an optional type then the corresponding column can contain a null value.

Essentially, that mapping procedure follows the stratification of types: elements in the physical types layer are mapped to standard columns, elements within the optional types layer are mapped to columns with null

values, and named types are used only to keep track of the child-parent relationship and for the generation of foreign keys.

For an instance ps of the p -schema, the relational schema defined by the above mapping is referred to as $rel(ps)$. Table 1 describes these mappings in detail (except computation of foreign keys). For instance: fixed size strings in XML are mapped to fixed sized strings in relational; nested elements are mapped to columns; top level types that contain data types are mapped to a special column that contains a `_data` column, etc. The μ function is used to map nested elements, the μ_o function is used to map optional nested elements and the $parent$ function computes the appropriate foreign key for each table. In fact, a similar function is used to propagate statistics from the p -schema to the relational schema, but this process is straightforward and omitted for clarity.

<i>P</i> -schema	Relational Schema
Datatypes	
$t = \text{String} \#<\text{size}>$	$\mu(t) = \text{CHAR}(\text{size})$
$t = \text{String}$	$\mu(t) = \text{STRING}$
$t = \text{Integer} \#<\text{size}>$	$\mu(t) = \text{INTEGER}$
...	
$t = \text{String} \#<\text{size}>$	$\mu_o(t) = \text{CHAR}(\text{size}) \text{ null}$
$t = \text{String}$	$\mu_o(t) = \text{STRING} \text{ null}$
$t = \text{Integer} \#<\text{size}>$	$\mu_o(t) = \text{INTEGER} \text{ null}$
...	
Elements	
$t = a[t']$	$\mu(t) = \langle a:a1:ps_1, \dots a:an:ps_n \rangle$, where $\mu(t') = \langle a1:ps_1, \dots an:ps_n \rangle$
$t = \tilde{t}'$	$\mu(t) = \langle \text{tilde STRING } a:a1:ps_1, \dots a:an:ps_n \rangle$, where $\mu(t') = \langle a1:ps_1, \dots an:ps_n \rangle$
$t = t1, t2$	$\mu(t) = \langle a1:ps_1, \dots an:ps_n, a1':ps_1, \dots am':ps_n \rangle$, where $\mu(t1) = \langle a1:ps_1, \dots an:ps_n \rangle$ and $\mu(t2) = \langle a1':ps_1, \dots am':ps_n \rangle$
$t = ot\{0,1\}$	$\mu(ot) = \mu_o(ot)$
nt	$\mu(nt) = \langle \rangle$
Schema	
type $T = \text{String}\langle\#\text{count}\rangle$	TABLE $T \langle T_id \text{ INT}, _data \text{ CHAR}(\text{size}) \rangle \circ \langle parent(T) \rangle$
type $T = \text{Integer}$	TABLE $T \langle T_id \text{ INT}, _data \text{ INT} \rangle \circ \langle parent(T) \rangle$
...	
type $T = pt$	TABLE $T \langle T_id \text{ INT} \rangle \circ \mu(pt) \circ \langle parent(T) \rangle$

Table 1: Mapping from Physical XML Schemas to Relations

It is noteworthy to mention that, although simple, this mapping deals appropriately with recursive types. In addition, it also maps XML Schema wildcards (the $\tilde{}$ elements) appropriately. Take for example the definition of the AnyElement in the XML Query Algebra:

```
type AnyElement =  $\tilde{[}$  (AnyElement|AnyScalar)*  $]$ 
type AnyScalar = Integer | String
```

This type is valid for all possible elements with any content. In other words, this is a type for untyped XML documents. Note also that this definition uses both recursive types (AnyElement is used in the content of any element) and a wildcard ($\tilde{}$). Again, applying the above rules, one would construct the following relational schema:

```
TABLE String          TABLE Integer          TABLE AnyElement =
```

```
( __data STRING,      ( __data INT,      ( Element_id INT,
  parent INT )        parent INT )        tilde STRING,
                    parent_Element INT )
```

This also shows that using XML Schema and the proposed mapping, LegoDB can deal with structured and semistructured documents in an homogeneous way. Indeed the AnyElement table is similar to the *overflow* relation that was used to deal with semistructured document in the STORED system [7].

3.3 Mapping XQuery queries

Although query mapping is an important part of the optimization process, rewriting XML queries into their equivalent SQL counterparts is not the focus of this paper and we omit any further discussion on this issue. We refer the interested reader to recently proposed mapping algorithms from XML query languages to SQL [10, 3].

4 Schema Transformations and Search

In this section, we describe possible transformations for *p-schemas*. By repeatedly applying these transformations, LegoDB generates a space of alternative *p-schemas* and corresponding relational configurations. As this space can be rather large (possibly infinite), we use a greedy search algorithm that our experiments show to be effective in practice (see Section 5). The greedy search algorithm and its interaction with a relational optimizer are presented in Section 4.2.

4.1 XML transformations

Before we define the *p-schema* transformations, it is worth pointing out that there are important benefits to performing these transformations at the XML Schema level as opposed to transforming relational schemas. Much of the semantics available in the XML schema is not present in a given relational schema and performing the equivalent rewriting at the relational level would imply complex integrity constraints that are not within the scope of relational keys and foreign keys. As an example, consider the rewriting on Figure 4(c): such partitioning of the Show table would be very hard to come up with just considering the original schema (a). On the other hand, we will see that this is a natural rewriting to perform at the XML level. In addition, working at the XML Schema level makes the framework more easily extensible to other non-relational stores such as native XML stores and flat files, where a search space based on relational schemas would be an obstacle.

There is large number of possible rewritings applicable to XML Schemas. Instead of trying to give an exhaustive set of rewriting, we focus on a limited set of such rewritings that correspond to interesting storage alternatives, and that our experiments show to be beneficial in practice.

Inlining/Outlining As we pointed out several times, one can either associate a type name to a given nested element (outlining) or nest its definition directly within its parent element (inlining). Rewriting a XML

schema in that way impacts the relational schema by inlining or outlining the corresponding element within its parent table. Inlining is illustrated below using the **TV** type of Figure 2(b).

```

type TV =
  seasons[ Integer ],
  Description,
  Episode*
⇒
type TV =
  seasons[ Integer ],
  description[ String ],
  Episode*

type Description =
  description[ String ]

```

At the relational level, this rewriting would correspond to the following transformation:

```

TABLE TV
( TV_id INT,
  seasons STRING,
  parent_Show INT)
⇒
TABLE TV
( TV_id INT,
  seasons STRING,
  description STRING,
  parent_Show INT)

TABLE Description
( Description_id INT,
  description STRING,
  parent_TV INT)

```

Two conditions must be satisfied for this transformation to be permissible: the type name must occur in a position where it is not within the production of a named type (*i.e.*, only within sequences or nested elements); and since this rewriting implies that one table is removed from the relational schema, the corresponding type cannot be shared.

Note that inlining was advocated as one of the main heuristics in [19]. Inlining has some similarities with vertical partitioning. It reduces the need for joins when accessing the contents of an element, but it increases the size of the corresponding table. Depending on the significance of accesses to the `description` element in the query workload, our search algorithm will actually decide whether to outline or inline that element.

Union Factorization/Distribution Union allows a high-degree of flexibility to XML Schema descriptions. As queries can have different access patterns on unions, e.g., access either parts together or independently, it is essential that appropriate storage structures for unions can be derived. In our framework, we use simple distribution laws. The first law $((a, (b|c)) == (a, b|a, c))$ allows distribution of a union within a regular expression and is illustrated below using the **Show** type of Figure 2(b).

```

type Show =
  show [ @type[ String ],
         title[ String ],
         year [ Integer ],
         Aka{1,10},
         Review*,
         ( Movie | TV ) ]
⇒
type Show =
  show [ (@type[ String ],
         title[ String ],
         year [ Integer ],
         Aka{1,10},
         Review*,
         box_office[ Integer ],
         video_sales[ Integer ])
        | (@type[ String ],
         title[ String ],
         year [ Integer ],
         Aka{1,10},
         Review*,
         seasons[ Integer ],
         description[ String ],
         Episode* ) ]

type Movie =
  box_office[ Integer ],
  video_sales[ Integer ]

type TV =
  seasons[ Integer ],
  description[ String ],
  Episode*

```

Note that the common part of the schema (`title`, etc.) is now duplicated, while each part of the union is distributed. The second law $(a[t1|t2] == a[t1]|a[t2])$ allows to distribute a union across an element and is illustrated on the result of the previous rewriting:

```

type Show =
  show [ (@type[ String ],
         title[ String ],
         year [ Integer ],
         Aka{1,10},
         Review*,
         box_office[ Integer ],
         video_sales[ Integer ])
        | (@type[ String ],
         title[ String ],
         year [ Integer ],
         Aka{1,10},
         Review*,
         seasons[ Integer ],
         description[ String ],
         Episode*) ]

type Show =
  ( Show'Part1 | Show'Part2)

type Show'Part1 =
  show [ @type[ String ],
        title[ String ],
        year [ Integer ],
        Aka{1,10},
        Review*,
        box_office[ Integer ],
        video_sales[ Integer ] ]

type Show'Part2 =
  show [ @type[ String ],
        title[ String ],
        year [ Integer ],
        Aka{1,10},
        Review*,
        seasons[ Integer ],
        description[ String ],
        Episode* ]

```

Here the distribution is done across element boundaries. This sequence of rewriting corresponds to the following relational configurations:

```

TABLE Show
( Show_id INT,
  type STRING,
  title STRING,
  year INT )

TABLE Movie
( Movie_id INT,
  box_office INT,
  video_sales INT,
  parent_Show INT )

TABLE TV
( TV_id INT,
  seasons INT,
  description STRING,
  parent_Show INT )

TABLE Show_Part1
( Show_Part1_id INT,
  type STRING,
  title STRING,
  year INT,
  box_office INT,
  video_sales INT )

TABLE Show_Part2
( Show_Part2_id INT,
  type STRING,
  title STRING,
  year INT,
  seasons INT,
  description STRING )

```

This results in the schema given on Figure 4(c) in Section 2. There are a few important remarks to be made here. First, this rewriting is similar to some form of horizontal partitioning, as Shows with different content will be split in different tables. Still, that partitioning follows the structure of the XML Schema which might correspond to quite complex criteria on the original relational schema. Note that the intermediate step in this rewriting is not a valid *p-schema* and will not be evaluated for cost before the second half of the transformation is applied. To the best of our knowledge, no previous XML storage approach has considered a similar rewriting.

Repetition Merge/Split Another useful rewriting exploits the relationship between sequencing and repetition in regular expressions by turning one into the other. The corresponding law over regular expressions ($a^+ == a, a^*$) is illustrated below on the `Aka` element in the `Show` type of Figure 2(b).

```

type Show =
  show [ @type[ String ],
        title [ String ],
        year[ Integer ],
        Aka{1,*} ]

type Show =
  show [ @type[ String ],
        title [ String ],
        year[ Integer ],
        Aka, Aka{0,*} ]

type Show =
  show [ @type[ String ],
        title [ String ],
        year[ Integer ],
        aka [ String ],
        Aka{0,*} ]

```

Followed by the appropriate inlining, this transformation captures the following relational configurations:

```

TABLE Show
( Show_id INT,
  type STRING,
  title STRING,
  year INT )

TABLE Aka
( Aka_id INT,
  aka STRING,
  parent_Show INT)

TABLE Show
( Show_id INT,
  type STRING,
  title STRING,
  year INT,
  aka STRING )

TABLE Aka
( Aka_id INT,
  aka STRING,
  parent_Show INT)

```

Note that this transformation corresponds to some of the rewritings proposed in [7].

Wildcard rewritings Wildcards are used to indicate a set of element names that can or cannot be used for a given element. Following [8], we will use '~' to indicate that any element name can be used, and '~!a' to indicate that any name but a can be used. In some cases, queries will access specific elements within a wildcard. In that context, it might be interesting to materialize an element name as part of a wildcard as illustrated in the following example:

```

type Review =
  review[ ~[ String ]* ]

type Reviews =
  review[ ( NYTReview | OtherReview)* ]

type NYTReview = nyt[ String ]
type OtherReview = (~!nyt) [ String ]

```

This transformation can be thought of as distributing of the (implicit) union in the wildcard over the element constructor (*i.e.*, $\sim = \text{nyt_reviews} \mid (\sim ! \text{nyt_reviews})$). Here again this results in some form of non-trivial horizontal partitioning over relations. As we show in Section 5, this rewriting is useful if some queries access NYTimes reviews independently of reviews from other sources.

From union to options All of the previously proposed rewritings preserve exactly the semantics of the original XML schema. This last rewriting that was proposed in [19] does not have this nice property, but allows to inline elements of a union using null values. This relies on the fact that a union is always contained in a sequence of optional types (*i.e.*, $(t_1 \mid t_2) \subset (t_1?, t_2?)$). This is illustrated below using the **Show** type of Figure 2(b).

```

type Show =
  show [ @type[ String ],
         title[ String ],
         year [ Integer ],
         Aka{1,10},
         Review*,
         ( Movie | TV ) ]

type Movie =
  box_office[ Integer ],
  video_sales[ Integer ]

type TV =
  seasons[ Integer ],
  description[ String ],
  Episode*

type Show =
  show [ @type[ String ],
         title[ String ],
         year [ Integer ],
         Aka{1,10},
         Review*,
         (box_office[ Integer ],
          video_sales[ Integer ])?,
         (seasons[ Integer ],
          description[ String ],
          Episode*)?

```

This often results in tables with a large number of null values, but allows the system to inline part of a union, which might improve performances for certain queries.

4.2 Search Algorithm

The exploration of the space of storage mappings is described in Algorithm 4.1. Note that the set of configurations that result from applying the various schema transformations is very large (possibly infinite), and since for each configuration queries and statistics must be translated and sent to the optimizer, this process is likely to take an excessive amount of time to complete and may be infeasible in some cases. Instead of exhaustively searching the space of all possible configurations, we use a *greedy heuristic* to find an efficient configuration.

The algorithm begins by deriving an initial configuration $pSchema$ from the given XML Schema $xSchema$ (line 3); details of how this initial configuration is derived appear in Section 3.1. Next, the cost of this configuration, with respect to the given query workload $xWkld$ and the data statistics $xStats$ is computed using the function $GetPSchemaCost$ which will be described in a moment (line 3). The greedy search (lines 5-16) iteratively updates $pSchema$ to the cheapest configuration that can be derived from $pSchema$ using a single transformation. Specifically, in each iteration, a list of candidate configurations $pSchemaList$ is created by applying all applicable transformations to the current configuration $pSchema$ (line 7). Each of these candidate configurations is evaluated using $GetPSchemaCost$ and the configuration with the smallest cost is selected (lines 8-14). This process is repeated until the current configuration can no longer be improved.

We now give details of how $GetPSchemaCost$ computes the cost of a given configuration $pSchema$ given the XML Query workload $xWkld$ and the XML data statistics $xStats$. First, $pSchema$ is used to derive the corresponding relation schema (see Section 3.2). This mapping is also used to translate $xStats$ into the corresponding statistics for the relational data, as well as to translate individual queries in $xWkld$ into the corresponding relational queries in SQL. The resulting relational schema and the statistics are used by a relational optimizer to compute the expected cost of computing a query in the SQL workload derived as above; this cost is returned as the cost of the given $pSchema$. Note that the algorithm does not put any restriction on the kind of optimizer used (transformational or rule-based, linear or bushy, etc. [12]); though for the exercise to make sense it is expected that it should be same as (or similar to) the optimizer used in the relational system which is going to be configured based on the recommendations of our mapper.

As we shall see in Section 5, configurations with significantly lower costs can be found through this greedy search.

5 Performance

The various components of LegoDB (*i.e.*, physical schema creation, schema transformation, and query translation) have been implemented in a prototype system. Our initial prototype is limited to exploring inlining/outlining rules in the greedy search—the other XML transformations are explored separately.

To evaluate the alternative configurations in our mapping engine (see Section 3), we used a variation of the Volcano relational query optimizer [12], as described in [16]. The cost of a query estimated by the query optimizer on the basis of a cost model that takes into account number of seeks, amount of data read, amount

Algorithm 4.1 Greedy Heuristic for Finding an Efficient Configuration

```
Procedure GreedySearch
Input:  xSchema : XML schema,
        xWkld  : XML query workload,
        xStats : XML data statistics
Output: pSchema : an efficient physical schema
1 begin
  minCost = ∞;
  pSchema = GetInitialPhysicalSchema(xSchema)
  cost = GetPSchemaCost(pSchema, xWkld, xStats)
5  while (cost < minCost) do
    minCost = cost
    pSchemaList = ApplyTransformations(pSchema)
    for each pSchema' ∈ pSchemaList do
      cost' = GetPSchemaCost(pSchema', xWkld, xStats)
10     if cost' < cost then
       cost = cost'
       pSchema = pSchema'
    endif
  endfor
15 endwhile
  return pSchema
end.
```

of data written, and CPU time for in-memory processing. Our cost model is fairly sophisticated and we have verified its accuracy by comparing its estimates with numbers obtained by running queries on Microsoft SQL-Server 6.5 (see [16]). We found close agreement (within around 10 percent) on most queries, which indicates that the numbers obtained in our performance study are fairly accurate.

5.1 Experimental Settings

We use an XML Schema based on the data from the Internet Movie Database (IMDB)[13] which contains information about movies, actors and directors. We compose workloads by drawing on two classes of queries: *lookup* queries and *publishing* queries. Lookup is representative of interactive SPJ queries, such as *Find the alternate titles for a given show*. Publishing queries are more document-oriented and return all available information about a particular element (or set of elements), for example *List all shows and their reviews*. Detailed statistics that include information about all elements (cardinalities, sizes, etc), as well as the XML schema and queries are given in the Appendix.

5.2 Efficiency of Greedy Search

In this experiment, we demonstrate the efficiency of the greedy search heuristic described in Section 4.2. We experimented with two variations of the greedy search: *greedy-so* and *greedy-si*. In the *greedy-so* search, all elements in the initial physical schema are outlined (except base types) and during the search, inlining transformations are applied. For *greedy-si*, all elements are initially inlined (except elements with multiple occurrences) and during the search, outlining transformations are applied.

For the purpose of this experiment, we considered two workloads: *lookup*, which contains five lookup queries (Q8, Q9, Q11, Q12 and Q13 in Appendix C), and *publish*, which consists of three queries that publish information about shows, directors and actors (Q15, Q16 and Q17 in Appendix C). Figure 10 shows the cost of the configurations obtained by *greedy-so* and *greedy-si* on successive iterations for each of these

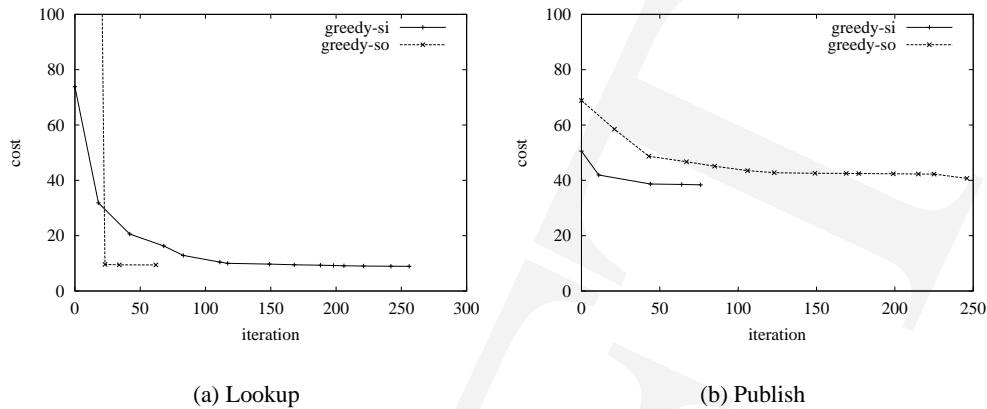


Figure 10: Cost at each greedy iteration

workloads. Each iteration took approximately 3 seconds.

An interesting observation is that *greedy-so* converges to the final configuration a lot faster than *greedy-si* for lookup queries, while the opposite happens for publish queries, *i.e.*, *greedy-si* converges faster. This can be explained as follows. The traversals made by lookup queries are localized. Therefore, the final configuration has only a few inlined elements. Naturally, *greedy-so* can reach this configuration earlier than *greedy-si*. On the other hand, since the publish queries typically traverse larger number of elements, the final configuration has several inlined elements. In this case, therefore, *greedy-si* can reach this configuration earlier than *greedy-so*.

Another point worthy of note is that the curves often have a point after which the improvement between iterations decreases considerably. This suggests that, as an optimization, we could stop the search as soon as the improvement falls below a certain threshold.

As the graphs show, *greedy-so* has higher initial costs for both workloads since it leads to a large number of tables which must be joined to compute the queries. However, note that both strategies converge to similar costs (the final configurations are also similar). This trend was observed for all variations of schemas, statistics and workloads we experimented with. For simplicity of presentation, *greedy-si* is the search strategy used in the experiments below.

5.3 Sensitivity of configurations to varied workloads

An important feature of the LegoDB framework is that the storage is designed taking an application and its query workload into account. One interesting question is how the resulting configuration performs if the workload changes. For example, the search interface of IMDB offers users a fixed set of queries. However, the frequency of these queries may vary over time. For example, in the week before the Academy Awards, the frequency of queries about movies may increase considerably. Because in many instances it may not be feasible to re-generate a new configuration and re-load the data, it is important that a chosen storage configuration leads to acceptable performance even when the frequency of queries varies.

In order to assess the sensitivity of our resulting configurations to changes in workloads, we created a

spectrum of workloads that combined the lookup queries and publish queries in Appendix C in the ratio $k : (1 - k)$, where $k \in [0, 1]$ is the fraction of lookup queries in the particular workload.

Using the same statistics and XML schema, we ran LegoDB for three workloads corresponding to $k = 0.25, 0.50$ and 0.75 , resulting in the three configurations $C[0.25]$, $C[0.50]$ and $C[0.75]$ attuned to the respective workloads. Next, we gathered these three resulting configurations and evaluated their costs across the entire workload spectrum; the cost of a configuration is defined as the average cost of processing a query on that configuration. We did a similar evaluation with the all-inlined configuration, $C[ALL-INLINED]$. For the sake of comparison, we also plotted a curve OPT giving, for each workload in the spectrum, the cost of the configuration obtained by LegoDB for that specific workload — this is a tight upper bound on best possible cost of a configuration at every point in the spectrum. (Note that, in contrast to the other curves, OPT does not correspond to a fixed schema.) The results are shown in Figure 11.

Before discussing the results, it is important to understand how inlining could affect the cost of a configuration with respect to a query workload. For queries that traverse the schema contiguously and access all related attributes, inlining helps by precomputing the numerous joins that may be required during the traversal. On the other hand, inlining could be a bad idea for several other kinds of queries, for example: (a) the query does limited, localized traversals and/or does not access all the attributes involved, and so does not benefit from the inlining but nevertheless pays the overhead of scanning wider relations; (b) the query has highly selective selection predicates — this could render a selection scan on the inlined wider relation more expensive than evaluation of the query by joining the filtered non-inlined leaner relations, especially in the presence of appropriate indexes; (c) the query involves join of attributes not structurally adjacent in the XML Schema (*e.g.*, `actor` and `director`) — since inlining causes respective relations to widen due to the inclusion of several additional attributes not required in the join, the join is significantly more expensive than in the case of other configurations. These two opposing factors lead to the possibility of different sets of inlining decisions for different workloads, each optimal in a certain region in the spectrum.

Overlap between the curves for $C[0.25]$ and $C[0.75]$ with the curve for OPT in the graph suggests that we can partition our spectrum into two regions: the region defined by $k \in [0, 0.55]$ and the region defined by $k \in [0.55, 1]$ such that $C[0.25]$ is the optimal configuration for *all* workloads in the former region and $C[0.75]$ is the optimal configuration for *all* workloads in the latter (or near enough). Moreover, the curves for $C[0.25]$ and $C[0.75]$ cross at a small angle. This further implies that even if the two workloads lie in different regions but are not too distant, the optimal configurations for the two are close enough in cost. This shows that the configurations found by LegoDB are very robust with respect to the variations in the workloads.

At the extremes of the spectrum, however, we found a significant difference in performance of the $C[0.25]$ and $C[0.75]$. Since these two configurations are based on slightly different inlining decisions, we see that both publish and lookup queries are sensitive to these decisions, and that inlining is indeed an important transformation. However, $C[ALL-INLINED]$ that includes all the inlining decisions in the above configurations (and some more) performed two to five times worse than optimal. This demonstrates that beyond a point, the overheads due to inlining significantly outweigh any benefits.

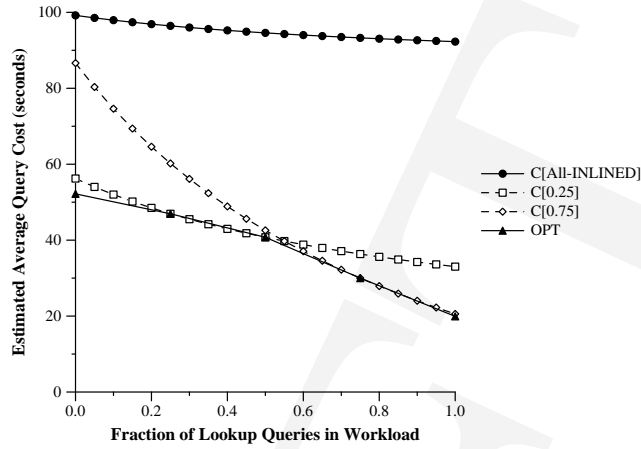


Figure 11: Sensitivity to variations in the workload

In summary, the above analysis clearly demonstrates that the cost-based approach of LegoDB leads to configurations that are not only 50% to 80% less costly than the rule-of-the-thumb approach of ALL-INLINED, but also are very robust with respect to the variations in the workloads.

5.4 Effectiveness of XML transformations

In Section 4 we described some XML-specific transformations that generate relational configurations which had not been considered in previous XML-to-relational mappings. In what follows, we study the performance of some of these transformations.

[Q4.]	<i>Display the description, title, year for a show with a given title (only TV shows have description)</i>
[Q5.]	<i>Display the box office, title, year for a show with a given title (only movies have box_office)</i>
[Q6.]	<i>Display the description, box office, title, year for a show with a given title</i>
[Q7.]	<i>Display the title and year for shows that have an episode directed by a given guest_director</i>
[Q13.]	<i>Find all people that acted and directed in the same movie as well as alternate titles for the movie</i>
[Q16.]	<i>Publish all shows</i>
[Q19.]	<i>Publish all the information about a show given its title</i>

Figure 12: Sample Queries

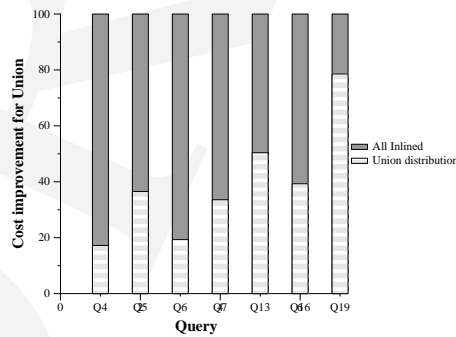


Figure 13: Cost of union-transformed configuration as a percentage of the cost of an all-inlined configuration

Union Distribution In order to measure the effectiveness of union distribution we compared the costs of

Total reviews Query NYT perc.	10,000		100,000	
	Q1		Q2	
	inlined	wild	inlined	wild
50%	5.42	6.3	48	26.3
25%	5.42	5.1	48	15
12.5%	5.42	4.4	48	9.4

Table 2: Cost for all-inlined vs wildcard-transformed

various queries for the configurations illustrated in Figure 4(a) (all elements inlined) and Figure 4(c) (where union is distributed over show). The queries considered are shown in Figure 12.²

As Figure 13 shows, the union-transformed configuration has lower costs for all queries. In this example, the union distribution is equivalent to horizontally partitioning the Show table into a table that contains information about movies, and a table that contains information about TV shows. Because the new tables are smaller, queries that refer to elements in only one of those tables will be cheaper (*e.g.*, Q4 accesses descriptions, Q7 accesses episodes, and Q5 accesses box_office).

These results are rather intuitive. A less intuitive finding is that even queries that access elements from both movies and TV shows (*e.g.*, Q6 that retrieves description and box_office) become cheaper under the union rewriting. Even though the original selection query:

$$\Pi_{title,description}\{\sigma_{title=c}shows\}$$

must be rewritten as the union of two subqueries for the transformed schema

$$\Pi_{title,description}\{\sigma_{title=c}tv_shows\} \cup \Pi_{title,box_of_fice}\{\sigma_{title=c}movies\}$$

not only does each subquery operate on tables with fewer tuples, but these tables are also narrower which reduce the cost of selection. This is also true of Q13, Q16 and Q19.

Repetition Split Another transformation we considered is splitting repetitions. This transformation was illustrated in Section 4. The effectiveness of such a transformation is highly dependent on the characteristics of the data and on the query workload. Consider for example two queries: a lookup query that finds all of the alternate titles (akas) for a given show title; and a publishing query which retrieves all information for all shows. The costs for these two queries under the *All Inlined* and the *Repetition-Split* transformed configurations for a varied number of total akas are given in Figure 14. For this example, the main effect of the Repetition Split transformation is that it reduces the size of the Aka table. As a result, the cost reduction is bigger for the publishing query—since the lookup query involves a selection on title and this selection can be pushed, the size of the Aka table will impact the show-aka join to a lesser extent than in the publishing query where no selection is performed. Also note that as the size of the Aka table increases (and becomes much larger than the Show table), the cost difference between the two configurations decrease.

Wildcards The wildcard transformation effectively partitions the set of elements tagged by the wildcard into different sorts that correspond to the wildcard labels that are present in the data. Consider for example the query *Find the NYTimes reviews for all shows produced in 1999*. The equivalent queries under the configurations in Figure 4(a) and (b) are:

²The corresponding XQueries are given in Appendix C.

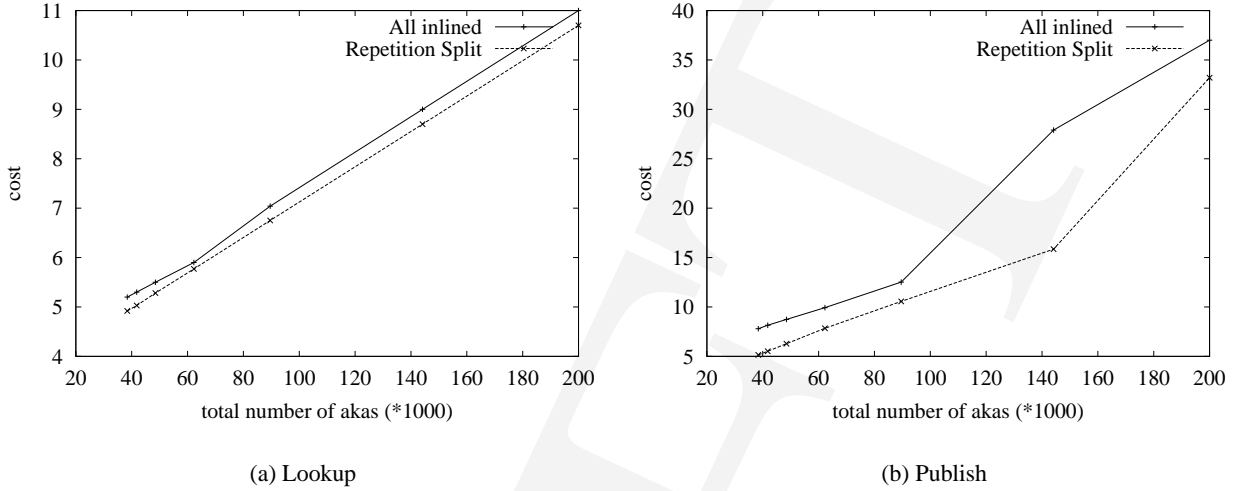


Figure 14: Cost comparison between an all-inlined and a repetition-split configuration

- 1 $\Pi_{title,data} \{ \sigma_{year=1999} shows \bowtie \sigma_{source=NYTimes} reviews \}$
- 2 $\Pi_{title,data} \{ \sigma_{year=1999} shows \bowtie nyt_reviews \}$

Table 2 shows the cost of these two queries for varying percentage of NYTimes reviews, when the total number of reviews is 10,000 and 100,000. As expected, whereas the cost for Query 1 remains constant, the cost for Query 2 decreases with the size of the `nyt_reviews` table.

6 Related Work

In this section we first compare LegoDB to prior work on storing XML data with relational engines. Following this discussion, we outline other related work, in particular the relationship between automatic XML storage mapping and automatic physical design for relational databases.

Recently, many approaches have been suggested for mapping XML documents to relations for storage [7, 11, 14, 18, 19, 20]. In [7], Deutsch, Fernandez and Suciu propose the STORED system for mapping between (schemaless) semi-structured data and the relational data model. They focus on a data mining technique which simultaneously solves schema discovery and storage mapping by identifying “highly supported” tree patterns for storage in relations. Even though they considered a cost optimization approach to the problem, they found it to be impractical, as in the absence of a schema, optimization is shown to be exponential in the *size of the data*. In contrast, we explore a space of storage structures but rely on the *schema* and *statistics* rather than directly mining the data. We use heuristics (*e.g.*, the greedy approach) to avoid an exponential search, but still explore a variety of useful mappings. In fact, the LegoDB strategy may lead to substantially different configurations than what is produced by the data-mining approach used by STORED. For example, we may break an extremely common pattern of data into multiple relations if the result is more efficient for the query workload.

In [19], Shanmugasundaram *et al* propose three strategies to map DTDs into relational schemas. The

basic idea behind these mappings is to create tables that correspond to XML elements defined in a DTD, inlining as many sub-elements as possible so as to reduce fragmentation—multi-valued elements and elements involved in recursive associations must be kept in separate tables. The three proposed mappings differ from one another in the degree of redundancy: they vary from being highly redundant (where an element can be stored in multiple tables), to containing no redundancy. While we do not consider mappings which duplicate data, we share with [19] the use of the schema to derive a heuristically “good” initial storage mapping (e.g., for the *greedy-si* search strategy), and the use of a modified schema for the storage mapping language. Regardless of the particular strategy, the mapping process of [19] begins by simplifying an input DTD into a DTD that can be easily mapped into relations. Instead of *simplifying* away hard-to-map XML Schema constructs, LegoDB takes advantage of them (through the use of our schema transformations) to generate a space of mappings. And as we have shown in Section 5, mappings that result from the XML-specific transformations may lead to significantly better configurations for a given application than mappings based on an inline-as-much-as-possible approach.

Schmidt *et al* [18] propose a highly fragmented relational storage model. In their proposed “Monet transformation”, the parent-child association terminating *each label-path* from the root of an XML document is stored as a binary relation of *oids*. Like STORED, they do not require a schema—the document structure is explored at parsing time. However, unlike Stored, they use a purely relational storage. Their experiments show that this approach performs well on the main-memory-oriented Monet database, a result in stark contrast to the conclusions presented in [19] where fragmentation and a large number of joins is identified as a key problem. These disparate performance results only emphasize the need for automated tools, like LegoDB, to determine the appropriate storage mapping for a given application *and DBMS platform*. Finally, while the search space in our work does not include horizontal fragmentation of tables based on incoming paths, our rewriting rules can easily be extended to consider this style of transformation.

Tian *et al* [22] compare the performance of several approaches to XML storage, one of which is a relational mapping similar to our “max-inlined” approach. It would be interesting to see how a more optimized mapping would affect the performance of the relational mapping relative to their other native and text-based storage methods. Florescu and Kossman [11] investigated several alternatives when designing a relational schema for storing an XML document including storing a node table and an edge table, and storing a “universal relation” with an attribute for every element or attribute name in the document. Shimura *et al* [20] propose an inverted-list-style storage structure in which nodes are mapped to regions in the document, and paths are present as strings in a “Path” table. Path queries are accomplished by using string operators (in particular the LIKE operator of SQL) to query this table. In all three of these cases, one or more *fixed* mappings are used, where we explore a *space* of storage mappings. Mappings from DTDs into nested schema structures of OO or OR/DBMS have been proposed [6, 14]. While Klettke and Meyer consider statistics and queries in the proposed heuristic mapping, no attempt is made to compare estimated costs for multiple mappings.

Several commercial DBMSs already offer some support for storing, querying, and exporting XML documents [24, 15]; however, the user must still design an appropriate storage mapping.

While LegoDB is (to our knowledge) the first XML storage mapping tool to take advantage of cost-based optimization, similar approaches have been applied to problems in relational storage design, such as index selection (*e.g.*, [17]) and view materialization (*e.g.*, [1, 23]) in physical optimization for relational DBMSs. Note that physical design tools are complementary to LegoDB, and can be applied to further optimize the relational schemas produced by our mapping, either during the search process or simply on the final schema produced.

7 Conclusions

We have introduced LegoDB, a system for generating relational storage mappings for XML data based on the schema for the data and statistics. In contrast to previous work, we explore a space of alternate storage configurations and evaluate the quality of each configuration by estimating its performance on an application workload. We also make original use of XML Schema to support new possible storage configurations, and proposed XML Schema rewritings as a means to explore possible configurations. The LegoDB system isolates the application developer from the underlying storage engine by taking only XML Schemas, queries and documents as input. Further, we have presented an initial performance study using a prototype implementation of our approach in the LegoDB system being built at Bell Labs. This study evaluates a greedy algorithm to inlining or outlining of elements and attributes. The results indicate that storage mappings of significantly improved quality can be found in a reasonable number of steps using greedy evaluation, and that these designs are not overly sensitive to small changes in the workload. In addition, we have shown that XML transformations other than inlining/outlining can lead to significant performance gains.

We consider this work as a first step towards a general purpose storage configuration engine for XML. To achieve that goal, we need to extend the LegoDB system in a number of ways. First we plan to adapt our approach to other storage platforms, such as native stores, text stores, and hybrid storage systems. We plan to extend the subset of XQuery supported currently by LegoDB, possibly using techniques similar to [3, 10]. Our work can also be extended in several simple ways, such as including updates in our workload, allowing redundancy in data storage, considering dynamic programming search strategies, etc. Finally, we plan to decrease the cost of evaluating a particular point in the space by allowing our query optimizer to reuse partial results from one evaluation to the next, and consider the integration of complementary relational storage design tools such as [17, 1].

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A Statistics

```
(["imdb"], STcnt(1));
(["imdb";"director"], STcnt(26251));
(["imdb";"director";"name"], STsize(40));
(["imdb";"director";"directed"], STcnt(105004));
(["imdb";"director";"directed"; "title"], STsize(40));
(["imdb";"director";"directed";"year"], STbase(1800,2100,300));
(["imdb";"director"; "directed";"info"], STcnt(50000));
(["imdb";"director"; "directed";"info"], STsize(100));
(["imdb";"director";"directed";"TILDE"], STsize(255));
(["imdb";"show"], STcnt(34798));
(["imdb";"show";"title"], STsize(50));
(["imdb";"show";"year"], STbase(1800,2100,300));
(["imdb";"show";"aka"], STcnt(13641));
(["imdb";"show";"aka"], STsize(40));
(["imdb";"show";"type"], STsize(8));
(["imdb";"show";"reviews" ], STcnt(11250));
(["imdb";"show";"reviews";"TILDE"], STsize(800));
(["imdb";"show";"box_office"], STcnt(7000));
(["imdb";"show";"box_office"], STbase(10000,100000000,7000));
(["imdb";"show";"video_sales"], STcnt(7000));
(["imdb";"show";"video_sales"], STbase(10000,100000000,7000));
(["imdb";"show";"seasons"], STcnt(3500));
(["imdb";"show";"description"], STsize(120));
(["imdb";"show";"episodes"], STcnt(31250));
(["imdb";"show";"episodes";"name"], STsize(40));
(["imdb";"show";"episodes";"guest_director"], STsize(40));
(["imdb";"actor"], STcnt(165786));
(["imdb";"actor";"name"], STsize(40));
(["imdb";"actor";"played"], STcnt(663144));
(["imdb";"actor";"played"; "title"], STsize(40));
(["imdb";"actor";"played";"year"], STbase(1800,2100,200));
(["imdb";"actor"; "played" ; "character"], STsize(40));
(["imdb";"actor";"played";"order_of_appearance"], STbase(1,300,300));
(["imdb";"actor"; "played" ; "award";"result"], STsize(3));
(["imdb";"actor"; "played" ; "award";"award_name"], STsize(40));
(["imdb";"actor"; "biography" ; "birthday"], STsize(10));
(["imdb";"actor"; "biography" ; "text"], STcnt(20000));
(["imdb";"actor"; "biography" ; "text"], STsize(30))
```

B Schema

XML Algebra notation

```
type IMDB =
  imdb [ Show{0,*},Director{0,*},Actor{0,*} ]

type Show =
  show [ title [ String ], year[ Integer ], type[ String ],
        aka [ String ]{0,*}, reviews[ TILDE[ String ] ]{0,*},
        (box_office [ Integer ], video_sales [ Integer ]
         | seasons[ Integer ], description [ String ],
         episodes [ name[String], guest_director[ String ]]{0,*}
        )
  ]

type Director =
  director [ name [String],
            directed [ title[ String ], year[ Integer ],
                      info[ String ], TILDE [ String ] ]{0,*}
            ]

type Actor =
  actor [ name [String],
         played[ title[ String ], year[ Integer ],
                character[String], order_of_appearance[Integer],
                award[ result [String], award_name[String] ]{0,5}
                ]{0,*},
         biography[ birthday[ String ], text[String] ]
```

]

XML Schema notation

```
<xsd:schema xmlns="http://www.w3.org/...">
  <element name="imdb" type="IMDB">
    <complexType name="IMDB">
      <element name="show" type="Show"
        minOccurs="0" maxOccurs="unbounded" />
      <element name="director" type="Director"
        minOccurs="0" maxOccurs="unbounded" />
      <element name="actor" type="Actor"
        minOccurs="0" maxOccurs="unbounded" />
    </complexType>
  </element>

  <complexType name="Show">
    <sequence>
      <element name="title" type="xsd:string" />
      <element name="year" type="xsd:integer" />
      <element name="aka" type="Aka"
        maxOccurs="unbounded" />
      <element name="reviews" type="AnyElement"
        minOccurs="0" maxOccurs="unbounded" />
      <choice>
        <group name="Movie" />
        <group name="TV" />
      </choice>
      </sequence>
      <attribute name="type" type="xsd:string" />
    </complexType>

  <complexType name="Aka">
    <simpleType name="xsd:string" />
  </complexType>

  <group name="Movie">
    <sequence>
      <element name="box_office" type="xs:integer" />
      <element name="video_sales" type="xs:integer" />
    </sequence>
  </group>

  <group name="TV">
    <sequence>
      <element name="seasons" type="xs:number" />
      <element name="description" type="xs:string" />
      <element name="episodes"
        minOccurs="0" maxOccurs="unbounded">
        <complexType name="Episodes">
          <sequence>
            <element name="name" type="xsd:string" />
            <element name="guest_director" type="xsd:string" />
          </sequence>
        </complexType>
      </element>
    </sequence>
  </group>

  <complexType name="Director">
    <sequence>
      <element name="name" type="xsd:string" />
      <element name="directed"
        minOccurs="0" maxOccurs="unbounded">
        <complexType name="Directed">
          <sequence>
            <element name="title" type="xsd:string" />
            <element name="year" type="xsd:integer" />
            <element name="info" type="xsd:string" />
            <element name="AnyElement" />
          </sequence>
        </complexType>
      </element>
    </sequence>
  </complexType>

  <complexType name="Actor">
    <sequence>
      <element name="name" type="xsd:string" />
      <element name="played"
        minOccurs="0" maxOccurs="unbounded">
        <complexType name="Played">
          <sequence>
            <element name="title" type="xsd:string" />
            <element name="year" type="xsd:integer" />
            <element name="character" type="xsd:string" />
            <element name="order_of_appearance" type="xsd:string" />
            <element name="award"
              minOccurs="0" maxOccurs="5">
              <complexType name="Played">
                <sequence>
                  <element name="result" type="xsd:string" />
                  <element name="award_name" type="xsd:string" />
                </sequence>
              </complexType>
            </element>
          </sequence>
        </complexType>
      </element>
    </sequence>
  </complexType>
</xsd:schema>
```

C Queries

C.1 Lookup

Q1 Display title, year and type for a show with a given title

```
FOR $v IN document("imdbdata")/imdb/show
WHERE $v/title = c1
RETURN $v/title, $v/year, $v/type
```

Q2 Display title, year for a show with a given title

```
FOR $v IN document("imdbdata")/imdb/show
WHERE $v/title = c1
```

```
RETURN $v/title, $v/year
```

Q3 Display title, year for all shows in a given year

```
FOR $v IN document("imdbdata")/imdb/show
WHERE $v/year = c1
RETURN $v/title, $v/year
```

Q4 Display the description, title, year for a show with a given title (only TV shows have "description")

```
FOR $v IN document("imdbdata")/imdb/show
```

```
WHERE $v/title = c1
RETURN $v/title, $v/year, $v/description
```

Q5 Display the box office, title, year for a show with a given title (only movies have "box_office")

```
FOR $v IN document("imdbdata")/imdb/show
WHERE $v/title = c1
RETURN $v/title, $v/year, $v/box_office
```

Q6 Display the description, box office, title, year for a show with a given title

```
FOR $v IN document("imdbdata")/imdb/show
WHERE $v/title = c1
RETURN $v/title, $v/year,
       $v/box_office, $v/description
```

Q7 Display the title and year for shows that have an episode directed by a given guest_director

```
FOR $v IN document("imdbdata")/imdb/show
RETURN
  $v/title,
  $v/year
  FOR $e IN $v/episode
  WHERE $e/guest_director = c1
  RETURN $e/guest_director
```

Q8 Display the birthday for an actor given his name

```
FOR $v IN document("imdbdata")/imdb/actor
WHERE $v/name = c1
RETURN $v/biography/birthday
```

Q9 Display the name, biography text for all actors born on a given date

```
FOR $v IN document("imdbdata")/imdb/actor
RETURN
  <result>
    $v/name
    FOR $v/biography $b
    where $b/birthday = c1
    RETURN $b/text
  </result>
```

Q10 Display the name, biography text and birthday for all actors born on a given date

```
FOR $v IN document("imdbdata")/imdb/actor
RETURN
  <result>
    $v/name
    FOR $v/biography $b
    where $b/birthday = c1
    RETURN $b
  </result>
```

Q11 Display name and order of appearance for all actors that played a given character

```
FOR $v IN document("imdbdata")/imdb/actor
RETURN
```

```
<result>
  $v/name
  FOR $v/played $p
  where $p/character = c1
  RETURN $p/order_of_appearance
</result>
```

Q12 Find all people that acted and directed in the same movie

```
FOR $i IN document("imdbdata")/imdb
  $a in $i/actor,
  $m1 in $a/played,
  $d in $i/director,
  $m2 in $a/directed,
WHERE $a/name = $d/name AND $m1/title = $m2/title
RETURN
  <result>
    $a/name
    $m1/title
    $m1/year
  </result>
```

Q13 Find all people that acted and directed in the same movie as well as alternate titles for the movie

```
FOR $i IN document("imdbdata")/imdb
  $s in $i/show,
  $a in $i/actor,
  $m1 in $a/played,
  $d in $i/director,
  $m2 in $a/directed,
WHERE $a/name = $d/name AND
      $m1/title = $m2/title AND
      $m1/title = $s/title
RETURN
  <result>
    $a/name
    $m1/title
    $m1/year
    FOR $v in $s/aka
    RETURN $v/title
  </result>
```

Q14 Find all directors that directed a given actor

```
FOR $i IN document("imdbdata")/imdb
  $a in $i/actor,
  $m1 in $a/played,
  $d in $i/director,
  $m2 in $a/directed,
WHERE $a/name = c1 AND $m1/title = $m2/title
RETURN
  <result>
    $d/name
    $m1/title
    $m1/year
  </result>
```

C.2 Publish

Q15 Publish all actors

```
FOR $a IN document("imdbdata")/imdb/actor
RETURN $a
```

Q16 Publish all shows

```
FOR $s IN document("imdbdata")/imdb/show
RETURN $s
```

Q17 Publish all directors

```
FOR $d IN document("imdbdata")/imdb/director
RETURN $d
```

Q18 Display all info about a given actor

```
FOR $a IN document("imdbdata")/imdb/actor
WHERE $a/name = c1
RETURN $a
```

Q19 Display all info about a given show

```
FOR $s IN document("imdbdata")/imdb/show
WHERE $s/title = c1
RETURN $s
```

Q20 Publish all info about a given director

```
FOR $d IN document("imdbdata")/imdb/director
WHERE $d/name = c1
RETURN $d
```