XEM: XML Evolution Management

by

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Abstract

As information on the World Wide Web continues to proliferate at an astounding rate, the Extensible Markup Language (XML) has been emerging as a standard format for data representation on the web. In many application domains, specific document type definitions (DTDs) are designed to enforce a semantically agreed-upon structure of the XML documents. In XML context, these structural definitions serve as schemata. However, both the data and the structure (schema) of XML documents tend to change over time for a multitude of reasons, including to correct design errors in the DTD, to allow expansion of the application scope over time, or to account for the merging of several businesses into one. Most of the current software tools that enable the use of XML do not provide explicit support for such data or schema changes. Using these tools in a changing environment entails making manual edits to DTDs and XML data and reloading them from scratch. In this vein, we put forth the first solution framework, called XML Evolution Manager (XEM), to manage the evolution of DTDs and XML documents. XEM provides a minimal yet complete taxonomy of basic change primitives. These primitives, classified as either data or schema changes, are consistency-preserving. For a data change, they ensure that the modified XML document conforms to its DTD both in structure and constraints. For a schema change, they ensure that the new DTD is well-formed, and all existing XML documents are transformed also to conform to the modified DTD. We prove both the completeness of our evolution taxonomy, as well as its consistency-preserving nature. To verify the feasibility of our XEM approach we have implemented a working prototype system in Java, using the XML4J parser from IBM and PSE Pro as our backend storage system. We present an experimental study run on this system where we compare the relative efficiencies of the primitive operations in terms of their execution times. We

then contrast these execution times against the time to reload the data, which would be required in a manual system. Based on the results of these experiments we conclude that our approach improves upon the previous method of making manual changes and reloading data from scratch by providing automated evolution management facilities for DTDs and XML documents.

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Chapter 1

Introduction

1.1 Motivation

When the World Wide Web was "invented" between 1989 and 1990, its primary purpose was the sharing of documents between people, mostly in the scientific and scholarly communities [BL89]. It is well known that the amount of data on the Web has exploded over the past decade, and increasingly, the information therein is not just for people anymore; the intended audience is often a computer. Thus, the need for an information interchange standard has been increasing, as the amount of data grows to the point where humans have become incapable of processing it all. Fortunately, XML, the Extensible Markup Language, has emerged to fill this gap [W3C98].

Although XML data is considered to be "self-describing", most application domains tend to use Document Type Definitions (DTDs) to specify and enforce the structure of XML documents within their systems. A DTD defines, for example, which tags are permissible in an XML document, in addition to the order in which such tags must appear. DTDs thus assume a similar role as types in programming languages and schemata in database systems.

Many database vendors, such as Oracle 8i [Net00], IBM DB2 [IBM00a] and Excelon [Obj99], have recently started to enhance their existing database technologies to accommodate XML data by means of storage, retrieval and traversal of XML documents. Many of them [Net00] assume that a DTD is provided in advance and will not change over the life of the XML documents. They hence utilize the given DTD to construct a fixed relational [IBM00a] (or object-relational [Net00]) schema which then can serve as the structure on which to populate the XML documents that conform to this DTD.

However, change is a fundamental aspect of persistent information and data-centric systems [Sjo93]. Information over a period of time often needs to be modified to reflect perhaps a change in the real world, a change in the user's requirements, mistakes in the initial design or to allow for incremental maintenance. While these changes are inevitable during the life of an XML repository, most of the current XML management systems unfortunately do not provide enough (if any) support for these changes.

1.2 Example of XML Changes

Here we present an example to illustrate changes in XML documents and the related management issues. Figure 1.1 depicts an example DTD on publications, called *Article.dtd* and Figure 1.2 shows a sample XML document conforming to this DTD. We omit the header information normally found at the top of the XML file as it is not pertinent here. These sample documents are used for running examples hence forth. Below we discuss two types of changes. The first is a data update and the second is a schema update.

An example of a data update is the deletion of the editor information, i.e., removal of *<editor name = "Won Kim">* from the XML document. In this case, an XML change support system would have to determine whether this is indeed a valid change that will result in an XML document still conforming to the given DTD. The element definition

```
<!ELEMENT article (title,author+,related?)>
<!ELEMENT title (#PCDATA)>
<!ELEMENT author (name)>
   <!ATTLIST author id ID #REQUIRED>
<!ELEMENT name (first,last)>
<!ELEMENT first (#PCDATA)>
<!ELEMENT last (#PCDATA)>
<!ELEMENT related (monograph)*>
<!ELEMENT monograph (title,editor)>
<!ELEMENT editor EMPTY>
   <!ATTLIST editor name CDATA #IMPLIED>
```

Figure 1.1: Article.dtd

```
<article>
  <title>XML Evolution Manager</title>
  <author id = "dk">
    <name>
      <first>Diane</first>
      <last>Kramer</last>
    </name>
  </author>
  <author id = "er">
    <name>
      <first>Elke</first>
      <last>Rundensteiner</last>
    </name>
  </author>
  <related>
    <monograph>
      <title>Modern Database Systems</title>
      <editor name = "Won Kim"></editor>
    </monograph>
  </related>
</article>
```

Figure 1.2: One Valid Sample XML Document Conforming to Article.dtd

for *monograph* shows that the *editor* subelement is *REQUIRED* to occur exactly once in the parent element.

```
<!ELEMENT monograph (title,editor)>
```

If the *editor* subelement had a "*" or "?" symbol next to it, this would indicate that it is optional, but it does not. Since *editor* is a *REQUIRED* element in the specified DTD, this data update should likely be rejected. If such a change were allowed, then the resulting XML document would no longer conform to the DTD, and a validating parser would return an error when trying to parse that document [IBM00b].

Next, consider the DTD change where the definition of the element *monograph*, which must have an *editor* subelement, is relaxed such that it is optional to have the *editor* subelement. This would be accomplished by inserting either a "*" (meaning zero or more occurrences) or a "?" (meaning zero or one occurrences) after the word *editor* in the definition of *monograph*. For any such DTD change, an evolution support system would need to verify that the suggested change leads to (1) a new well-formed DTD and (2) corresponding changes are propagated to all old XML documents to conform to the changed DTD. In our example, the constraint we are changing from means "exactly one

occurrence". The single occurrence of the *editor* subelement in the XML data would still conform to a new DTD definition with either "*" or "?". Therefore this leads to a DTD change requiring no changes to the underlying XML data.

1.3 Problems with XML Management Systems

XML management systems attempt to expose a virtual XML document-view independent of the underlying storage system, be it relational, object-based or some specialized XML data structure. However in most current XML data management systems [Net00, IBM00a], evolution support, if any, is still inherently tied to the underlying storage system, to its data model and its change specification mechanism. For example, in Oracle 8i, if the structured XML documents are stored as object-relational instances, the user has to write SQL code to perform any type of updates. This requires users to be aware of the underlying storage system, its data model, and the mapping mechanism between XML, DTD and the underlying storage model. It prevents users from expressing desired transformations independent of the underlying data management system. It is likely to result in errors in terms of mismatches between desired XML transformations and what actually changes in the system. In addition, the specification of transformations required in a system may induce extensive re-engineering work either for migration to another system or integration of several systems. In short, the development of a standard XML change specification and support system is necessary.

Moreover, as illustrated above, structural inconsistency may arise in the XML data management system. Hence, it is critical to detect in advance whether an update is a valid operation that preserves the structural consistency of both XML documents and DTDs [ALP91, FS00, LC00, Ler00]. However, this problem is ignored in most existing XML data management systems and is not directly treated by the tools [Gro, Inf00] specially

designed for transforming XML documents from one format to another.

1.4 XML Evolution Manager (XEM) Approach

In this work we propose a general XML evolution management system that provides uniform XML-centric data and schema evolution facilities. To the best of our knowledge, XEM is the first effort to provide such uniform evolution management for XML documents. A preliminary version of this thesis was published in [SKC+01]. In brief the contributions of our work are:

1. We identify the lack of generic support for change in current XML data management systems such as [Net00, IBM00a, Obj99].
2. We propose a taxonomy of XML evolution primitives that provides a system independent way to specify changes both at the DTD and XML document level.
3. We identify three forms of system integrity which must be maintained during evolution in order for the change support system to be sound: *well-formed* DTDs and XML documents which conform to the XML language specification; *consistent* XML documents which conform to the invariants in the data model; and *valid* XML documents which conform to the constraints specified in the associated DTD.
4. We analyze the semantics of evolution operations and introduce the notion of pre- and post-conditions to ensure that the above forms of system integrity are indeed maintained during evolution. We use pre-conditions to determine whether a change should be vetoed because it would violate some form of system integrity, and we use post-conditions to assure that after any change is made to the DTD, appropriate data changes are also propagated to the XML documents so that they conform to the changed DTD.
5. We show that our proposed change taxonomy is complete and sound.

6. We develop a working XML Evolution Management prototype system using a Java object server (PSE Pro, by Object Design, Inc.) to verify the feasibility of our approach.

7. We conduct experimental studies to assess the relative costs associated with different change operations, and analyze the dependency between specific implementation choices made and the resulting impact on change performance.

1.5 Outline of Thesis

The remainder of this thesis proceeds as follows. Chapter 2 provides background information on XML documents and DTDs, and shows how we model these constructs in our system. In Chapter 3 we present our taxonomy of evolution primitives, and provide proofs showing that the taxonomy is both complete and sound. Chapter 4 reviews our prototype design and implementation. In Chapter 5 we present our experimental studies, including tests run on our prototype system and the results from those tests. Chapter 6 discusses other related research upon which we base our work. And finally, in Chapter 7 we present our conclusions, including future areas of study that could be taken up to continue this research, and a summary of the main contributions of this thesis.

Chapter 2

Background

2.1 Introduction to XML

The Extensible Markup Language (XML) is a subset of the Standard Generalized Markup Language (SGML), first published as a recommendation by the World Wide Web Consortium in February 1998 [W3C98], and that continues to be updated to this day. The most recent version of the XML language recommendation is described in [W3C00].

Definition 1 *A* **well-formed** *XML document is one which syntactically conforms to the XML language specification as defined in [W3C00].*

In order to define the structure, content and semantics of an XML document, the document may be accompanied by either an XML Schema [W3C01b] or a Document Type Definition (DTD), the format of which is also described in [W3C00]. Either of these may be used to specify constraints on an XML document, such as which element and attribute types are allowed, whether the elements and attributes are required or optional, and the types of values the elements and attributes may take on.

Definition 2 *A* **valid** *XML document is one which conforms to the constraints specified in either an XML Schema or a DTD.*

XML Schemas provide more powerful features for defining the structure and content of an XML document than do DTDs. For example, an XML Schema can specify ranges of acceptable values for an attribute, i.e., a domain, whereas a DTD cannot. However, the format of an XML Schema is still in the preliminary stages of a proposed recommendation, while the format of a DTD is a more stable, better defined standard, being derived directly from SGML, which dates back to 1986 [Gol91]. For this thesis, therefore, we chose to focus on DTDs for specifying constraints on XML documents, rather than XML Schemas. However, our results should be transferable to XML Schemas, possibly requiring some extensions to also handle the more specific data types and value domains which are possible to specify in an XML Schema.

According to the syntax defined in [W3C00], an XML document specifies its corresponding DTD either "in place" at the top of the XML document, or as a reference to an external resource. In this latter case, the DTD is contained in a separate document file, and referenced in the XML file by a URI - Uniform Resource Identifier. Our XML Evolution Management system assumes that we are operating on a well-formed XML document (or a set of them), which is also valid, meaning it conforms to its corresponding DTD.

In the remainder of this chapter we describe our data models for capturing XML documents and DTDs. We first review each of these constructs, defining the constraints which the models must represent, and then show how the two models relate to each other.

2.2 The XML Data Model

XML is inherently an ordered tree-structured representation format, where XML documents are composed of nested tagged elements. Each tagged element has a sequence of zero or more attribute/value pairs, and an ordered sequence of zero or more sub-elements. These sub-elements may themselves be tagged elements, or they may be "tag-less" seg-

ments of text data. A well-formed document may have an associated schema, derived from one or more XML Schema documents; it may have an associated DTD; or it may have no schema, then called "schema-less". In our work we assume that all XML documents have an associated DTD.

An instance of the XML data model represents a single complete XML document. The model is a node-labeled, ordered tree-structured representation that includes the concept of node identities. Multiple XML documents are represented by multiple instances of the model. We use the following notation to describe our model of an XML data tree.

Definition 3 *An XML data tree* T *is a three tuple with* $\mathrm{T} = (\mathrm{N}, \mathrm{children}, \mathrm{label})$*, where* N *is the set of labeled nodes in the tree,* $\mathrm{children}$ *is a function which returns the direct descendents of a node in an ordered sequence,* $\mathrm{children} : \mathrm{N} \rightarrow \mathcal{N}$*, where* $\mathcal{N}$ *is a sequence of nodes from* N*; and* label *is the labeling function which returns the node's identity,* $\mathrm{label} : \mathrm{N} \rightarrow \mathcal{I}$*, where* $\mathcal{I}$ *is the set of node identities.*

According to [W3C01a], the basic concept in the XML data model is a *Node*, which has one of eight possible identities: document, element, attribute, value, namespace, processing instruction, comment or information item. A node is thus defined as the disjoint union of these eight types. In this thesis we focus on the following subset of node types which make up the set $\mathcal{I}$.

Definition 4 *The set of possible node identities* $\mathcal{I}$ *is defined as:*

$\mathcal{I}$ = {`DocNode` | `ElemNode` | `AttrNode` | `ValueNode`}[1]

An XML document is represented by a unique `DocNode` node. We use the function `getDocNode` to obtain this node from the XML tree, `getDocNode` : $\mathrm{T} \rightarrow n$, where T is the XML data tree, and n is the unique `DocNode` in the set of nodes N such that

[1] `U1` | `U2` denotes the disjoint union of values with types `U1`, `U2`.

$label(n) =$ `DocNode`. A `DocNode` contains a URI reference value to the corresponding DTD and a non-empty ordered sequence of children nodes. The function `getURI` returns the string value corresponding to the DTD reference from the `DocNode`, `getURI` : $n \rightarrow String$, and the sequence of children nodes returned by the function `children`(n) must contain exactly one reference to an `ElemNode`.

An `ElemNode` contains a tag value for the element's name, an ordered sequence of children nodes, and a reference to the node's type (DTD element definition). The function `getTag` returns the element's name, `getTag` : N $\rightarrow$ $String$, and the `ElemNode`'s children is an ordered sequence of `ElemNode`, `AttrNode` and `ValueNode` nodes. We use the function `typeOf` to map an `ElemNode` to its DTD definition, `typeOf` : N $\rightarrow$ $ElemDef$, where $ElemDef$ is the set of DTD element definitions described in Section 2.4.

An `AttrNode` contains a name and a single `ValueNode` child, along with a reference to the node's type (DTD attribute definition). We use the function `getName` to return the attribute's name, `getName` : N $\rightarrow$ $String$. The function `typeOf` maps an `AttrNode` to its DTD definition, `typeOf` : N $\rightarrow$ $AttrDef$, where $AttrDef$ is the set of DTD attribute definitions described in Section 2.4.

A `ValueNode` may be a child of either an `ElemNode` or an `AttrNode` node, and the function `getValue` returns the actual string value stored in the `ValueNode`, `getValue` : N $\rightarrow$ $String$.

Figure 2.1 illustrates an XML data tree which represents the XML document of Figure 1.2. Although we omit numbers on the edges to simplify the diagram, the order of the nodes is captured in the model via the *children* function.

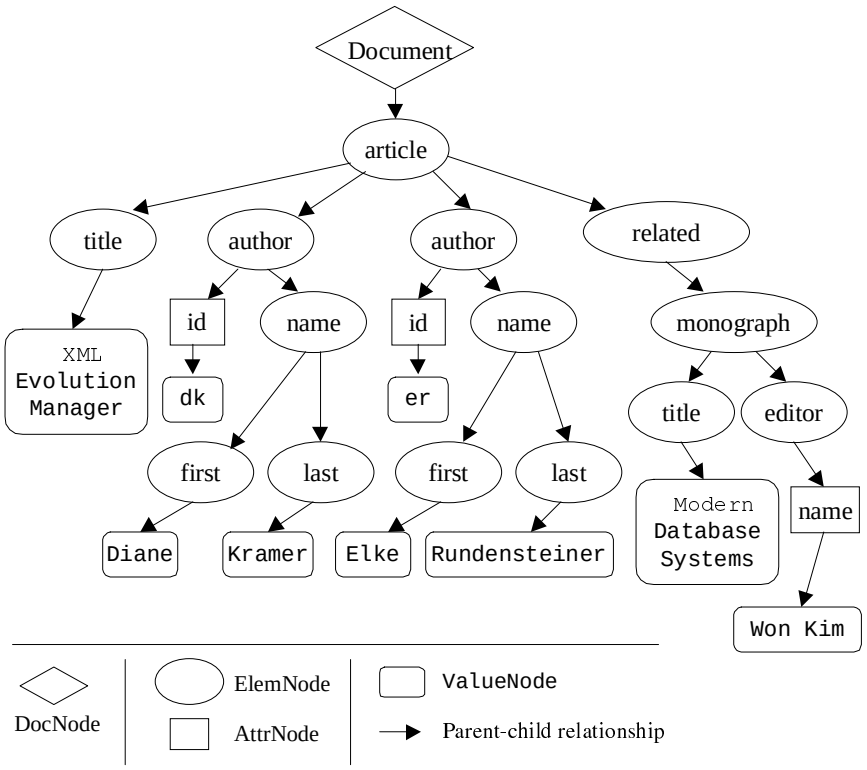


Figure 2.1: Tree Representation of XML Document from Figure 1.2 Conforming to Article.dtd of Figure 1.1.

2.3 Invariants for the XML Data Model

In addition to the constraints specified in an XML Schema or DTD, the XML Query Data Model [W3C01a] defines a set of *invariants* which must also be satisfied in order for an XML document to be valid.

Definition 5 *A* **consistent** *XML document is one which satisfies all invariants of the XML Data Model.*

Here in Table 2.1 we first define a set of functions for the XML data tree needed to describe the invariants, and then we summarize the set of invariants for the XML Data Model defined in [W3C01a].

- **Node Identity:** The function `ref` is one-to-one and onto, i.e., `ref_equal(ref(`n_1`), ref(`n_2`))` = `TRUE` holds if and only if n_1 and n_2 are the same node.

Function Name	Mapping	Description
`ref(n)`	N → N	Reference to a node `n` which uniquely identifies the node
`ref_equal(`n_1`,`n_2`)`	N,N → Boolean	Boolean function which returns `TRUE` only if n_1 and n_2 are the same node
`parent(n)`	N → N	Inverse of `children` function, returns the parent of the node `n`
`attributes(n)`	N → $\mathcal{N}$	Specialized children function which returns only those children of type `AttrNode`

Table 2.1: Functions Used to Define Invariants

- **Unique Parent:** The parent accessor, `parent(n)`, is a many-to-one function, i.e., a node has exactly one parent but many nodes may share one parent.

- **Parent-child Relationships:** Given two `ElemNode` references `ref(p)` and `ref(n)`, `ref_equal(parent(n),ref(p)) = TRUE` holds if and only if `ref(n)` is in `children(p)`. Similarly, given a `DocNode` reference `ref(d)` and a node reference `ref(n)`, `ref_equal(parent(n),ref(d)) = TRUE` holds if and only if `ref(n)` is in `children(d)`. Finally, given a `AttrNode` reference `ref(a)` and a node reference `ref(n)`, `ref_equal(parent(a),ref(n)) = TRUE` holds if and only if `ref(a)` is in `attributes(n)`.

- **Duplicate-free list of Children:** Given a node `n` and any two node references r_1 and r_2 at distinct positions in the sequence `children(n)`, `ref_equal (`r_1`,` r_2`) = FALSE` must hold, i.e., the ordered list of children nodes is duplicate free.

2.4 The DTD Data Model

In order to enforce constraints on XML elements and attributes and on the structure characterizing how instance elements in an XML document relate to each other, we assume that all XML documents have an associated DTD [W3C00]. A DTD allows properties or constraints to be defined on XML elements and attributes. In order to distinguish an ele-

ment specification in a DTD from an element instance in an XML document, we use the term *"element definition"* to refer to a DTD element, as opposed to *"element instance"* in an XML document. Similarly, *"attribute definition"* refers to a DTD attribute specification, as opposed to *"attribute instance"* in an XML document. In a DTD, element definitions indicate the tag names to be used in a conforming XML document. Element definitions can in turn contain subelement definitions or attribute definitions or be empty.

The structure of an element definition is defined via a *content-model* built out of operators applied to its content particles. *Content particles* are either simple subelement definitions or groups of subelement definitions. Groups may be sequences indicated by ",", such as (*a*,*b*) or choices indicated by "|", such as (*a*|*b*). For every content particle, the content-model can specify its occurrence in its parent content particle using regular expression operators such as $?, *, +$. The semantics of these operators are defined below in the description of the Quantifier node. Particular cases of the content-model have the following names: *EMPTY* for an element with no content particles; *PCDATA* for an element that can contain only text; *COMPLEX* for an element that contains children subelements; and *ANY* for an element that can contain any of the above content particles. When the element can contain content particles together with text, the content-model is called *MIXED* for mixed content.

A DTD can be modeled as a directed ordered graph with nodes and edges. The direction of an edge is from a parent node to a sequence of zero or more children. We use the following notation to describe our model of a DTD graph.

Definition 6 *A DTD graph* G *is a three-tuple* $\mathrm{G} = (\mathrm{N}, \mathrm{children}, \mathrm{label})$*, where* N *is the set of nodes in the graph,* $\mathrm{children}$ *is the edge function which returns an ordered sequence of direct descendent nodes,* $\mathrm{children} : \mathrm{N} \rightarrow \mathcal{N}$*, where* $\mathcal{N}$ *is a sequence of* N*; and* label *is the labeling function representing a node's properties, such as its name,* $\mathrm{label} : \mathrm{N} \rightarrow \mathcal{P}$*, where* $\mathcal{P}$ *is the set of properties a node can take on.*

In addition to the `children` function above which returns a sequence of nodes, we define another edge function to return a single node. `childAt(pNode,pos)` returns the single child node in the children sequence of the parent node `pNode` at position `pos`, `childAt` : (N, `pos`) $\rightarrow$ N.

Since a node's label represents a set of properties, the unqualified labeling function returns a set of key-value pairs which could be iterated over to access the various properties and their corresponding values. To refer to a specific property, we use a qualification on the label function. For example, we use the qualified notation `label(`n`).Name` to denote the `Name` property (key) of node n, where this function returns n's name (value). Each node $n \in$ N is guaranteed to contain an *identity* as one of its properties. The set of possible identities includes ElemDef, AttrDef, GroupDef, Quantifier, Root, and Primitive data type nodes. We group these identities into three high-level categories below, and indicate which properties (in addition to the identity) are available from the labeling function for that node.

1. **Tag nodes:**

   (a) **ElemDef:** Each element definition node `e` represents an element type. `label(e)`=$< Name, Type >$ where $Name$ is the unique tag name for element definition `e`, and $Type$ is the content type, such as EMPTY, COMPLEX, ANY, PCDATA or MIXED.

   (b) **AttrDef:** Each attribute definition node `a` represents an attribute type. `label(a)`=$< Name, Type, DefType, DefVal >$ where $Name$ is attribute `a`'s name, $Type$ is `a`'s content type, i.e., CDATA, ID, IDREF, IDREFS, ENUMERATION etc., $DefType$ is `a`'s default type, e.g., *#REQUIRED*, *#IMPLIED* or *#FIXED*, and $DefVal$ is `a`'s default value, if any.

2. **Constraint nodes:**

(a) **GroupDef:** Each group definition node `g` contains a group of children content particles. `label(g)`=< $Type$ >, where $Type$ indicates how `g`'s direct children are grouped together, that is, by sequence (i.e., `label(g).Type`=< ", " >) or by choice (i.e., `label(g).Type`=< "|" >).

(b) **Quantifier node:** Each quantifier node `q` has only one child. The node `q` indicates how many times that child can occur in its parent, that is, the parent of the node `q`. `label(q)`=< $Type$ >, where $Type$ can be *, + or ?, with the following semantics:

i. `label(q).Type`=< " $*$ " >: child is repeatable but not required

ii. `label(q).Type`=< " $+$ " >: child is repeatable and required

iii. `label(q).Type`=< "?" >: child is neither repeatable nor required

The set of nodes with identities including ElemDef nodes, GroupDef nodes and Quantifer nodes are all called *content particle* nodes. In a DTD, the absence of a quantifier means the content particle must appear exactly once. Correspondingly in the DTD graph, the absence of a quantifier node between two non-quantified content particle nodes means the child node must appear exactly once in the parent.

3. **Built-in nodes:**

(a) **Root node:** The `dtdRtNode` node is the entry for the DTD graph. All the nodes in a DTD graph can be reached by traversing the graph starting from this node. A `dtdRtNode` node has no label properties other than its identity.

(b) **Primitive data type node:** A `PCDATA` node `p` represents a textual value. `label(p)`=< $Value$ >. The parent of a `PCDATA` node must be an element definition node, indicating a content type of ANY, PCDATA or MIXED.

Figure 2.2 illustrates a DTD graph representing the Article.dtd document of Figure 1.1.

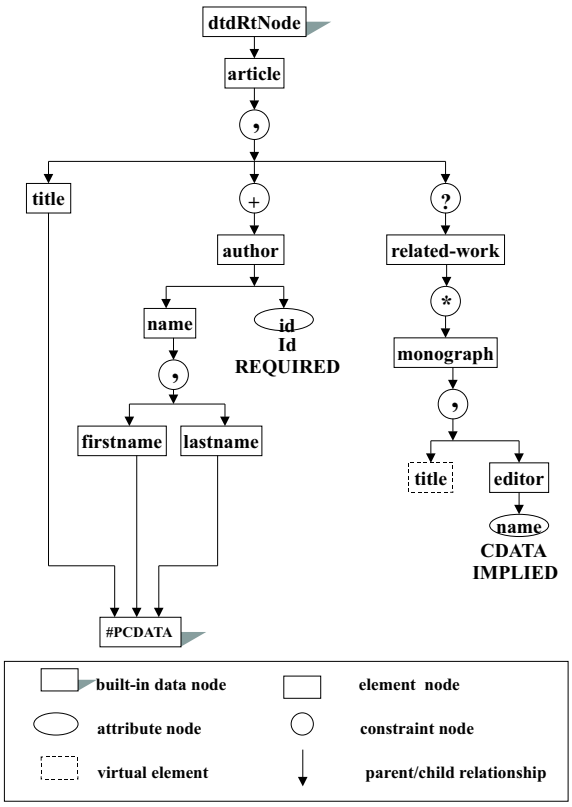


Figure 2.2: Graph Representation of Article.dtd of Figure 1.1

2.5 Relationships Between DTD Graphs and XML Data Trees

An XML data tree is related to the DTD graph of the DTD to which the XML data conforms by the URI in the `DocNode` of the XML tree. The function `related`(G) = $\mathcal{T}$ defines this relationship where G is the DTD graph and $\mathcal{T}$ is the set of XML data trees which correspond to that graph G. Each element and attribute node in the XML tree corresponds to a definition for that element/attribute in the DTD graph. In order to ensure that the XML data does not violate any constraints indicated in the corresponding DTD, when operating on an element or attribute instance in the XML data, we need a way to refer back to the definition of the corresponding content particle in the DTD. In this sense,

the DTD content particle definition provides *typing* information which is needed during transformation of the XML data. Similarly, when operating on an element or attribute definition in the DTD, we need a way to refer to the corresponding data instances in the XML tree(s). We therefore define two relationships between the XML data tree nodes and the DTD graph nodes for this purpose.

First, to find the node in the DTD graph G which contains the DTD definition for a data node instance in the XML tree, we define the function `typeOf(dataN)=def`, which provides a mapping from a node in an XML data tree $T \in \mathcal{T}$ to a node in the DTD graph G, `typeOf` : $NT \rightarrow NG$, where NT is the set of nodes in the XML tree T, and NG is the set of nodes in the DTD graph G. Here `dataN` denotes the data node instance in the XML tree, and `def` refers to the corresponding DTD type definition. `dataN` can either be an element or attribute data node instance in T. In the former case, `def` is an element type definition in G, while in the latter case, `def` denotes the corresponding attribute type definition in G. The function `typeOf` is undefined for other types of nodes in the XML tree. In Section 2.2 where we discuss our XML data model, we define both `ElemNode`s and `AttrNode`s as containing a reference to the node's type. This provides the mechanism by which we can retrieve the DTD definition for a given data node instance.

Second, to find all data node instances which correspond to a given DTD definition, we define the function `ext(def)=dataNodes`, which provides the reverse mapping: from a node in the DTD graph G to a set of nodes in the XML data tree(s), `ext` : $NG \rightarrow NT$, where NG is the set of nodes in the DTD graph G and NT is the set of nodes in the XML data tree T. Here `def` denotes a type definition in the DTD graph G, and `dataNodes` is the set of all instance nodes in the XML data tree T (with $T \in \mathcal{T}$) of type `def`. As above, `def` may denote either an element or an attribute type definition in the DTD graph G. In the former case, `dataNodes` is the set of all element data instance

nodes in the XML data tree T corresponding to that element type, whereas in the latter case, `dataNodes` is the set of all data attribute nodes in T which correspond to the DTD attribute definition. The function `ext` is undefined for other types of nodes in the DTD graph. Again, the reference to the node's type in the XML data tree(s) provides the mechanism for this mapping.

Chapter 3

Taxonomy and Semantics of Evolution Primitives

3.1 Introduction

In this section we present our proposed taxonomy of evolution primitives and define their semantics. The primitives fall into two categories: those pertaining to the DTD, and those pertaining to the XML data. Since our primitive operations are intended to manage *evolution* of DTDs and XML data, we do not provide explicit operations to create a new DTD graph or XML data tree. Rather, we assume that the management system is initialized with a valid XML document (or a set of them), from which we find and load the associated DTD. The DTD graph is thus created during system initialization as is the initial XML data tree (or trees). Our evolution primitives then operate on that loaded data. In particular, the DTD primitives operate on the DTD graph, while the XML data primitives operate on the XML data trees. Our goal is to provide a set of primitives with the following characteristics:

- **Complete:** While we aim for a minimal set of primitives, at the very least all valid changes to manipulate DTDs and XML data can be specified by one or by a sequence of our primitives.

- **Sound:** Every primitive is guaranteed to maintain system integrity in terms of well-formedness of both DTD and XML data, and validity in terms of consistency between DTD and XML data. We ensure that the execution of primitives violates neither the invariants nor the constraints in the content model.

We list our complete taxonomy of primitives for DTD and XML data changes in Table 3.1. We then give a more detailed explanation of the primitives and provide examples of their use.

DTD Operation	**Description**
createDTDElement(e, t)	Create element with name e and content type t
destroyDTDElement(e)	Destroy element with name e
insertDTDElement(E,i,q,d)	Add element E at position i to parent element with quantifier q and default value d
removeDTDElement(E,i)	Remove sub-element at position i in parent E
changeQuant(E,i,q,d)	Change quantifier of element E at position i in parent to quantifier q with default value d
convertToGroup(start,end,gt)	Group sub-elements from position start to position end in parent into a group of type gt
flattenGroup(i)	Flatten group at position i in parent element, converting children to simple sub-elements
changeGroupQuant(i,q)	Change quantifier of group at position i in parent element to q
addDTDAttr(a,at,dt,dv)	Add attribute with name a to parent element with type at, default type dt, and default value dv
destroyDTDAttr(a)	Destroy attribute with name a from parent element
XML Data Operation	**Description**
addDataAttr(a, av)	Add an attribute with name a and value av to parent
destroyDataAttr(a)	Destroy attribute with name a
addDataElement(de, i)	Add element de at position i
destroyDataElement(de, i)	Destroy element de at position i

Table 3.1: Taxonomy of DTD and XML Data Change Primitives

3.2 Notation Conventions

Since the DTD and XML data models are similar, we require some notation conventions to distinguish between various aspects of the model under consideration. In the background section in Chapter 2, in keeping with current trends in the literature, the data model for an XML tree uses the term *nodes*, while in descriptions of the DTD graph it is natural to refer to parts of the graph using the term *nodes* as well. To avoid confusion here, we continue to refer to nodes in the DTD graph as *nodes*, while we use the term *vertices* to refer to nodes in the XML data trees. We provide Table 3.2 as a guide to the notation used in the remainder of this chapter.

Notation	**Description**
G	Generic DTD graph
N	Set of nodes in DTD graph
n ∈ N	Single node in DTD graph
children(n) = C	Function returning ordered sequence of children of node n in DTD graph
childAt(n,pos) = c	Function returning single child of node n in DTD graph at position pos
numCh(n) = i	Function returning number (i) of children of node n in DTD graph
label(n)	Function returning set of key-value pairs of node n in DTD graph
dtdRtNode	Root node of DTD graph
e	DTD Element name (string) used as function parameter
E	Node in DTD graph referring to an Element definition
a	DTD Attribute name (string) used as function parameter
A	Node in DTD graph referring to an Attribute definition
Grp	Node in DTD graph referring to a Group definition
$\mathcal{T}$ = related(G)	Set of XML data trees corresponding to DTD graph G
T	Single instance of XML tree
V	Set of vertices in XML tree
v ∈ V	Single vertex in XML tree
children(v) = C	Function returning ordered sequence of children of vertex v in XML tree
childAt(v,pos) = c	Function returning single child of vertex v at position pos
numCh(v) = i	Function returning number (i) of children of vertex v in XML tree
label(v)	Function returning label of vertex v in XML tree
DE = ext(E)	Set of element vertices corresponding to DTD element definition E
DA = ext(A)	Set of attribute vertices corresponding to DTD attribute definition A
de	Single vertex corresponding to instance of data element
da	Single vertex corresponding to instance of data attribute

Table 3.2: Notation Conventions used in Taxonomy of Primitives

While we distinguish between nodes in a DTD graph and vertices in an XML data tree, the functions applicable to the various data types have the same names. For example, we use children, childAt and label, both in terms of nodes in the DTD graph and vertices in the XML trees. The reasoning behind this is that the functionality for these operations is the same. In both cases, the children function returns an ordered sequence of either nodes or vertices. The childAt function returns either a single node or a single vertex. And the label function returns properties which can be used to identify the node or vertex. We assume that there will be no confusion here, as the meaning of the particular function should be clear within the context in which it is used.

We use standard set notation for items in a set, such as nodes in the DTD graph and vertices in the XML tree. We introduce here notation needed for the ordered sequences of children. We use angled brackets "<>" to denote a sequence, and we apply the following operations to sequences:

- **"<C> + n"** means add item n to the end of sequence C. Assume p is the parent node (or vertex) containing the children sequence C. We use the function numCh(p) = i to determine the number of current children of p in the sequence C, and then we add n to position i+1.

- **"<C> + (n, pos)"** means add item n at position pos to sequence C. All other items in the sequence C in positions greater than pos will have their positions incremented by one.

- **"<C> - n"** means remove the first occurrence of item n from wherever it is found in sequence C. We iterate over the items in the sequence C until we find n, and then remove only that occurrence of n from C. If any other items remain in the sequence in positions after n, those items will each have their positions decremented by one.

- **"<C> - (n, pos)"** means remove item n at position pos from the sequence C. All

other items in the sequence C in positions greater than pos will have their positions decremented by one.

- **"<C> + (<N>,pos)"** means insert each item in the sequence N into the sequence C, starting at position pos. For each n in the sequence N, this operation functions the same as "<C> + (n,pos+i)", where i starts at zero for the first n and increments for each additional item n in the sequence N.

- **"<C> - <N>"** means remove each item in the sequence N from the sequence C. For each n in the sequence N, this operation functions the same as "<C> - n".

These operations may be applied sequentially to the same sequence, where the precedence is from left to right, i.e., "<C> - n_1 + n_2" means we first remove n_1 from <C> producing $<C_1>$ as an intermediate result. Then we insert n_2 into $<C_1>$, producing $<C_2>$ as the end result. Finally, we use standard set notation on sequences only to determine membership, i.e., "n $\in$ <C>" means that the item n exists as a member of the sequence C at some position at least once, and "n $\notin$ <C>" means the item n does not exist at all as a member of the sequence C.

3.3 Details of Change Primitives

In this section, we define the precise syntax and semantics of each DTD and XML change primitive. We assume that the input DTD graph G_1 and input XML data trees $\mathcal{T}_1$ are well-formed, valid and consistent to begin with. To ensure that the targeted output DTD graph G_2 and XML data trees $\mathcal{T}_2$ remain well-formed, valid and consistent after the application of our primitive operations, pre- and post-conditions are enforced on each change primitive. This means that the primitive will not be executed unless the corresponding pre-conditions are satisfied, and changes will not be committed unless the corresponding

post-conditions are accomplished. Post-conditions are given in the descriptions below in terms of resulting DTD and XML data changes that are necessary in order to maintain system integrity for the given change operation.

In the following descriptions, change primitives are applied to the input DTD graph G_1 = (N_1, $children_1$, $label_1$) and produce the DTD graph G_2 = (N_2, $children_2$, $label_2$) as output. When a DTD change requires some change to the XML data, we apply the changes to the set of XML data trees $\mathcal{T}$ = `related`(G), which correspond to the DTD graph G using the `related` function defined in Section 2.5. For the XML data trees, change primitives are applied to the input set of XML trees $\mathcal{T}_1$, where each tree in the set $T_{1i} \in \mathcal{T}_1$ = (V_{1i}, $children_{1i}$, $label_{1i}$) and produce a new set of XML trees $\mathcal{T}_2$, with $T_{2i} \in \mathcal{T}_2$ = (V_{2i}, $children_{2i}$, $label_{2i}$) as output.

3.3.1 Changes to the Document Definition

Primitive 1: *createDTDElement*

Syntax: `G.createDTDElement(String e, ElemType t)`

Semantics: Create a new DTD element definition node named e with content type t for the DTD graph G.

Preconditions: No existing element definition node with name e has been defined in the DTD graph G, i.e., $\forall n \in N_1, label_1(n).Name \neq e$. ElemType t must be either $EMPTY$ or $PCDATA$.

Resulting DTD Changes: A new DTD element definition node E with name e will be created with content type t, and will be added to the end of the sequence of children of the root node. We get a graph $G_2 = (N_2, children_2, label_2)$ where $N_2 = N_1 \cup E$, $children_2(dtdRtNode)$ = $children_1(dtdRtNode)$ + E, $label_2(E).Name = e$, and $label_2(E).Type = t$. $\forall n \in N_1 - dtdRtNode, children_2(n) = children_1(n)$, and $\forall m \in N_1, label_2(m) = label_1(m)$.

Resulting Data Changes: Since this primitive only creates a top-level DTD element definition node, and the element is not (yet) a subelement of any other element, we call this a "dangling" top-level element. At this point instances of E cannot exist in the data, i.e., $ext(E) = \emptyset$, until it is assigned as a child subelement to some other element in the DTD graph. Therefore, this primitive causes no changes to the XML data, that is, $\mathcal{T}_2 = \mathcal{T}_1$.

Example 1 *We add a DTD element definition to represent the concept of an author's middle initial as follows:*

```
document.createDTDElement("middle", EMPTY);
```

Execution of this primitive operation has the effect of adding a new dangling top-level element definition for the middle initial, as shown in Figure 3.1 on the Article DTD of Figure 1.1.

```
<!ELEMENT article (title,author+,related?)>
<!ELEMENT title (#PCDATA)>
<!ELEMENT author (name)>
   <!ATTLIST author id ID #REQUIRED>
<!ELEMENT name (first,last)>
<!ELEMENT first (#PCDATA)>
<!ELEMENT last (#PCDATA)>
<!ELEMENT related (monograph)*>
<!ELEMENT monograph (title,editor)>
<!ELEMENT editor EMPTY>
   <!ATTLIST editor name CDATA #IMPLIED>

            BEFORE
```

```
<!ELEMENT article (title,author+,related?)>
<!ELEMENT title (#PCDATA)>
<!ELEMENT author (name)>
   <!ATTLIST author id ID #REQUIRED>
<!ELEMENT name (first,last)>
<!ELEMENT first (#PCDATA)>
<!ELEMENT last (#PCDATA)>
<!ELEMENT middle EMPTY>
<!ELEMENT related (monograph)*>
<!ELEMENT monograph (title,editor)>
<!ELEMENT editor EMPTY>
   <!ATTLIST editor name CDATA #IMPLIED>

            AFTER
```

Figure 3.1: Results of createDTDElement Primitive Operation

Primitive 2: *destroyDTDElement*

Syntax: `G.destroyDTDElement(String e)`

Semantics: Destroy the element definition node named e from the DTD graph G.

Preconditions: An element definition node named e must exist in the DTD graph G: $\exists E \in N_1$ such that $label_1(E).Name = e$. The element definition node E named e in G must be a non-nested element node whose content model is either *EMPTY* or composed of only *PCDATA*, i.e., $label_1(E).Type = EMPTY$ or $label_1(E).Type = PCDATA$.

The element definition node E must also be a "top-level" element, meaning it cannot exist as a child of any node other than the root: $\forall n \in N_1$ - $dtdRtNode$, $E \notin children_1(n)$.

Resulting DTD Changes: The element definition node E with name e will be removed from the root node of the DTD graph G. We get a graph G_2 = (N_2, $children_2$, $label_2$) where N_2 = N_1 - E, $children_2(dtdRtNode)$ = $children_1(dtdRtNode)$ - E, and $\forall n \in N_1$ - $dtdRtNode$, $children_2(n)$ = $children_1(n)$. $\forall m \in N_1$ - E, $label_2(m)$ = $label_1(m)$.

Resulting Data Changes: In order for the preconditions above to be satisfied, there must be no instances of element E in the XML data trees, i.e., $ext(E) = \emptyset$. Since E cannot exist in the DTD graph G as a child of any node other than the root, there are only two possibilities for the relationship between E in the DTD graph and instances of E in the XML data trees $\mathcal{T}$. First, the element definition node E in G could correspond to the only child of the top-level `DocNode` in the XML trees $\mathcal{T}_1$. In our running example, E would correspond to the *article* node in Figure 2.2, and instances of E in the XML data trees would correspond to the single child of the `DocNode` as shown in Figure 2.1. In this case destroying the element definition node E would cause the DTD graph G to be empty, triggering the removal of all corresponding XML data trees for that graph, i.e., $\mathcal{T}_2$ = $\emptyset$. Second, the element definition node E could be a "dangling" top-level element in the DTD graph other than the one corresponding to the single child of the `DocNode`. In this case, since it is not a child subelement of any other node, instances of E cannot exist in the data. Therefore this primitive would cause no changes to the XML data, that is, $\mathcal{T}_2$ = $\mathcal{T}_1$.

Example 2 *We destroy the dangling top-level element definition representing the concept of an author's middle initial, which was created above in Example 1 as follows:*

```
document.destroyDTDElement("middle");
```

Execution of this primitive operations has the effect of restoring the Article DTD of Example 1 to the original form of Figure 1.1.

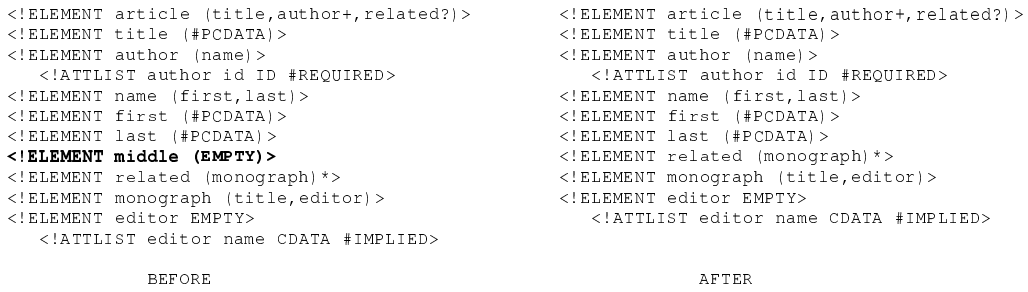


Figure 3.2: Results of destroyDTDElement Primitive Operation

3.3.2 Changes to an Element Type Definition

Primitive 3: *insertDTDElement*

Syntax: `p.insertDTDElement(Elem E, int pos, QuantType q, String d)`

Semantics: Insert the element definition node E into the children sequence of the parent node p at position pos, with quantifier q, and default value d.

Preconditions: An element definition node E must already exist in the DTD graph G which contains the parent node p: $\exists E \in N_1$. The quantifier q must have one of the following values: {`STAR` | `PLUS` | `QMARK` | `NONE`}. See Section 2.4 for the definitions of these constraint values. If the quantifier q signifies a *required* constraint and E is a *PCDATA* element, i.e., $label_1(E).Type = PCDATA$, then the default value d must not be null.

Resulting DTD Changes: An existing element definition node E will be added to the children sequence of the parent element node p at position pos. We get a graph G_2 = (N_2, $children_2$, $label_2$) where $N_2 = N_1$, and $children_2(p)$ = $children_1(p) + (E, pos)$. $\forall n \in N_1 - p$, $children_2(n) = children_1(n)$, and $\forall m \in N_1$, $label_2(m) = label_1(m)$.

Resulting Data Changes: If q signifies a *required* constraint ($label_1(q).Type \in$ {STAR, NONE}), then a new data element vertex de will be created with default value d for each instance of the parent element definition node p. We find the extent of the parent node p,

$DP = ext(p)$, and then for each vertex $dp \in DP$, we add a new vertex de to the children sequence of dp at position pos. We find the set of input XML data trees corresponding to the DTD graph G using $\mathcal{T}_1$ = `related`(G). For each $T_{1i} \in \mathcal{T}_1$, we get a new tree T_{2i} = (V_{2i}, $children_{2i}$, $label_{2i}$) where $V_{2i} = V_{1i} \cup de$, and $label_{2i}(de) =$ `ElemNode`. For each parent vertex $dp \in DP$, $children_{2i}(dp)$ = $children_{1i}(dp)$ + (de, pos). $\forall v \in V_{1i} - DP$, $children_{2i}(v)$ = $children_{1i}(v)$, and $\forall w \in V_{1i}$, $label_{2i}(w)$ = $label_{1i}(w)$.

Example 3 *First we create the middle initial element, as was done above in Example 1, except this time we use type PCDATA, rather than EMPTY.*

```
document.createDTDElement("middle", PCDATA);
```

We then use the insertDTDElement operation to insert the middle initial element into the parent `name` *element.*

```
name.insertDTDElement("middle", 1, QMARK, null);
```

Since a middle initial is not normally required, we pass `QMARK` *as the quantifier value which represents an optional constraint, and* `null` *for the default value. As a result, no data changes are required for this operation. However, after these operations have been completed, appropriate individual middle initial values could then be inserted into the data when so desired. Execution of these operations has the effect of first creating a new top-level element definition for the* `middle` *element, and then inserting that as a subelement into the* `name` *parent element definition. This effect is illustrated in Figure 3.3 on the Article DTD of Figure 1.1.*

```
<!ELEMENT article (title,author+,related?)>
<!ELEMENT title (#PCDATA)>
<!ELEMENT author (name)>
   <!ATTLIST author id ID #REQUIRED>
<!ELEMENT name (first,last)>
<!ELEMENT first (#PCDATA)>
<!ELEMENT last (#PCDATA)>
<!ELEMENT related (monograph)*>
<!ELEMENT monograph (title,editor)>
<!ELEMENT editor EMPTY>
   <!ATTLIST editor name CDATA #IMPLIED>

            BEFORE
```

```
<!ELEMENT article (title,author+,related?)>
<!ELEMENT title (#PCDATA)>
<!ELEMENT author (name)>
   <!ATTLIST author id ID #REQUIRED>
<!ELEMENT name (first,middle?,last)>
<!ELEMENT first (#PCDATA)>
<!ELEMENT last (#PCDATA)>
<!ELEMENT middle (#PCDATA)>
<!ELEMENT related (monograph)*>
<!ELEMENT monograph (title,editor)>
<!ELEMENT editor EMPTY>
   <!ATTLIST editor name CDATA #IMPLIED>

            AFTER
```

Figure 3.3: Results of insertDTDElement Primitive Operation

Primitive 4: *removeDTDElement*

Syntax: `p.removeDTDElement(String e, int pos)`

Semantics: Remove the element definition node E with name e from the children sequence in the parent element definition node p at position pos.

Preconditions: An element definition node named e must exist in the DTD graph G which contains the parent definition node p: $\exists E \in N_1$ such that $label_1(E).Name = e$. The parent element definition p must contain the subelement E in its children sequence at position pos, i.e., $childAt(p, pos) = E$. The element E must be a non-nested element node, meaning it may not have any children subelements of its own: $children_1(E) = \emptyset$.

Resulting DTD Changes: The element definition node E is removed from position pos in the children sequence of the parent node p. We get a graph $G_2 = (N_2, children_2, label_2)$ where $N_2 = N_1$ and $children_2(p) = children_1(p) - (E, pos)$. $\forall n \in N_1 - p$, $children_2(n) = children_1(n)$, and $\forall m \in N_1$, $label_2(m) = label_1(m)$.

Resulting Data Changes: All the instance vertices of element E, $DE = ext(E)$, are removed from instances of the parent element definition node p. We find the extent of the parent node p, $DP = ext(p)$, and then for each vertex $dp \in DP$, we remove the vertex $de \in DE$ from the children sequence of dp at position pos. For each input XML data tree $T_{1i} \in \mathcal{T}_1$, we get a new tree $T_{2i} = (V_{2i}, children_{2i}, label_{2i})$ where $V_{2i} = V_{1i} - DE$. For each parent vertex $dp \in DP$, $children_{2i}(dp) = children_{1i}(dp) - (de, pos)$. $\forall v \in V_{1i} - DP$,

$children_{2i}(v) = children_{1i}(v)$, and $\forall w \in V_{1i} - DE, label_{2i}(w) = label_{1i}(w)$.

Example 4 *To illustrate use of this primitive operation, we remove the subelement* `editor` *from the parent element* `monograph` *(the second child subelement) as follows.*

```
monograph.removeDTDElement("editor", 2);
```

Execution of this primitive operation causes the `editor` *subelement to be removed from the parent* `monograph` *element, as illustrated in Figure 3.4 on the Article DTD of Figure 1.1 and XML data of Figure 1.2.*

```
<!ELEMENT article (title,author+,related?)>
<!ELEMENT title (#PCDATA)>
<!ELEMENT author (name)>
   <!ATTLIST author id ID #REQUIRED>
<!ELEMENT name (first,last)>
<!ELEMENT first (#PCDATA)>
<!ELEMENT last (#PCDATA)>
<!ELEMENT related (monograph)*>
<!ELEMENT monograph (title,editor)>
<!ELEMENT editor EMPTY>
   <!ATTLIST editor name CDATA #IMPLIED>
```

BEFORE

```
<article>
  <title>XML Evolution Manager</title>
  <author id = "dk">
    <name>
      <first>Diane</first>
      <last>Kramer</last>
    </name>
  </author>
  <author id = "er">
    <name>
      <first>Elke</first>
      <last>Rundensteiner</last>
    </name>
  </author>
  <related>
    <monograph>
      <title>Modern database systems</title>
      <editor name = "Won Kim"></editor>
    </monograph>
  </related>
</article>
```

BEFORE

```
<!ELEMENT article (title,author+,related?)>
<!ELEMENT title (#PCDATA)>
<!ELEMENT author (name)>
   <!ATTLIST author id ID #REQUIRED>
<!ELEMENT name (first,last)>
<!ELEMENT first (#PCDATA)>
<!ELEMENT last (#PCDATA)>
<!ELEMENT related (monograph)*>
<!ELEMENT monograph (title)>
<!ELEMENT editor EMPTY>
   <!ATTLIST editor name CDATA #IMPLIED>
```

AFTER

```
<article>
  <title>XML Evolution Manager</title>
  <author id = "dk">
    <name>
      <first>Diane</first>
      <last>Kramer</last>
    </name>
  </author>
  <author id = "er">
    <name>
      <first>Elke</first>
      <last>Rundensteiner</last>
    </name>
  </author>
  <related>
    <monograph>
      <title>Modern database systems</title>
    </monograph>
  </related>
</article>
```

AFTER

Figure 3.4: Results of removeDTDElement Primitive Operation

Primitive 5: *changeQuant*

Syntax: `p.changeQuant(Elem E, int pos, QuantType q, String d)`

Semantics: Change the quantifier constraint for the element definition node E in the children sequence of parent element node p at position pos to type q, with default value d.

Preconditions: The element definition node E must exist in the DTD graph G which contains the parent definition node p: $\exists E \in N_1$. The parent element definition p must contain the node E in its children sequence at position pos, i.e., $childAt(p, pos) = E$. The QuantType q must have one of the following values: {STAR | PLUS | QMARK | NONE}. See Section 2.4 for the definitions of these constraint values. If the quantifier q signifies a *required* constraint, the default value d must not be null.

Resulting DTD Changes: There are three possibilities which will determine what changes are required to the DTD graph G for this operation. First, if the original element definition node E was not previously quantified and the QuantType q is not NONE, then a new quantifier node must be created and inserted into the DTD graph. Second, if the original element definition node E was previously quantified and the QuantType q is NONE, then the old quantifier node must be removed from the DTD graph. Third, if the original element definition node E was previously quantified and the QuantType q is not NONE, then we simply need to change the quantifier node's type to q. The fourth possibility would be that original element definition node E was not previously quantified and the QuantType q is NONE. In this case we are not actually changing the quantifier of the node E, so no DTD changes would be required. We now show the resulting DTD changes for each of the three possibilities which require changes to the DTD graph.

1. First we remove the node E from the children sequence in the parent node p at position pos. Next we create a new quantifier node Q with type q and insert Q into the children sequence of the parent node p at position pos. Finally, we insert the node E into the children sequence of the quantifier node Q. We get a graph $G_2 = (N_2, children_2, label_2)$ where $N_2 = N_1 \cup Q$, $children_2(p)$ = $children_1(p)$ - (E, pos) + (Q, pos), and $label_2(Q).Type$ = q. $\forall n \in N_1 - p$, $children_2(n) = children_1(n)$, and $\forall m \in N_1$, $label_2(m)$ = $label_1(m)$.

2. First we remove the quantifier node Q from the children sequence in the parent node p at position pos. We then find the node E in the children sequence of the node Q, and insert E into the children sequence in the parent node p at position pos. Finally we destroy the quantifier node Q which is no longer needed. We get a graph $G_2 = (N_2, children_2, label_2)$ where $N_2 = N_1 - Q$ and $children_2(p)$ = $children_1(p)$ - (Q, pos) + (E, pos). $\forall n \in N_1 - p$, $children_2(n) = children_1(n)$, and $\forall m \in N_1 - Q$, $label_2(m)$ = $label_1(m)$.

3. In the simplest case, we need only change the quantifier node Q's type to q in the children sequence of the parent node p at position pos. We get a graph $G_2 = (N_2, children_2, label_2)$ where $N_2 = N_1$ and $label_2(Q).Type$ = q. $\forall n \in N_1$, $children_2(n)$ = $children_1(n)$, and $\forall m \in N_1 - Q$, $label_2(m) = label_1(m)$.

Resulting Data Changes: The XML data changes required for this primitive depend on the old and new quantifier values. These changes can be summarized using the following two rules:

1. If the old quantifier represented a *repeatable* constraint and the new quantifier does not, we find all the instance vertices of element E, DE_1 = $ext(E)$, and remove all but the first occurrence, DE_2 = DE_1 - the first $de \in DE_1$, from instances of the parent element node p. We find the extent of the parent node p, $DP = ext(p)$, and then for each vertex $dp \in DP$, we remove each vertex $de \in DE_2$ from the children sequence of dp. For each input XML data tree $T_{1i} \in \mathcal{T}_1$, we get a new tree T_{2i} = (V_{2i}, $children_{2i}$, $label_{2i}$) where V_{2i} = $V_{1i} - DE_2$. For each parent vertex $dp \in DP$, $children_{2i}(dp)$ = $children_{1i}(dp)$ - (DE_2). $\forall v \in V_{1i} - DP$, $children_{2i}(v)$ = $children_{1i}(v)$, and $\forall w \in V_{1i} - DE_2$, $label_{2i}(w)$ = $label_{1i}(w)$.

2. If the new quantifier represents a *required* constraint and the old quantifier did not, for each instance of the parent node p which did not contain any instance of the child

element node E, we must create a new instance vertex de of element E with default value d and insert de into instances of the parent node p. We find the extent of the parent node p, $DP = ext(p)$, and then for each vertex $dp \in DP$ we first check whether a de exists at position pos. If not, then we insert de into dp at position pos. Let DE be this set of newly created and inserted instances of de. For each input XML data tree $T_{1i} \in \mathcal{T}_1$, we get a new tree T_{2i} = (V_{2i}, $children_{2i}$, $label_{2i}$) where V_{2i} = $V_{1i} \cup DE$. For each vertex $de \in DE$, $label_{2i}(de) =$ `ElemNode`, and for each parent vertex $dp \in DP$, $children_{2i}(dp)$ = $children_{1i}(dp)$ + (de, pos), wherever de did not exist at position pos before. $\forall v \in V_{1i} - DP$, $children_{2i}(v)$ = $children_{1i}(v)$, and $\forall w \in V_{1i} - DE$, $label_{2i}(w)$ = $label_{1i}(v)$.

The remaining combinations of old and new quantifiers such as not repeatable becomes repeatable, or required becomes not required, cause no changes to the XML data.

Example 5 *We change the* `author` *subelement's quantifier in the parent* `article` *element from repeatable (*`PLUS`*) to a non-repeatable constraint (*`NONE`*) as follows:*

```
article.changeQuant(author, 2, NONE, null);
```

Execution of this primitive operation, in addition to changing the quantifier in the DTD element definition, also causes the removal of multiple `author` *elements found in the data (all but the first occurrence are removed). The effect on the Article DTD, the first line of which is all that changes, of Figure 1.1 and XML data of Figure 1.2 is illustrated in Figure 3.5.*

Figure 3.5: Results of changeQuant Primitive Operation

Primitive 6: *convertToGroup*

Syntax: `p.convertToGroup(int start, int end, GroupType gt)`

Semantics: Group together a sequence of children subelement definition nodes, whose positions range from $start$ to end in the children sequence of the parent element p, with group type gt.

Preconditions: The position variables $start$ and end must be valid positions in the children sequence of the parent node p, i.e., numCh(p) $\geq start$ and numCh(p) $\geq end$ must both hold. These variables must also be valid relative to each other, meaning $start \leq end$ must hold. To convert a single child subelement into a group of one, $start$ must equal end. All the content particles falling within the range $(start, end)$ must share the same parent, meaning they cannot already be contained in *different* groups. gt must have one of the following values: {`LIST` | `CHOICE`}. If the content particles within the range $(start, end)$ are already contained in a group, that existing group must have the same group type as gt.

Resulting DTD Changes: All the content particles that range from position $start$ to end in the children sequence of the parent node p are converted into a group of type gt.

First we create a new group definition node Grp. We then iterate over the children sequence of p, removing children nodes within the range $(start, end)$, and inserting them in the same order into the children sequence of Grp. Let CH be this sequence of children nodes. Finally, we insert Grp into the children sequence of the parent node p at position $start$. We get a graph $G_2 = (N_2, children_2, label_2)$ where $N_2 = N_1 \cup Grp$, $children_2(p) = children_1(p) - (CH) + (Grp, start)$ and $label_2(Grp).Type = gt$. $\forall n \in N_1 - p$, $children_2(n) = children_1(n)$, and $\forall m \in N_1$, $label_2(m) = label_1(m)$.

Resulting Data Changes: Since this primitive does not allow creating a nested group of a different type from the parent group, this primitive causes no changes to the XML data, as groups are for hierarchical organization purposes only. In a DTD element definition, a children sequence does not change semantically when a new set of parentheses is added. We illustrate with an example, where the following two DTD element definitions for the parent node x have the same meaning in terms of the corresponding XML data. Thus, $\mathcal{T}_2 = \mathcal{T}_1$.

```
<!ELEMENT x (a, b, c, d, e)>
<!ELEMENT x (a, (b, c), d, e)>
```

The same argument holds if both the new nested group and the old parent group are of type `CHOICE`, as illustrated with the following example where both DTD element definitions have the same semantics in terms of the XML data.

```
<!ELEMENT x (a | b | c | d | e)>
<!ELEMENT x (a | (b | c) | d | e)>
```

Example 6 *This operation is performed on a parent element, in order to convert a range of its subelements into a group. To illustrate, we create a* `LIST` *group of one, for the single* `author` *subelement in the parent* `article` *element as follows:*

```
article.convertToGroup(2, 2, "LIST");
```

Execution of this primitive operation has the effect of converting the second subelement (`author`) in the `article` parent element to a group of one. The effect on the first line of the Article DTD of Figure 1.1 is shown in Figure 3.6. There are no other changes to the DTD, and no data changes are required as a result of this primitive operation.

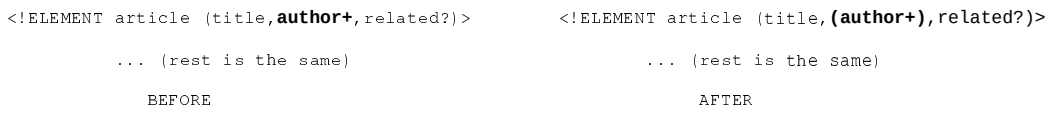


Figure 3.6: Results of convertToGroup Primitive Operation

Primitive 7: *flattenGroup*

Syntax: `p.flattenGroup(int pos)`

Semantics: Convert a group of content particles at position pos in the children sequence of the parent node p into simple subelements, i.e., remove the group node containing those subelements.

Preconditions: The content particle at position pos in the children sequence of the parent node p must be a group definition node, i.e., $label(childAt(p, pos)).identity = GroupDef$.

Resulting DTD Changes: First the group definition node at position pos in the children sequence of the parent node p, $Grp = childAt(p, pos)$, is removed from p. Then all of the content particles which were contained in the children sequence of that group, $GE = children(Grp)$, become direct descendents of the parent node p. We iterate over the children nodes $ge \in GE$, inserting the first into p at position pos, the second at position $pos + 1$, the third at position $pos + 2$, and so on. We get a graph $G_2 = (N_2, children_2, label_2)$ where $N_2 = N_1 - Grp$ and $children_2(p) = children_1(p) - (Grp, pos) + (GE, pos)$. $\forall n \in N_1 - p$, $children_2(n) = children_1(n)$, and $\forall m \in N_1$, $label_2(m) = label_1(m)$.

Resulting Data Changes: Since group nodes are not represented in the XML data, the

children instance vertices are already children of the correct parent instance vertices. Therefore, this primitive causes no changes to the XML data, i.e., $\mathcal{T}_2 = \mathcal{T}_1$.

Example 7 *This operation is performed on a parent element definition node in order to flatten a group of subelements. To illustrate, we use the newly created group from Example 6 directly above, where flattening the group of one for the single* `author` *subelement in the parent* `article` *element, restores the* `article` *definition to its original state as follows:*

```
article.flattenGroup(2);
```

Execution of this primitive operation has the effect of reverting the first line of the Article DTD from the previous example to its original state. There are no other changes to the DTD, and no data changes are required as a result of this primitive operation.

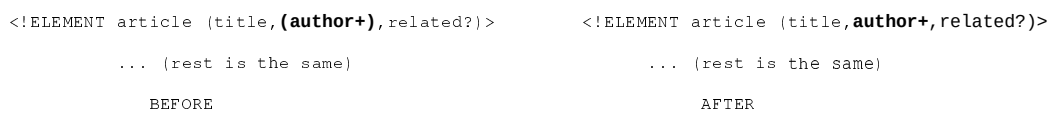


Figure 3.7: Results of flattenGroup Primitive Operation

Primitive 8: *changeGroupQuant*

Syntax: `p.changeGroupQuant(int pos, QuantType q)`

Semantics: Change the quantifier constraint for the group definition node at position pos in the children sequence of the parent definition node p to type q.

Preconditions: The content particle at position pos in the children sequence of the parent node p must be a group definition node, i.e., $label(childAt(p, pos)).identity = GroupDef$. The quantifier q must have one of the following values: {`STAR` | `PLUS` | `QMARK` | `NONE`}. However, we do not allow the new quantifier q to represent a *required* constraint if the old quantifier did not because it would be difficult to specify appropriate default values for an entire group of elements to assign to their data instances in cases where the group does not already exist in the data.

Resulting DTD Changes: The changes we describe here are the same as those for primitive 5 above, with the simple replacement of Grp for E, since we are now dealing with a group definition node rather than an element definition node. There are three possibilities which will determine what changes are required to the DTD graph G for this operation. First, if the original group definition node Grp was not previously quantified and the QuantType q is not `NONE`, then a new quantifier node must be created and inserted into the DTD graph. Second, if the original group definition node Grp was previously quantified and the QuantType q is `NONE`, then the old quantifier node must be removed from the DTD graph. Third, if the original group definition node Grp was previously quantified and the QuantType q is not `NONE`, then we simply need to change the quantifier node's type to q. The fourth possibility would be that original group definition node Grp was not previously quantified and the QuantType q is `NONE`. In this case we are not actually changing the quantifier of the node Grp, so no DTD changes would be required. We now show the resulting DTD changes for each of the three possibilities which require changes to the DTD graph.

1. First we remove the node Grp from the children sequence in the parent node p at position pos. Next we create a new quantifier node Q with type q and insert Q into the children sequence of the parent node p at position pos. Finally, we insert the node Grp into the children sequence of the quantifier node Q. We get a graph $G_2 = (N_2, children_2, label_2)$ where $N_2 = N_1 \cup Q$, $children_2(p)$ = $children_1(p)$ - (Grp, pos) + (Q, pos), and $label_2(Q).Type = q$. $\forall n \in N_1 - p$, $children_2(n) = children_1(n)$, and $\forall m \in N_1$, $label_2(m) = label_1(m)$.

2. First we remove the quantifier node Q from the children sequence in the parent node p at position pos. We then find the node Grp in the children sequence of the node Q, and insert Grp into the children sequence in the parent node p at position

pos. Finally we destroy the quantifier node Q which is no longer needed. We get a graph $G_2 = (N_2, children_2, label_2)$ where $N_2 = N_1 - Q$ and $children_2(p)$ = $children_1(p)$ - (Q, pos) + (Grp, pos). $\forall n \in N_1 - p$, $children_2(n) = children_1(n)$, and $\forall m \in N_1 - Q$, $label_2(m)$ = $label_1(m)$.

3. In the simplest case, we need only change the quantifier node Q's type to q in the children sequence of the parent node p at position pos. We get a graph $G_2 = (N_2, children_2, label_2)$ where $N_2 = N_1$ and $label_2(Q).Type$ = q. $\forall n \in N_1$, $children_2(n)$ = $children_1(n)$, and $\forall m \in N_1 - Q$, $label_2(m) = label_1(m)$.

Resulting Data Changes: Similar to the resulting data changes for Primitive 5 above, if the old quantifier represented a *repeatable* constraint and the new quantifier does not, we find all the instance vertices of the group Grp, $DG_1 = ext(Grp)$, and remove all but the first occurrence, DG_2 = DG_1 - the first $dg \in DG_1$, from instances of the parent node p. We find the extent of the parent node p, $DP = ext(p)$, and then for each vertex $dp \in DP$, we remove each vertex $dg \in DG_2$ from the children sequence of dp. For each input XML data tree $T_{1i} \in \mathcal{T}_1$, we get a new tree T_{2i} = (V_{2i}, $children_{2i}$, $label_{2i}$) where V_{2i} = $V_{1i} - DG_2$. For each parent vertex $dp \in DP$, $children_{2i}(dp)$ = $children_{1i}(dp)$ - (DG_2). $\forall v \in V_{1i} - DP$, $children_{2i}(v)$ = $children_{1i}(v)$, and $\forall w \in V_{1i} - DG_2$, $label_{2i}(w)$ = $label_{1i}(w)$

Example 8 *This operation is performed on a parent element to change the quantifier of a group subelement node. To illustrate, we change the quantifier on the* `monograph` *group node in the parent* `related` *element definition from repeatable but not required ("*") to not repeatable and not required ("?") as follows:*

```
related.changeGroupQuant(1, "?");
```

Execution of this primitive operation causes a change to the quantifier on the `monograph` *group node in the parent* `related` *element definition. Since the XML data only*

contains a single instance of the `monograph` *content particle, no data changes are required as a result of this primitive. The effect on the Article DTD of Figure 1.1 is shown in Figure 3.8.*

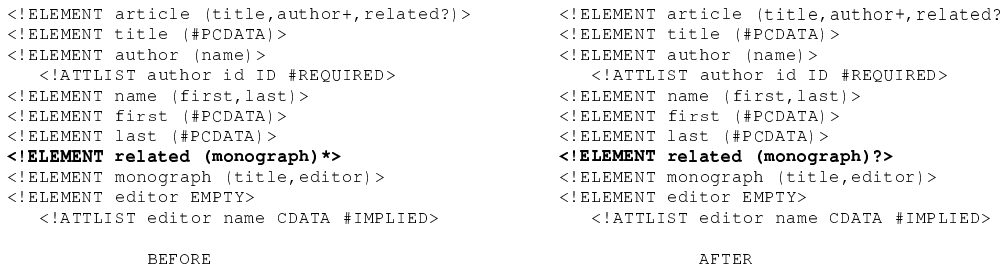


Figure 3.8: Results of changeGroupQuant Primitive Operation

Primitive 9: *addDTDAttr*

Syntax: `p.addDTDAttr(String a, AttrType at, DefType dt, String dv)`

Semantics: A new attribute definition node with name a, attribute type at, default type dt, and default value dv will be created and added to the children sequence of the parent node p.

Preconditions: No attribute with name a has been defined in the parent element definition p, i.e., $\forall n \in children(p)$ where $label(n).identity = AttrDef$, $label(n).Name \neq a$. The attribute type at must have one of the following values: {`CDATA` | `CHOICE` | `HREF` | `ID` | `IDREF` | `IDREFS` | `NMTOKEN`}. The default type dt must have one of the following values: {`#REQUIRED` | `#IMPLIED` | `#FIXED` | `#DEFAULT`}. If the default type dt is anything other than `#IMPLIED`, the default value dv must not be null.

Resulting DTD Changes: A new attribute definition node A will be created with name a, attribute type at, default type dt, and if $dv \neq \emptyset$, default value dv. A will then be added to the children sequence of the parent node p. We get a graph $G_2 = (N_2, children_2, label_2)$ where $N_2 = N_1 \cup A$, $children_2(p) = children_1(p) + A$, $label_2(A).Name = a$, $label_2(A).Type$

= at, $label_2(A).DefType$ = dt, and $label_2(A).DefVal$ = dv. $\forall n \in N_1 - p$, $children_2(n)$ = $children_1(n)$, and $\forall m \in N_1$, $label_2(m)$ = $label_1(m)$.

Resulting Data Changes: If the default type dt = `#REQUIRED`, then a new data attribute vertex da will be created with default value dv for each instance of the parent element definition node p. We find the extent of the parent node p, $DP = ext(p)$, and then for each vertex $dp \in DP$, we add a new vertex da to the children sequence of dp. For each input XML data tree $T_{1i} \in \mathcal{T}_1$, we get a new tree T_{2i} = (V_{2i}, $children_{2i}$, $label_{2i}$) where V_{2i} = $V_{1i} \cup da$, and $label_{2i}(da) =$ `AttrNode`. For each parent vertex $dp \in DP$, $children_{2i}(dp)$ = $children_{1i}(dp)$ + da. $\forall v \in V_{1i} - DP$, $children_{2i}(v)$ = $children_{1i}(v)$, and $\forall w \in V_{1i}$, $label_{2i}(w)$ = $label_{1i}(w)$.

Example 9 *This operation is performed on a parent element to add a new attribute definition. To illustrate, we add a* `published` *attribute to the* `article` *element definition to indicate whether this article has been published or not. We pass* CDATA *as the attribute type,* #REQUIRED *as the default type, meaning each instance of the* `article` *element in the data must have this new attribute, and* `TRUE` *for the default value as follows:*

```
article.addDTDAttr("published", CDATA, #REQUIRED,
                   TRUE);
```

Execution of this primitive operation causes a new line to be added after the first line of the Article DTD of Figure 1.1, and the rest of the DTD remains the same. Since there is only one instance of the `article` *content particle in the data, only the first line of the XML data from Figure 1.2 changes, as shown in Figure 3.9.*

```
<!ELEMENT article (title,author+,related?)>
<!ELEMENT title (#PCDATA)>

      ... (rest is the same)

<article>
  <title>XML Evolution Manager</title>

      ... (rest is the same)

            BEFORE
```

```
<!ELEMENT article (title,author+,related?)>
   <!ATTLIST article published CDATA #REQUIRED>
<!ELEMENT title (#PCDATA)>

      ... (rest is the same)

<article published="TRUE">
  <title>XML Evolution Manager</title>

      ... (rest is the same)

            AFTER
```

Figure 3.9: Results of addDTDAttr Primitive Operation

Primitive 10: *destroyDTDAttr*

Syntax: `p.destroyDTDAttr(String a)`

Semantics: The attribute definition node with name a will be removed from the children sequence in the parent node p.

Preconditions: An attribute definition node with name a must already exist in the children sequence of the parent node p, i.e., $\exists n \in children(p)$ such that $label(n).identity = AttrDef$ and $label(n).Name = a$.

Resulting DTD Changes: The attribute definition node A with name a will be removed from the children sequence of the parent node p. We get a graph $G_2 = (N_2, children_2, label_2)$ where $N_2 = N_1 - A$ and $children_2(p) = children_1(p) - A$. $\forall n \in N_1 - p$, $children_2(n) = children_1(n)$, and $\forall m \in N_1 - A$, $label_2(m) = label_1(m)$.

Resulting Data Changes: All the instance vertices of attribute A, $DA = ext(A)$ are removed from instances of the parent element definition node p. We find the extent of the parent node p, $DP = ext(p)$, and then for each vertex $dp \in DP$, we remove the vertex $da \in DA$ from the children sequence of dp. For each input XML data tree $T_{1i} \in \mathcal{T}_1$, we get a new tree $T_{2i} = (V_{2i}, children_{2i}, label_{2i})$ where $V_{2i} = V_{1i} - DA$. For each parent vertex $dp \in DP$, $children_{2i}(dp) = children_{1i}(dp) - da$. $\forall v \in V_{1i} - DP$, $children_{2i}(v) = children_{1i}(v)$, and $\forall w \in V_{1i} - DA$, $label_{2i}(w) = label_{1i}(w)$.

Example 10 *This operation is performed on a parent element to remove an existing attribute. To illustrate, we remove the* `published` *attribute from the* `article` *element which was added in Example 9 above as follows:*

```
article.destroyDTDAttr("published");
```

Execution of this primitive operation causes the new line which was added in the previous example to be removed, while the rest of the DTD remains the same. Since there is only one instance of the `article` *content particle in the data, only the first line of the XML data from the example above changes. The result after execution of this primitive is*

to restore both the DTD and the XML data to its original form of Figures 1.1 and 1.2 as shown in Figure 3.10.

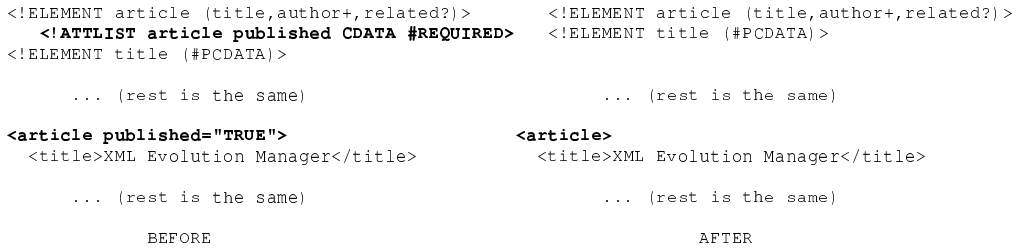


Figure 3.10: Results of destroyDTDAttr Primitive Operation

3.3.3 Changes to the XML Data

Primitive 11: *addDataAttr*

Syntax: `de.addDataAttr(String a, String av)`

Semantics: A data attribute instance da will be created with name a and value av, and will be added to the children sequence of the data element vertex de .

Preconditions: An attribute definition A for the attribute instance vertex da must exist in the DTD graph, i.e., $\exists A$ such that $typeOf(da) = A$. If the default type of the attribute definition node A is *required*, i.e., $label(A).DefType =$ `#REQUIRED`, then this attribute must already exist in the data, so the addDataAttr primitive is not valid for such an attribute. If the default type of the attribute definition node A is *fixed*, i.e., $label(A).DefType =$ `#FIXED`, then the value dv must be null since the fixed value is already specified in the DTD attribute definition A, and a fixed value may not be changed.

Resulting DTD Changes: This is an XML data change primitive operation. Therefore there are no resulting changes to the DTD graph, i.e., $G_2 = G_1$.

Resulting Data Changes: An instance da of the attribute named a will be added to the children sequence of the data element vertex de. If $av \neq \emptyset$, the value av will be assigned to the data attribute vertex da. Otherwise, if the default type of the DTD attribute definition

node A is *fixed*, i.e., $label(A).DefType$ = `#FIXED`, then the fixed value declared in the attribute definition, $label(A).DefVal$ will be assigned to the data attribute instance da. For each input XML data tree $T_{1i} \in \mathcal{T}_1$, we get a new tree T_{2i} = (V_{2i}, $children_{2i}$, $label_{2i}$) where V_{2i} = $V_{1i} \cup da$, $children_{2i}(de)$ = $children_{1i}(de)$ + da, and $label_{2i}(da)$ = `AttrNode`. $\forall v \in V_{1i} - de$, $children_{2i}(v)$ = $children_{1i}(v)$, and $\forall w \in V_{1i}$, $label_{2i}(w)$ = $label_{1i}(w)$.

Example 11 *To illustrate use of this primitive operation, we first add a new attribute definition called "primary" to the* `author` *element in the DTD to indicate whether an author is the primary author of an article or not, using* #IMPLIED *for the default type. We then use the addDataAttr primitive to assign values to the two authors of the article in the example. This operation is performed on an instance of an element in the data. To address such an instance, we use the XPath notation, as defined in [W3C99] as follows:*

```
author.addDTDAttr("primary", CDATA, IMPLIED, null);
author1 = findDataElement("article[1]/author[1]");
author1.addDataAttr("primary", TRUE);
author2 = findDataElement("article[1]/author[2]");
author2.addDataAttr("primary", FALSE);
```

Execution of these primitive operations first causes a new line to be added to the DTD for the `primary` *attribute in the* `author` *element definition. Then data instances of the attribute are added to the two* `author` *element instances in the XML data with appropriate values. The effect on the Article DTD of Figure 1.1 and the XML data of Figure 1.2 is shown in Figure 3.11.*

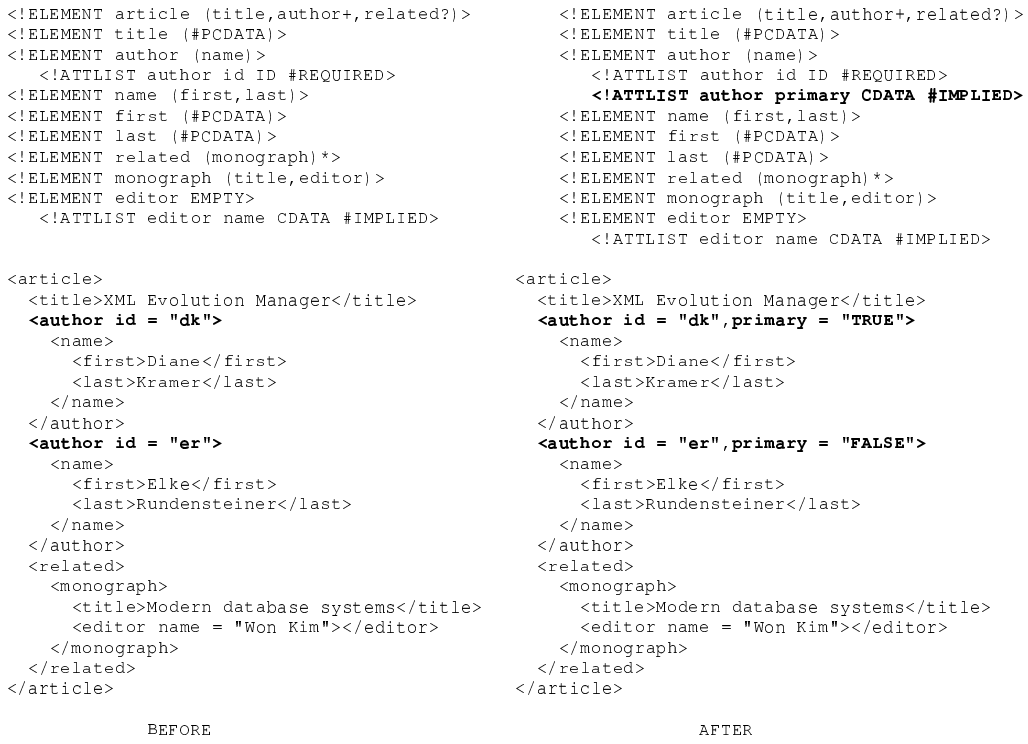


Figure 3.11: Results of addDataAttr Primitive Operation

Primitive 12: *destroyDataAttr*

Syntax: `de.destroyDataAttr(String a)`

Semantics: The data attribute instance da with name a will be removed from children sequence of the data element vertex de.

Preconditions: An attribute definition A for the attribute instance vertex da must exist in the DTD graph, i.e., $\exists A$, such that $typeOf(da) = A$. The default type of the attribute definition node A must not be *required*, i.e., $label(A).DefType \neq$ `#REQUIRED`, since a required attribute may not be removed. The data element vertex de must contain the attribute da named a in its children sequence, i.e., $da \in children(de)$.

Resulting DTD Changes: This is an XML data change primitive operation. Therefore there are no resulting changes to the DTD graph, i.e., $G_2 = G_1$.

Resulting Data Changes: The instance da of the attribute named a will be removed

from the children sequence of the data element vertex de. For each input XML data tree $T_{1i} \in \mathcal{T}_1$, we get a new tree T_{2i} = (V_{2i}, $children_{2i}$, $label_{2i}$) where $V_{2i} = V_{1i} - da$ and $children_{2i}(de)$ = $children_{1i}(de)$ - da. $\forall v \in V_{1i} - de$, $children_{2i}(v) = children_{1i}(v)$, and $\forall w \in V_{1i}$, $label_{2i}(w) = label_{1i}(w)$.

Example 12 *We illustrate use of this primitive operation by destroying the "primary" attribute introduced in Example 11 above, from the second instance of the* `author` *element as follows:*

```
author2 = findDataElement("article[1]/author[2]");
author2.destroyDataAttr("primary");
```

Execution of this primitive only changes the second instance of the `author` *element in the data. There are no changes to the DTD, and no other changes to the XML data from Example 11 above. The effect is shown in Figure 3.12.*

```
<author id = "er",primary = "FALSE">
  <name>
    <first>Elke</first>
    <last>Rundensteiner</last>
  </name>
</author>
```

BEFORE

```
<author id = "er">
  <name>
    <first>Elke</first>
    <last>Rundensteiner</last>
  </name>
</author>
```

AFTER

Figure 3.12: Results of destroyDataAttr Primitive Operation

Primitive 13: *addDataElement*

Syntax: `dp.addDataElement(ElemNode de, int pos)`

Semantics: Insert the data element instance de into the children sequence of the parent data element vertex dp at position pos.

Preconditions: An element definition node E for the vertex de must exist in the DTD graph, i.e., $\exists E$ such that $typeOf(de) = E$. An element definition node p for the parent vertex dp must also exist in the DTD graph, i.e., $\exists p$ such that $typeOf(dp) = p$. The element definition node E must be allowed in the children sequence of the parent node p at position pos, i.e., $childAt(p, pos) = E$.

Resulting DTD Changes: This is an XML data change primitive operation. Therefore there are no resulting changes to the DTD graph, i.e., $G_2 = G_1$.

Resulting Data Changes: The data element instance de will be added to the children sequence of the parent element vertex dp at position pos. For each input XML data tree $T_{1i} \in \mathcal{T}_1$, we get a new tree $T_{2i} = (V_{2i}, children_{2i}, label_{2i})$ where $V_{2i} = V_{1i} \cup de$, $children_{2i}(dp) = children_{1i}(dp) + (de, pos)$, and $label_{2i}(de) =$ `ElemNode`. $\forall v \in V_{1i} - dp$, $children_{2i}(v) = children_{1i}(v)$, and $\forall w \in V_{1i}$, $label_{2i}(w) = label_{1i}(w)$.

Example 13 *To illustrate use of this primitive, we first add the middle initial element to the DTD as was done above in Section 3.3.1. We then add a data instance of the middle initial subelement to the first instance of the* `author` *element as follows:*

```
document.createDTDElement("middle", PCDATA);
name.insertDTDElement("middle", 1, "?", null);
parent = findDataElement("article[1]/author[1]/name");
child = new ElemNode("middle", "S");
parent.addDataElement(child, 2);
```

Execution of these primitive operations has the effect of first creating the `middle` *DTD element definition, then inserting that into the parent* `name` *element definition, and finally adding an instance of the* `middle` *element to the data. The effect on the Article DTD and XML data of Figures 1.1 and 1.2 is shown in Figure 3.13.*

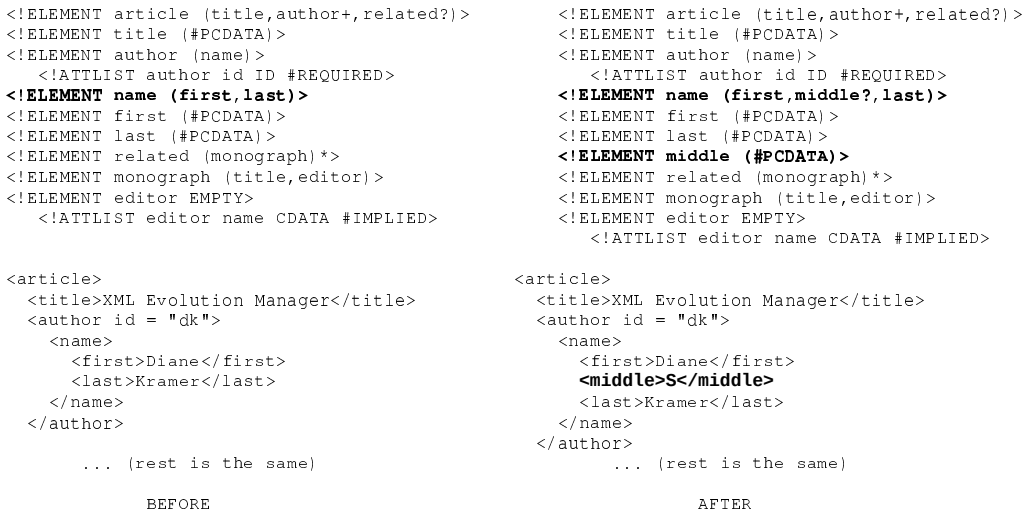


Figure 3.13: Results of addDataElement Primitive Operation

Primitive 14: *destroyDataElement*

Syntax: `dp.destroyDataElement(ElemNode de, int pos)`

Semantics: Remove the data element instance de from the children sequence of the parent data element vertex dp at position pos.

Preconditions: An element definition node E for the vertex de must exist in the DTD graph, i.e., $\exists E$ such that $typeOf(de) = E$. An element definition node p for the parent vertex dp must also exist in the DTD graph, i.e., $\exists p$ such that $typeOf(dp) = p$. The element definition node E must be an *optional* child subelement in the parent definition p, meaning E has either quantifier QMARK or quantifier STAR to be allowed to be removed.

Resulting DTD Changes: This is an XML data change primitive operation. Therefore there are no resulting changes to the DTD graph, i.e., $G_2 = G_1$.

Resulting Data Changes: The data element instance de will be removed from the children sequence of the parent element vertex dp at position pos. For each input XML data tree $T_{1i} \in \mathcal{T}_1$, we get a new tree $T_{2i} = (V_{2i}, children_{2i}, label_{2i})$ where $V_{2i} = V_{1i}$ - de and $children_{2i}(dp) = children_{1i}(dp)$ - (de, pos). $\forall v \in V_{1i} - dp$, $children_{2i}(v) = children_{1i}(v)$, and $\forall w \in V_{1i}$, $label_{2i}(w) = label_{1i}(w)$.

Example 14 *To illustrate use of this primitive, we remove the middle initial element which was added in Example 13 above as follows:*

```
parent = findDataElement("article[1]/author[1]/name");
parent.destroyDataElement("middle", 2);
```

Execution of these primitive operations causes no changes to the DTD, but has the effect of restoring the XML data from the previous example to its original form of Figure 1.2:

```
<article>                                    <article>
  <title>XML Evolution Manager</title>         <title>XML Evolution Manager</title>
  <author id = "dk">                           <author id = "dk">
    <name>                                       <name>
      <first>Diane</first>                         <first>Diane</first>
      <middle>S</middle>                           <last>Kramer</last>
      <last>Kramer</last>                        </name>
    </name>                                    </author>
  </author>
    ... (rest is the same)                      ... (rest is the same)

            BEFORE                                       AFTER
```

Figure 3.14: Results of destroyDataElement Primitive Operation

3.4 Completeness of DTD Change Operations

The taxonomy in Section 3.3 intuitively captures all changes needed to manipulate a DTD. We have taken care to define minimal semantics as well as a minimal set of primitives, i.e., no primitive defined in the taxonomy subsumes the functionality of another primitive defined in the taxonomy. In this section we show that this set of changes indeed provides for every possible type of DTD change (completeness criteria). The proof given here has its basis on the completeness proof for the evolution taxonomy of Orion [BKKK87].

With the DTD graph we focus primarily on manipulations of nodes and of the directed edges between parent and children nodes. Towards that end we define seven operations from those which we have defined for a DTD in Table 3.1 in Section 3.3, mapping our primitives to ones which correspond to the “essential schema changes” in the Orion taxonomy. We prove that every legal DTD graph operation is achievable using this set of seven operations. The proof is based on the concept of a single-rooted, directed acyclic

graph, from hereon referred to as a DAG, to which our DTD graph model conforms. The set of operations and its basic semantics for the DTD graph are given in Table 3.3. [1]

Notation	Operation	Description	Taxonomy Equivalent
op1	add-attribute	Adds new attribute to node	3.3.2.9
op2	delete-attribute	Deletes new attribute from node (element)	3.3.2.10
op3	remove-node-edge	Removes the edge from parent to node	3.3.2.4
op4	add-node-edge	Adds an edge between the parent and node	3.3.2.3
op5	create-nonattr-node	Creates a new node; default is no parent	3.3.1.1
op6	delete-nonattr-node	Deletes a leaf node	3.3.1.2
op7	add-root	Adds a given node to the root set R	3.3.1.1

Table 3.3: The DTD Graph Operations.

Lemma 1 *For any given DTD graph* G*, there is a finite sequence of* {op6} *that can reduce the DTD graph* G *to another DTD graph* G′ *with only one root node.*

Proof: It is apparent that if we repeatedly apply the operation op6 which removes a non-nested element node n, we can after a finite number of applications reduce any given DTD graph G to a new DTD graph G′ which only has the root node.

Lemma 2 *There is a finite sequence of operations* {op1, op4, op5, op7} *that generates any desired DTD graph* G *from a DTD graph* G′ *with only a root node.*

Proof: Let G be a DAG with a finite number of nodes, edges and roots and G′ be a DAG with only a root node, i.e., the document root is a single element. We can observe the following construction pattern, a finite sequence of operations listed above in Lemma 2, and transform the DAG G′ to become identical to the DAG G.

Traverse DAG G in a breadth-first order and perform the following for each node n visited:

- For every node n in G, add a corresponding node n′ to DAG G′ using the operation op5.

[1] We disregard at this point constraints such as #REQUIRED which are a semantic extension to the graph model that could be fairly easily addressed as an extension to the proofs sketched here.

- Add all attributes of n to the new node n′ in G′ using the operation op1.
- For each incoming edge into the node n add a corresponding incoming edge to the node n′ in G′ using the operation op4.
- Let R be the set of nodes directly descended from the root. If the node n exists in the root set R, add the equivalent node n′ to the root set R′ in G′ using the operation op7.

The resultant DAG G′ will be equivalent to the initial DAG G as they will have the same set of nodes N, edges E and roots R.

Theorem 1 *Given two arbitrary DTD graphs* G *and* G′*, there is a finite sequence* M *of* {op1, op4, op5, op7}*, such that* M(G) = G′.

Proof: We can prove this by first reducing the DTD graph G to an intermediate DTD graph G1 using Lemma 1. The DTD graph G1 can then be converted to the DAG G′ using Lemma 2.

Theorem 2 *Given two arbitrary DTD graphs* G *and* G′*, there is a finite sequence of DTD graph operations* N *of* {op1, op2, op3, op4, op5, op6, op7}*, such that* N(G) = G′.

Proof: The set of operations {op1, op4, op5, op7} is a subset of the operations {op1, op2, op3, op4, op5, op6, op7}. Hence the completeness of this set of operations is given from Theorem 1.

3.5 Soundness of Change Primitives

A taxonomy of XML and DTD change primitives is sound if the following properties hold true:

- Every operation on a well-formed input DTD graph produces a well-formed output DTD graph, and every operation on a well-formed input XML tree produces a well-formed output XML tree (well-formedness criteria).
- Every operation on a valid set of input XML trees produces a new valid set of output XML trees (validity criteria).
- Every operation on an input DTD graph which corresponds to a valid set of input XML trees produces a valid set of output XML trees which are consistent with the output DTD graph (consistency criteria).

A formal proof of soundness would be rather laborious, requiring proof steps to demonstrate that each of the above properties holds for each defined primitive. Instead, we therefore investigate individual primitive operations for each of the above properties to summarize the soundness proof.

3.5.1 Well-formedness

The soundness criteria under consideration here is to determine whether an operation applied to the input DTD graph or the input XML trees produces an output DTD graph or output XML trees respectively which syntactically conform to the XML language specification as defined in [W3C00]. We choose to look at the `changeQuant` primitive, an operation which makes a syntactic change to the DTD.

Prior to executing this primitive, we first ensure that the pre-conditions are satisfied. Among numerous pre-condition checked at the onset of this primitive operation, the one which ensures the well-formedness criteria is the one which checks the input QuantType q. According to the syntax specification in [W3C00], the possible values which are allowed in this context are $\{$`STAR` | `PLUS` | `QMARK` | `NONE`$\}$. Checking that this pre-condition is satisfied ensures that we will not introduce any notation into the DTD graph which is not syntactically permissible.

Once we have ensured that the pre-conditions are satisfied, we proceed to perform the appropriate operation on the DTD graph. In this case, we must first explore the semantics of the requested change. We find that there are four possibilities which will determine what changes are required to the DTD graph in executing this operation. We summarize these possibilities in Table 3.4.

Input Quantified	**Output Quantified**	**DTD Change Required**
TRUE	TRUE	Change quantifier node's type to q
TRUE	FALSE	Remove old quantifier node
FALSE	TRUE	Add new quantifier node
FALSE	FALSE	None

Table 3.4: Required DTD Changes for `changeQuant` Primitive Operation

The first column of Table 3.4 contains the options for the state of the input DTD element definition before execution of the `changeQuant` primitive, while the second column shows the requested state after the change is made. The third column indicates the action which is required to get from the input state to the output state. We assume that we start with a well-formed input DTD graph to begin with.

We have already determined via the pre-conditions that a change to the quantifier node's type to q will produce a well-formed output DTD graph. If we remove a quantifier node, we will still have a well-formed output DTD graph since a quantifier is not required on an element definition. If we add a new quantifier node, we will still have a well-formed output DTD graph since a quantifier is permissible on an element definition. Finally, if we make no changes to the DTD graph, we are guaranteed to produce a well-formed output DTD graph. Since Table 3.4 indicates all possible outcomes of this primitive operation, where each row in the table corresponds to a change which creates a well-formed output DTD graph from a well-formed input DTD graph, and the primitive operation takes precisely the action indicated in third column based on the states in the first two, we conclude

that the `changeQuant` operation maintains the well-formedness criteria.

3.5.2 Validity

The soundness criteria under consideration here is to determine whether an operation applied to the input XML trees produces an output set of XML trees which are still valid with respect to the associated DTD graph. We assume that the input set of XML trees is valid to begin with. We choose here to look at the `addDataElement` primitive, an operation which makes a change to an XML data tree.

Prior to executing this primitive, we first ensure that the pre-conditions are satisfied. These include: checking that a DTD element definition exists for the element instance being added, checking that a DTD element definition exists for the parent element instance being added to, and checking that the element instance being added is valid at the requested position within the parent element instance. By not allowing an element instance for which there is no corresponding DTD element definition to be added, we prevent producing an invalid output XML data tree. By not allowing an element instance to be added to a parent instance for which there is no corresponding DTD element definition, we again prevent producing an invalid output XML data tree. Finally, by not allowing a child instance to be added to a parent instance where such a child is not permissible, we prevent producing an invalid output XML data tree.

Once we have ensured that the pre-conditions are satisfied, we proceed to perform the appropriate operation on the XML tree. In this case, we add a data element instance to the parent element instance in the position indicated by the input parameters. Again, we have already determined via the pre-conditions that it is valid to insert this new element instance into the parent at the requested position. We therefore conclude that after the insertion of the child data element instance into the parent instance, we are left with a valid output XML tree.

3.5.3 Consistency

The soundness criteria under consideration here is to determine whether an operation applied to the input DTD graph also makes whatever changes are necessary to ensure that the corresponding XML data trees remain valid and consistent with respect to the output DTD graph. We choose to look at the `removeDTDElement` primitive, an operation which causes changes to both the DTD and the XML data.

Prior to executing this primitive, we first ensure that the pre-conditions are satisfied. These include: checking that the element definition (e) we are removing actually exists in the DTD, checking that the parent element definition from which we are removing e actually contains e as a subelement, and checking that e does not contain any children subelements of its own. We obviously could not remove a DTD element that does not exist, nor could we remove a child subelement from a parent which does not contain that child. Finally, removing an element which contains subelements of its own could potentially violate the consistency criteria.

Once we have ensured that the pre-conditions are satisfied, we proceed to perform the appropriate operation on the DTD graph. In this case, we remove the subelement e from the children sequence of the parent element definition. If we stopped at this point, we would have a well-formed DTD graph and well-formed XML trees, but the XML trees would no longer be consistent with the output DTD graph. We therefore continue at this point to make appropriate changes to the XML trees.

Once we have removed the DTD element definition for the node e from its parent, we must now remove all corresponding instances of the node e from the XML data trees in order to maintain consistency with the output DTD graph. To do this, we find all instances of the parent in the XML trees, and remove instances of the child element e from those parent instances. Assuming we had a valid and consistent set of input XML trees to begin with, and by ensuring that the DTD element definition for the node e did not have

any children subelements of its own, we determine that the only places in the XML data trees where instances of subelement e must be removed are those found within the parent instances. We therefore conclude that after removal of the children instances from the parent instances in the XML data, we are left with a valid set of output XML trees which are consistent with the output DTD graph.

3.5.4 Summary of Soundness

In the sections above we have taken various example primitive operations and explored their implications in terms of the three soundness properties. While we acknowledge that this summary does not formally and completely prove the soundness of our primitive taxonomy, we believe that such a proof would be possible were we to look at each operation individually with respect to the three soundness properties in a manner similar to that which we use for the examples above.

Prior to the execution of each primitive operation, we check that the pre-conditions are satisfied. Any DTD or XML constraints and invariants can be expressed in terms of pre-conditions, and checking these first ensures that an operation will not be performed under conditions which might lead to a violation of those constraints or invariants.

Definition 3 in Section 2.2 shows how we model the XML data in terms of a tree construct. Each primitive definition in Section 3.3 indicates what the effects of the primitive operation are in terms of this model. Since we begin with a valid XML tree which is consistent with the corresponding DTD and we could demonstrate one by one that all changes to the XML tree produce a valid XML tree as output which is still consistent with the corresponding DTD, we conclude that the XML data operations are sound.

Definition 6 in Section 2.4 shows how we model the DTD data in terms of a graph construct. Each primitive definition in Section 3.3 indicates what the effects of the primitive operation are in terms of this graph model. Since we begin with a valid DTD and we

could demonstrate one by one that all changes to the DTD graph produce a valid DTD graph as output, we conclude that the DTD change operations are sound.

Finally, the primitive definitions in Section 3.3 specify precisely when a change to a DTD also requires a change to the XML data in order to maintain consistency via post-conditions. Since any given change will either be rejected due to the pre-conditions not being satisfied, or will occur in both the DTD and the XML data when required, and since we could demonstrate one by one that all of our operations fulfill these requirements, we conclude that our taxonomy of combined DTD and XML change primitives is sound.

Chapter 4

XEM Prototype System Design and Implementation

4.1 Introduction

To verify the feasibility of our approach, we have realized the ideas presented in this thesis in a functioning prototype system for XML evolution management[1], called Exemplar. In this chapter we first give some general background upon which we base our implementation. Then we present our system design, including overall architecture, system dictionary and application classes. Next we discuss our mapping model, and finally provide some implementation details. In particular, we show how the primitive operations introduced in Section 3.3 were implemented in Exemplar.

In our background research for this thesis, we found some other projects underway to map DTDs and XML data to relational database structures [LMZ00, FK99, Koe99]. To distinguish our work, we therefore decided to use an Object Oriented (OO) approach for Exemplar. In our prototype implementation we use Excelon Inc.'s PSE Pro [Obj93], a

[1]The preliminary prototype system, ReWeb [RCC+00] has been demonstrated at ACM SIGMOD 2000.

lightweight object database system repository, as the underlying persistent storage system for DTDs and XML documents. We require that the DTDs with which the incoming XML documents comply be entered first into the system. PSE Pro's schema repository has been enhanced to not only manage traditional OO schemata but also DTDs as meta-data, since in an XML management system, a DTD serves the purpose of a schema. The DTD-OO schema mapper generates an OO schema according to the DTD meta-data. Then we load the XML documents into the just prepared schema. The mapping and loading details are given below. Comparison of the performance of using our primitives to achieve incremental change versus reloading from scratch can be found in Chapter 5.

4.2 Exemplar Architecture

Figure 4.1 depicts the architecture of the XML Evolution Management Prototype system (Exemplar), which provides the facilities to describe desired DTD and XML transformations via combining the change primitives. Exemplar utilizes functionality provided by the SERF system [CJR98b], which interacts directly with the database to store and access the Schema and Object repositories, and also provides the basis for schema evolution. The main modules of the Exemplar system architecture include the following:

- The DTD-Mapper parses the input DTD and interacts with the System Dictionary Manager, as described below in Section 4.3.
- The XML-Loader parses the input XML documents and interacts with the Application Classes Manager, as described below in Section 4.4.
- The XML-Dumper also interacts with the Application Classes Manager to extract the XML data stored in the database, and then it writes the results to a new XML file.

- The system management classes which interact with the SERF system include storage, retrieval and maintenance of System Dictionary and Application classes, in addition to providing the evolution primitive operations.

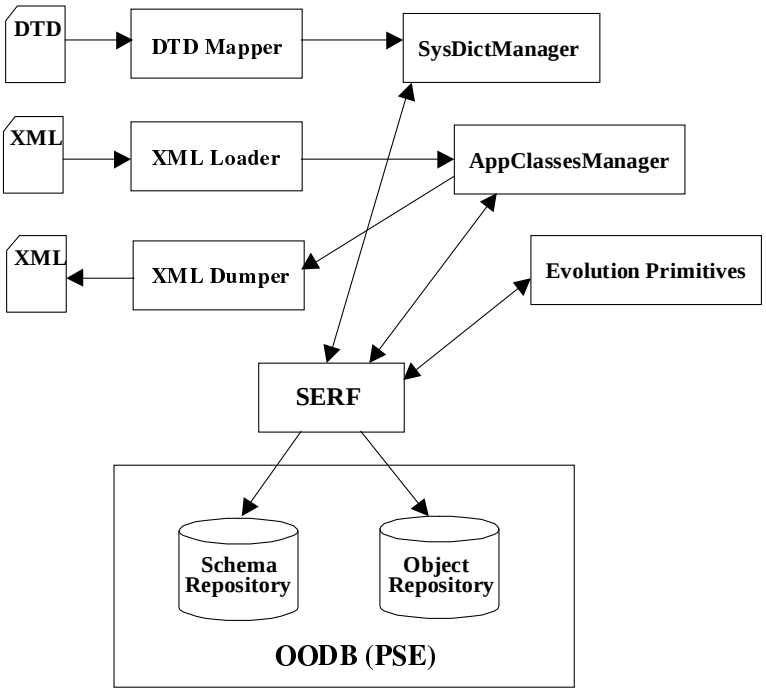


Figure 4.1: Architecture of Exemplar System

4.3 System Dictionary and the DTD-Mapper

The DTD-Mapper module is responsible for parsing the DTD, creating system dictionary objects that model the respective DTD semantics, and populating those objects with the meta-data found in the DTD. The DTD-mapper then generates appropriate application classes for each element definition, which are later instantiated by the XML-Loader class. (See Section 4.4 below.) Figure 4.2 illustrates the system dictionary class hierarchy.

The DTDNode is an abstract base class from which all other DTD classes inherit. The DocDef is responsible for document-wide concepts such as the unique DTD ID, the

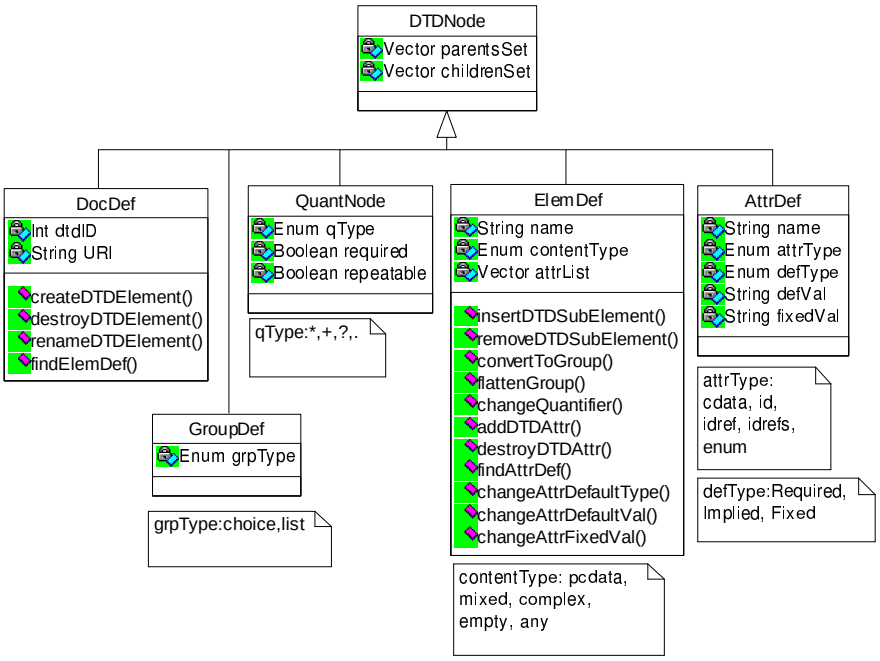


Figure 4.2: System Dictionary Class Hierarchy

URI for the DTD, and document-level methods that manage top-level element definitions. A GroupDef object is created for each nested group defined within the DTD element definitions, and QuantNodes are created whenever an element or group has quantifiers "*", "+", or "?". An ElemDef object is created for each element definition within the DTD. Similarly, an AttrDef object is created for each attribute definition. The permissible values for enumerated types are shown in the small boxes below the class diagrams above.

4.4 Application Classes and the XML-Loader

The XML-Loader module is responsible for parsing the XML document(s) which conform to a previously loaded DTD, and instantiating the application classes which were created by the DTD-Mapper. The XML-Loader then populates the application classes with data objects according to the XML document file(s). Figure 4.3 illustrates the pre-

defined application class hierarchy, and shows some sample application classes.

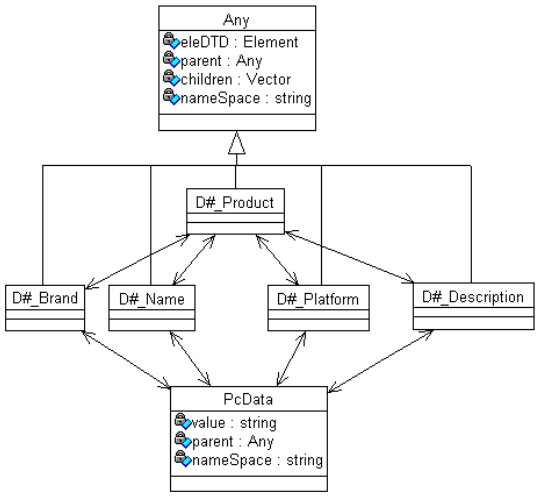


Figure 4.3: Application Classes Which Represent XML Data

Any is an abstract base class from which all application classes inherit. It contains a reference to the corresponding DTD element definition found in the system dictionary, a reference to the parent element, and a vector of children elements. The parent and children variables are used to keep track of relationships among elements. For example, subelements are stored as children of their parent element. In order to distinguish same-named elements which come from different DTDs, the application classes are assigned a DTD ID as part of their name. The element name as it is defined in the DTD is then appended to this ID. For example, if a "Product" element is defined in two different DTDs, the first might be named `D1_Product`, and the second `D2_Product`. Finally, the predefined PcData class is used to store the values of XML data elements.

4.5 Mapping Model

Table 4.1 shows how the content types found in the DTD are mapped to corresponding OO model representations in the system dictionary. Some constructs, such as Document

and Element, are represented by the various system dictionary objects described above, while others, such as constraints, are stored as member variables of those objects.

DTD Content Types	OO Model Representation
Document	Document Definition object
Element	Element Definition object
Element Quantifier	Quantifier object
Element Content Constraint	*contentType* member variable in Element object
Group	Group Definition object
Group Content Constraint	*grpType* member variable in Group object
Group Quantifier	Quantifier object
Attribute	Attribute Definition object
Attribute Default Constraint	*defaultType* member variable in Attribute object
Attribute Type Constraint	*attrType* member variable in Attribute object

Table 4.1: Mapping the DTD to System Dictionary Objects

Mapping from DTD and XML files into system dictionary and application classes proceeds as follows. First, the DTD is parsed by the DTD-Mapper, and instances of the system dictionary objects are created as indicated for the content types in Table 4.1 above. Then the DTD-Mapper creates the application classes: one Java source file for each element definition found in the DTD. On the application side, DTD attribute definitions are just mapped to member variables in these Java files. Then subelements are later stored in the children vector by the XML-Loader which instantiates and populates the application classes with the XML data.

We illustrate with an example. Below we again show the Article.dtd from Figure 1.1, along with the DTD graph from Figure 2.2 which models our internal representation of this DTD once it is processed by the DTD-Mapper. We then describe the system dictionary objects and application classes created by the DTD-Mapper. Finally, we indicate how the application classes are instantiated and populated by the XML-Loader.

```
<!ELEMENT article (title,author+,related?)>
<!ELEMENT title (#PCDATA)>
<!ELEMENT author (name)>
   <!ATTLIST author id ID #REQUIRED>
<!ELEMENT name (first,last)>
<!ELEMENT first (#PCDATA)>
<!ELEMENT last (#PCDATA)>
<!ELEMENT related (monograph)*>
<!ELEMENT monograph (title,editor)>
<!ELEMENT editor EMPTY>
   <!ATTLIST editor name CDATA #IMPLIED>
```

Figure 4.4: Contents of Article.dtd File, repeated here from Figure 1.1

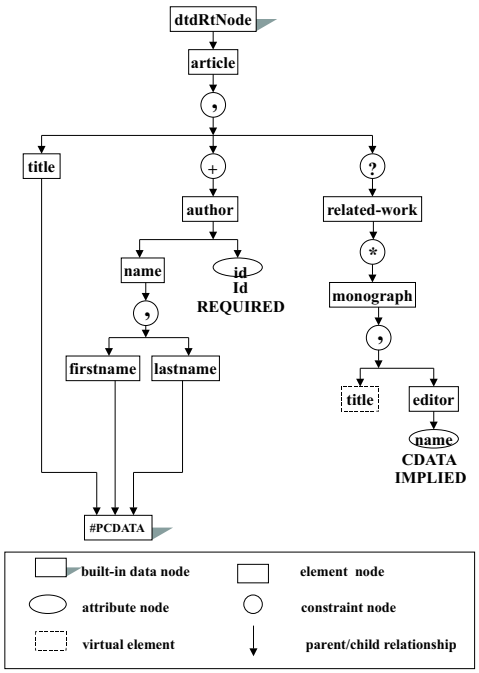


Figure 4.5: Graph Representation of Article.dtd, repeated here from Figure 2.2

4.5.1 Create System Dictionary Objects

First, a `DocDef` is created for the Article.dtd with a DTD ID of 1 (assuming this is the first DTD to be entered into our system), and a URI which indicates the location of the DTD file. Next, the DTD is parsed, and the system dictionary objects are created as indicated in Table 4.1. The results of this process are shown below.

1. `ElemDef` objects are created for the following element definitions in the DTD: article, title, author, name, first, last, related, monograph, and editor.
2. Element content constraints are stored as member variables in the `ElemDef` objects: `PCDATA` is the content constraint for elements title, first, and last; `COMPLEX` is the content constraint for elements article, author, name, related and monograph, meaning they contain subelements in their content; and `EMPTY` is the content constraint for element editor.

3. `AttrDef` objects are created for the two attribute definitions in the DTD: `id` (defined in the DTD as an attribute of the `author` element) and `name` (defined in the DTD as an attribute of the `editor` element).
4. Attribute default constraints are stored as member variables in the `AttrDef` objects: `REQUIRED` is the default constraint for the id attribute, and `IMPLIED` is the default constraint for the name attribute.
5. Attribute type constraints are also stored as member variables in the `AttrDef` objects: `ID` is the type constraint for the id attribute, and `CDATA` is the type constraint for the name attribute.
6. `GroupDef` objects are created for groups of more than one child subelement: we create one `GroupDef` each for the children of elements article, name, and monograph. There is no need to create `GroupDef` objects for groups of only one subelement, as would be the case for the children of elements author and related.
7. Group constraints are stored as member variables in the `GroupDef` objects: `LIST` is the constraint for all groups in this example.
8. `QuantNode` objects are created for each quantifier, in this case one for the "+" in `author+`, one for the "?" in `related?`, and one for the "*" in `(monograph)*`.

4.5.2 Create Application Classes

The next task accomplished by the DTD-Mapper is to create application class definitions for each element in the DTD. This is done by creating Java source files, named according to the element name in the DTD, prepended by the DTD ID, adding member variables for attributes where required, and then compiling the Java files to create the byte-codes. Each of these Java classes inherits from the pre-defined application class "Any". Table 4.2 shows the Java source files which get created by the DTD-Mapper when processing

the Article.dtd in our example, and the member variables (if any) associated with those Java files.

Java Source File Name	Member Variables
D1_article.java	none
D1_title.java	none
D1_author.java	name="id", type=String
D1_name.java	none
D1_first.java	none
D1_last.java	none
D1_related.java	none
D1_monograph.java	none
D1_editor.java	name="name", type=String

Table 4.2: Application Classes Created by DTD-Mapper

4.5.3 Instantiate and Populate Application Classes

At this point the DTD-Mapper has finished its job, and the XML-Loader takes over. It is the XML-Loader's responsibility to instantiate the application classes just created by the DTD-Mapper, and to populate them with the XML data. For our example, we again present the XML file from Figure 1.2 which corresponds to the Article.dtd in Figure 1.1, along with the XML tree from Figure 2.1 which models our internal representation of this XML data once it is processed by the XML-Loader.

```
<article>
  <title>XML Evolution Manager</title>
  <author id = "dk">
    <name>
      <first>Diane</first>
      <last>Kramer</last>
    </name>
  </author>
  <author id = "er">
    <name>
      <first>Elke</first>
      <last>Rundensteiner</last>
    </name>
  </author>
  <related>
    <monograph>
      <title>Modern Database Systems</title>
      <editor name = "Won Kim"></editor>
    </monograph>
  </related>
</article>
```

Figure 4.6: Contents of Sample.xml File, repeated here from Figure 1.2

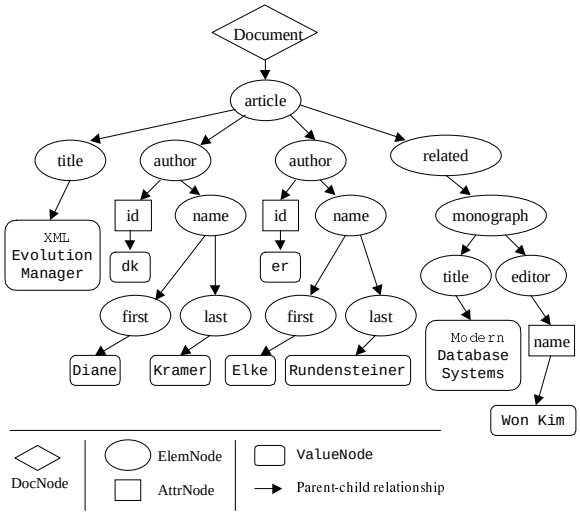


Figure 4.7: Tree Representation of Sample.xml, repeated here from Figure 2.1

To describe the objects created by the XML-Loader, we start with the leaf nodes at the bottom of the tree, and work our way up. First, six instances of the pre-defined application class “PcData” are created for the following text values, and the text is stored in the “value” member variables, one per instance:

1. XML Evolution Manager
2. Diane
3. Kramer
4. Elke
5. Rundensteiner
6. Modern Database Systems

Next, two instances of D1_first are created, and each is assigned a single child in its children vector: One for Diane, which gets assigned PcData instance number 2 above, and one for Elke, which gets assigned PcData instance number 4 above. Similarly, two instances of D1_last are created, and assigned instance numbers 3 and 5 above in their respective children vectors. Two instances of D1_title are created next, and assigned instance numbers 1 and 6 above in their respective children vectors. Then one instance of D1_editor is created, and the “name” member variable is assigned the String value “Won Kim”. Next, two instances of D1_name are created. The first of these is assigned the

two children, D1_first and D1_last, for Diane and Kramer. The second is assigned the two children, D1_first and D1_last, for Elke and Rundensteiner. Next, one instance of D1_monograph is created, and the instance of D1_title for number 6 above, plus the instance of D1_editor are assigned to its children vector. Then two instances of D1_author are created. The first of these is assigned the String value “dk” to its “id” member variable, and the first instance of D1_name to its children vector. The second instance of D1_author gets the String value “er” assigned to its “id” member variable, and the second instance of D1_name to its children vector. Next, an instance of D1_related is created, and the D1_monograph instance is assigned to its children vector. Finally, one instance of D1_article is created, and assigned to its children vector are the instance of D1_title, the two instances of D1_author, and the instance of D1_related.

4.6 Implementation Details

4.6.1 Development Environment

Goals for the Exemplar system include to provide Object-Oriented storage, manipulation and retrieval of DTD and XML data, and to provide a platform-independent execution environment. We therefore chose Excelon Inc’s PSE Pro [Obj93] for our database repository, and the Java 2 programming language (JDK 1.3 from Sun Microsystems [Sun00]) for our implementation. For the XML parser, we used XML4J/Xerces, version 3.0.1 (IBM’s XML parser for Java [IBM00b]). Development was done on the Microsoft Windows NT platform. In total, the implementation contains 54 Java class files, and over 10,000 lines of code.

4.6.2 SERF System

Excelon's PSE Pro is a rudimentary Java object store, which does not contain many of the evolution facilities provided by traditional database management systems. On top of PSE we have a base evolution support layer called SERF [CJR98b], which provides more powerful mechanisms for Object-Oriented storage, maintenance and retrieval, including schema evolution. SERF models OO classes by means of an object called `MetaClass`, which we utilize in Exemplar to represent an XML element definition. An `Attribute` is also represented in SERF, originally designed to model member variables in OO, and used in Exemplar to represent an XML attribute definition. Each instance of `MetaClass` contains a Java vector of attributes.

When an instance of an application class object is created in SERF (for example, when we create an instance of D1_author, D1_title, etc.), that instance is added to the *extent* of the corresponding MetaClass. This mechanism is used during schema evolution to determine the set of objects which are affected by a change to an OO class (or in our case, a change to an XML element definition). The schema evolution functions provided by SERF include methods such as add_attribute and delete_attribute, which perform a complicated set of activities in order to maintain consistency between the application class objects and the schema repository. For example, the following steps are required in order to execute an add_attribute transaction on a Java class "A":

1. Create a new `Attribute` object.
2. Update the `MetaClass` object for A to reflect the newly added attribute. This entails the simple addition of a new object (attribute) to a collection (vector) in Java.
3. Create a new temporary Java source file, A' , containing all of the code from the original class file A, plus the additional new attribute.

4. Compile and post-process the temporary Java file, A′. Post-processing is a step required by PSE, which annotates the compiled class file with mechanisms used internally by the ObjectStore database.
5. For each instance of class A, create a new instance of class A′, copying the data from the object of type A into the new object of type A′. During this step the newly created objects are added to the extent of A′.
6. Swap the object identifiers (OID's) for each pair of objects: original instance of A and corresponding newly created instance of A′. This allows references, which used to point to type A objects, to now refer to the new type A′ objects.
7. Delete the old objects of type A, removing them from the extent of A, and delete the old class file A. After completion of this step, the database is in a consistent state with the newly added attribute, but the class file has the temporary name A′, and the objects are of type A′.
8. Create a new Java file called A, containing all of the code from class file A′.
9. Compile and post-process the newly defined Java file A.
10. For each object in the extent of class A′, create an instance of the new class A, copying the data from the object of type A′ into the new object of type A. During this step the newly created objects are added to the extent of A.
11. Swap the OID's for each pair of objects: temporary instance of A′ and newly created instance of A.
12. Delete the temporary objects of type A′, removing them from the extent of A′, and delete the temporary class file A′. After completion of this step, the database is in a consistent state with the newly added attribute: the class file has the correct name A, and the objects are of the correct type.

4.6.3 Missing Functionality

Although Exemplar requires all of the above functionality to be in place in order to properly perform the desired transformations on DTD and XML data, some of the steps above were not implemented in SERF due to a complication in the Java Virtual Machine (JVM), and had to be filled in by the developers of Exemplar. To be precise, steps 1 through 5 were implemented in SERF, providing the functionality for in-memory transformations only, leaving the name of the class file and the object types in an inconsistent state. The complication arose at the completion of step 9, because at this point there are two distinct class files defined with the same name: the original class file called A, and the newly defined class file with the additional attribute, also called A. Help was elicited from the producers of PSE [Obj99] to implement the underlying functionality required to swap OID's in the database. But this functionality was not fully integrated into the SERF system, nor tested, because of the above mentioned difficulty in the JVM.

A theoretical solution to the JVM problem was proposed in [LB98], work which describes dynamic class loading in Java. The paper provides a solution via a custom class loader, which can load in a newly defined class with a pre-existing name. Using this method, a Java class can no longer simply be referred to by its name, but must also be qualified by its class loader. This solution was implemented in Exemplar [KSC+01]. Having this functionality in place, the SERF system could then be augmented to include the swapping of OID's, completing the required functionality for schema evolution.

4.6.4 Primitive Operations

The following list of primitives were implemented in Exemplar:

1. **Changes to the Document:**
   - createDTDElement
   - destroyDTDElement

- renameDTDElement

2. **Changes to DTD Element:**
   - insertDTDSubElement
   - removeDTDSubElement
   - changeQuantifier
3. **Changes to DTD Group:**
   - changeQuantifier
   - convertToGroup
   - flattenGroup
4. **Changes to DTD Attribute:**
   - addDTDAttr
   - destroyDTDAttr
   - changeAttrDefaultType
   - changeAttrDefaultVal
   - changeAttrFixedVal
5. **Changes to XML data:**
   - changeAttribute
   - addElement
   - destroyElement
   - changeElement

This list differs from the primitives described in Table 3.1 in the following ways:

- One goal in our original design of DTD and XML primitives was for the set to be minimal, meaning no overlap of functionality among the operations. During our implementation, however, we chose to remove this restriction and instead attempt to achieve a set of primitives which are easy to use. We therefore added some primitives which allow changes to be made to existing element and attribute definitions in the DTD, as well as allowing changes to existing data elements.

For example, in the original set of primitives, we provide createDTDElement and destroyDTDElement. These two primitives combined allow for any desired changes to element definitions in the DTD. In our implementation, however, we additionally supply a renameDTDElement primitive, which provides the combined functionality of removing an element using destroyDTDElement and adding the same element with a different name using createDTDElement. The renameDTDElement primitive therefore allows for more ease of use by combining the two operations into one method call.

- The original list of primitives in Table 3.1 includes one method called changeQuant for changing the quantifier of an element, and another method called changeGroupQuant for changing the quantifier of a group. Both of these two primitives were implemented using a single method called changeQuantifier for two reasons. One, it was determined that much of the functionality is the same, and two, it is not difficult to determine inside the method which of the two types (element or group) we are dealing with.

- The original list of primitives includes two data change methods called addDataAttr and destroyDataAttr. Since an attribute is modeled by a member variable of a Java class in our Exemplar system, it is not possible to add or remove a data instance of an attribute. Adding or removing an attribute is effectively a schema evolution operation, as described in Section 4.6.2. Therefore we have only implemented the changeAttribute primitive, which changes the value of a data instance of an attribute. This way it can be used to simulate the removal an instance of an attribute which is not required by simply setting its value to null.

4.6.5 Indexing Algorithm

Of the many different algorithms used to implement Exemplar, one in particular deserves mention. During the design phase of the evolution primitives, we knew that we would need to refer to the subelements contained in a DTD element definition by position. This can be seen in Table 3.1, where we refer to various subelements by position, for example, in the insertDTDSubElement primitive. When it came to implementing these primitives, we found that a simple integer index would be insufficient, since element definitions can be nested within groups, and subelements can be repeated within a single definition. Additionally, when it comes to an insert operation, we need a way to distinguish between "insert before" and "insert after". Plus, we need to refer to a nested group by position, in addition to referring to a single element, in order to accomplish the flattenGroup primitive, for example. We therefore devised the following mechanism for referring to "content particles" (either an element or a group) which may appear in an element definition.

An index is represented as a linked list of integers, where the length of the list specifies the depth of the index in the DTD graph (the number of nested groups). The number at each level in the linked list specifies the ith child at the corresponding level in the DTD graph. An index of 0 at the last level means "insert before"; any other number means "insert after". To illustrate, we use the following original DTD element definition: `(a, (b, c, (d, e)))`, and the insertDTDSubelement primitive. Table 4.3 shows the format of our indexing notation in the first column, and the result of inserting a DTD subelement into the above element definition using that index in the second column. The dashes (-) in the index notation indicate the links in the linked list. In other words, an index with notation 2-3-1 represents three integers in a linked list, where the first integer is 2, linked to the second integer, 3, followed by a link to the final integer, 1.

Index	DTD definition after inserting element "x"
0	(x, a, (b, c, (d, e)))
1	(a, x, (b, c, (d, e)))
2-0	(a, (x, b, c, (d, e)))
2-1	(a, (b, x, c, (d, e)))
2-2	(a, (b, c, x, (d, e)))
2-3-0	(a, (b, c, (x, d, e)))
2-3-1	(a, (b, c, (d, x, e)))
2-3-2	(a, (b, c, (d, e, x)))
2-4	(a, (b, c, (d, e), x))
2	(a, (b, c, (d, e)), x)

Table 4.3: Indexing a Content Particle in a DTD Element Definition

It is important to note that the indices discussed above are *only* used as parameters to the method calls of the evolution primitives, and we do *not* store indices in the element definitions themselves. If we did, this would introduce the complication of having to re-index subelements when one is added or removed. Rather, we store subelements in the `children` vector of the parent element definition. Therefore, when we add or remove a subelement, the indices are automatically maintained internally by the Java vector class.

Chapter 5

Experiments

5.1 Experimental Setup

5.1.1 Introduction

Once the Exemplar implementation was complete, experiments were carried out to gauge the relative efficiency of the primitive operations. The measure under consideration was the time to complete the various operations. In Java, the system call currentTimeMillis() was used before and after calls to the primitive operations in order to determine how long a particular operation takes. Each experiment was run ten times, and the results we present are the averages of the ten runs. Since some simple operations took less than one millisecond, some measurements are approximate for small numbers. However, we knew of no other method which would produce more accurate results.

The experimental results presented here come from our Exemplar system, and consequently have performance characteristics specific to the choices made during our design and implementation. For example, we chose an object-oriented approach, so our mapping model is quite distinct from one which might have been implemented on top of a relational database. Our specific choices for using the Java programming environment

and other third-party tools also play a significant role in the results we achieved when experimenting with Exemplar.

Due to the nature of PSE, the underlying database system, once a change has been made to data in memory, it is necessary to "commit" the transaction. This has the effect of writing the changes to disk, saving them in more permanent storage. While implementing the XEM primitives, a decision was made not to include the commit operation within the primitive itself in order to make the primitives more database-independent. This means that the caller is responsible for starting a transaction before invoking a primitive, and committing the transaction afterwards.

All primitive operations return a boolean result, allowing the caller to determine whether the operation was successful. If any error occurs during the primitive execution, in addition to returning a boolean value of false, an exception is raised, indicating precisely what went wrong. The decision not to include the commit inside a primitive operation also provides more flexibility to the caller, since it allows one to "bundle" multiple primitive operations into a single transaction. Since the time to commit a transaction is dependent on the underlying database system, and not under the control of the Exemplar developers, the experimental results do not include the time to commit a transaction. In this way it was possible to examine purely the time to execute an evolution operation.

5.1.2 Execution Platform

All experiments were performed on the same machine in order to make proper comparisons. The execution platform is Microsoft Windows NT Enterprise Server Edition, version 4.0, with service pack 6. The processor in the machine is an Intel Pentium II, with an operating speed of 433 MHz. The amount of memory in the machine is 128 Megabytes. Although it is not possible to determine at all times all of the processes running on the machine due to system services and operating system activities that run in the

background, an attempt was made to minimize other processes running on the machine while the experiments were executing. One step that was taken to ensure this was to close all applications during the execution of the experiments, with the exception of the DOS command window used to run the experiments.

5.1.3 Data Set Statistics

While testing the time that various primitive operations take, the primary variables which can be altered for experimental purposes include the following:

- The number of element and/or attribute definitions in a DTD
- The level of nesting of subelements in the element definitions
- Which element or attribute to perform an operation on
- Which primitive operation to perform (schema or data changes, for example)
- The number of data elements in an XML file
- The number of XML files processed

In order to run the experiments it was necessary to have at least one DTD and preferably many XML files conforming to that DTD to work with. In preparing for the experiments, one option considered was to manually create a synthetic DTD and some XML files from scratch. But it was determined that a better option would be to find some "real life" data files to work with. We thus selected the set of Shakespeare's plays [Bos] for our experiments. Some statistics about the Shakespeare files are as follows:

- 1 DTD with 21 element definitions
- 37 XML data files, one play per file
- Smallest data file is 141,345 bytes long, and contains 3133 Elements

- Largest data file is 288,735 bytes long, and contains 6600 Elements
- Average data file is 213,449 bytes long, and contains 4840 Elements.

Since the original Shakespeare DTD did not contain any attribute definitions, in order to test our primitives that deal with attributes, we simply had to add some attributes first. Once added, other manipulation operations became possible. All of the experiments described below were executed on this set of Shakespeare XML data files and their corresponding DTD.

5.2 Experimental Results

Below we show the results obtained from our experiments run on the Exemplar system. For each experiment we plot the total execution times of various operations under consideration. We also analyze the results in terms of the number of objects in the system which are affected by an operation. In order to show the execution times in detail, some of the results are broken out into separate charts with different time scales (seconds vs. milliseconds).

5.2.1 Exemplar System Initialization

The purpose of the first experiment was to examine the Exemplar system initialization. We used a fixed DTD and varied the amount of XML data to load. Eight different tests were run, each time increasing the number of XML data files processed, and each test was run ten times to get an accurate measure. The results presented are the averages of the ten runs. We measured the time to map the DTD elements to system dictionary classes, plus the time to load the XML data, plus the time to dump out the XML data. Also included in the measurements is the time to initialize and shut down the database. The first two charts

below show the varying amounts of time to accomplish these tasks, separated into two different charts because they are in different time scales. The third chart shows the total execution time for all of the tasks combined, while the fourth chart compares the amount of time to load versus the time to dump on a per-element basis.

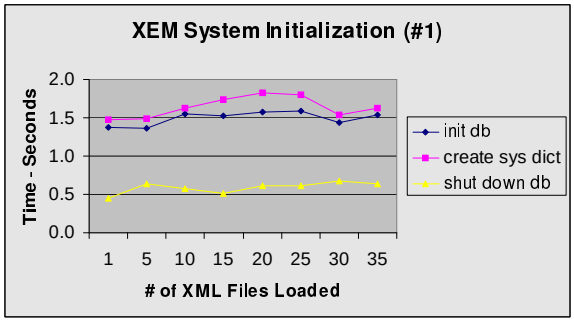


Figure 5.1: Low End Times for System Initialization

Figure 5.1 shows the fixed costs associated with initializing the database, creating the system dictionary classes, and then shutting down the database. Although they are not strictly straight lines, we consider these to be fixed costs because they do not vary by much. If we had included these times in Figure 5.2, the next chart below, they would indeed appear as straight lines relative to other higher costs, and they would all overlap each other at the bottom of the chart. We separate them out here in order to "zoom in" and see the detail of the results. Initializing and shutting down the database are understandably fixed costs. In this experiment, creating the system dictionary classes is also a fixed cost because we use the same single DTD for each test. Since all of the XML files conform to this DTD, each test takes roughly the same amount of time to create the system dictionary classes.

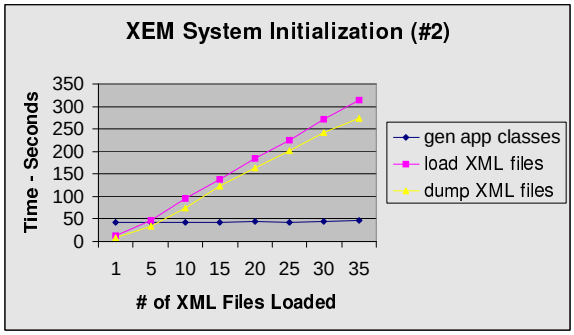


Figure 5.2: High End Times for System Initialization

Figure 5.2 shows the fixed time it takes to generate the application classes, and the increasing times to load and dump out the XML files. Generation of application classes is a fixed cost in this experiment, again because we use the same single DTD for each test. This fixed cost is included in this chart rather than the previous chart because the time scale is considerably different: close to 50 seconds, as opposed to one or two seconds. As expected, the time to load and dump out the XML data increases as the amount of XML data increases.

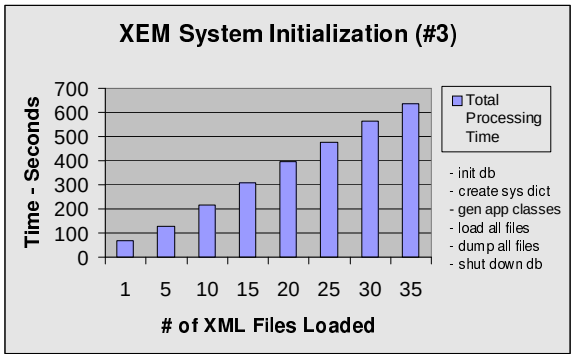


Figure 5.3: Total Times for System Initialization

Figure 5.3 shows the combined times to initialize the Exemplar system, over varying amounts of XML data. The chart includes the time to initialize and shut down the database, the time to create system dictionary classes and generate application classes, plus the time to load and dump the XML data. This chart provides an overall picture of the costs associated with Exemplar system initialization.

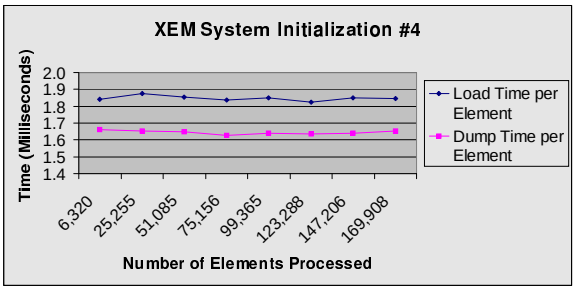


Figure 5.4: System Initialization Time per Element

Figure 5.4 analyzes the amount of time required to load and dump the XML data on a per-element basis. We showed in Figure 5.2 that the total amount of time to load or dump XML documents is dependent on the amount of data we are processing. As expected, the time increases as the amount of data increases. This chart, however, shows that the load and dump times are actually fixed, when viewed relative to each element. This chart also has a different time scale from the other charts in this experiment. The previous three charts plot time in seconds, whereas this one plots time in milliseconds in order to show the results in more detail.

5.2.2 Compare Two Schema Change Operations

The purpose of the second experiment was to compare the execution times of two different schema change operations. We chose to compare the insertDTDSubElement and addDTDAttr primitives because we feel these operations are likely to be commonly desired by users of an XML evolution management system. In this section we first discuss the differences between the two operations in terms of the specific implementation details. We then show the effects of each of these operations separately. Finally, we compare the two operations in terms of the number of objects affected and the average execution times per element. Since we chose similar data to operate on in each case, the percentage of data affected by each operation is the same. Approximately 17.5% of the total amount of

data loaded is affected on average by the execution of each primitive operation.

Both the insertDTDSubElement and addDTDAttr primitives operate on the DTD. Thus in XML context, they are both schema changes. As is often the case with a schema change, both operations require an "implied" data change, described in more detail below. On the surface, the operations appear to be similar. However, due to our implementation, what happens in each case is quite distinct.

The first operation, insertDTDSubElement, requires a simple change to the structure of the DTD: an existing element is added to the children of some parent element definition. The children vector itself does not change, only the contents change. This operation also implies a data change: for any instance of that parent element in the data, an instance of the child must also be created and inserted.

The second operation, addDTDAttr, also requires a change to the structure of the DTD, but this one is not so simple. As described in Section 4.6.2, when a new attribute definition is created and added to some element definition, this requires making a change to the Java file which represents that element. Once a change to a Java file is introduced, the process becomes complicated by the need to create temporary files, copy objects, swap OID's, etc. Hence this second primitive operation is expected to take more time than the first. This expectation is indeed verified by the experiments, as shown in the charts below.

Figure 5.5 shows the initial results of testing the insertDTDSubElement primitive, while Figure 5.6 shows those of the addDTDAttr primitive. As was done in the first experiment involving system initialization, eight different tests were run for each primitive, increasing the number of XML data files processed, and again, each test was run ten times for accuracy. Both charts in Figures 5.5 and 5.6 compare the total time to load all of the XML data from scratch against the time to execute one of the two primitives. It is clear from these two that the addDTDAttr operation takes longer than the insertDTDSubelement operation.

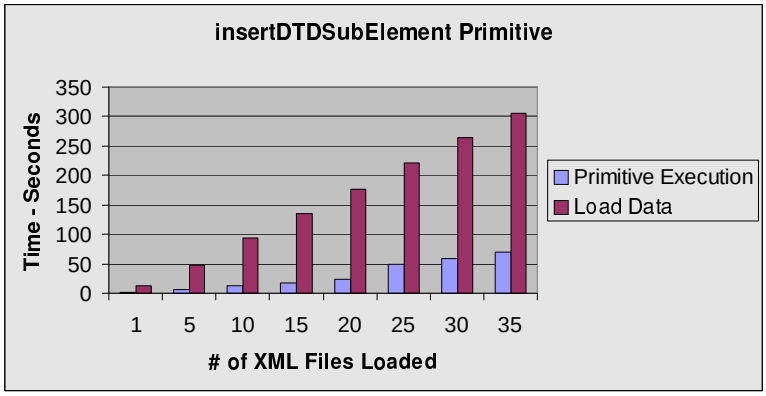


Figure 5.5: Executing Incremental Data Set Updates Using insertDTDSubelement Vs. Complete Reload of Data

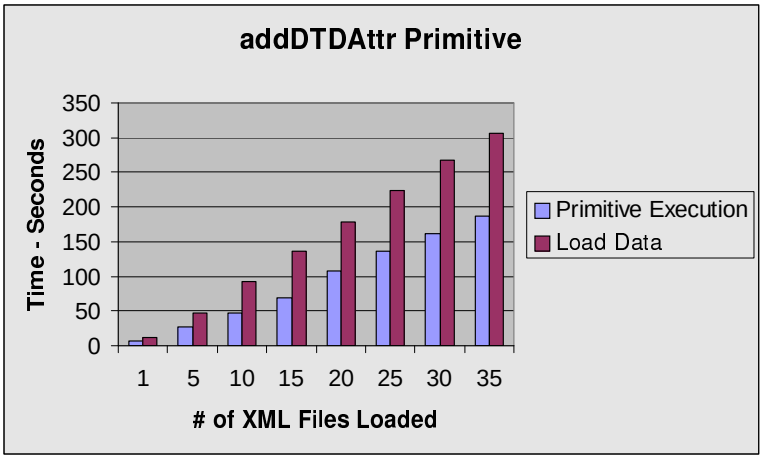


Figure 5.6: Executing Incremental Data Set Updates Using addDTDAttr Vs. Complete Reload of Data

Due to the precise details of the operations chosen for these tests as described below, the number of XML Element objects affected by the execution of the two primitives is the same. In the first test we insert a subelement into the parent SPEECH element, while in the second test we add an attribute to the same parent SPEECH element. So the number of occurrences of the objects affected in the data is the same. However, the total number of objects in the data files themselves is significantly higher, because not every element in the data files is a SPEECH element. Therefore, below we examine the impact of the primitive operations on a per-element basis.

Figure 5.7 compares the number of objects in the data set (and here reloaded from scratch) with the number of objects affected by the operation of the primitives. The first XML file contains 6,320 element objects, each of which is counted in the load time. But the primitive operations only affect 1,174 objects, the number of SPEECH elements in the data file. The first five XML data files combined contain 25,255 objects, but the primitive operations only affect 4,633 objects, and so on. We look at these numbers in preparation for the next chart, Figure 5.8, where we compare the average execution times of the primitive operations vs. the average load time on a per-element basis.

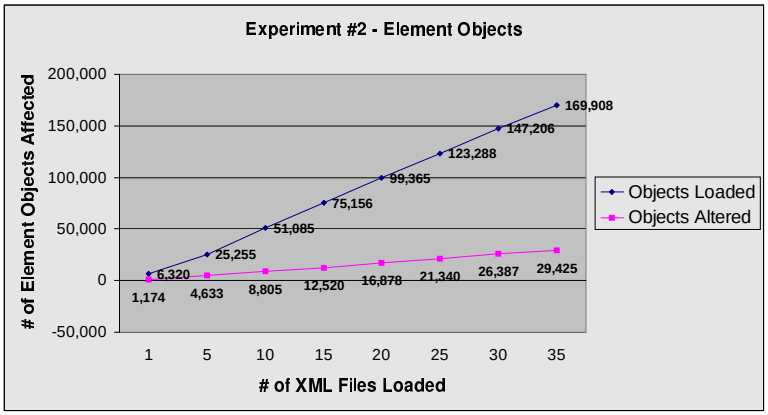


Figure 5.7: Number of Objects Loaded Vs. Number of Objects Changed

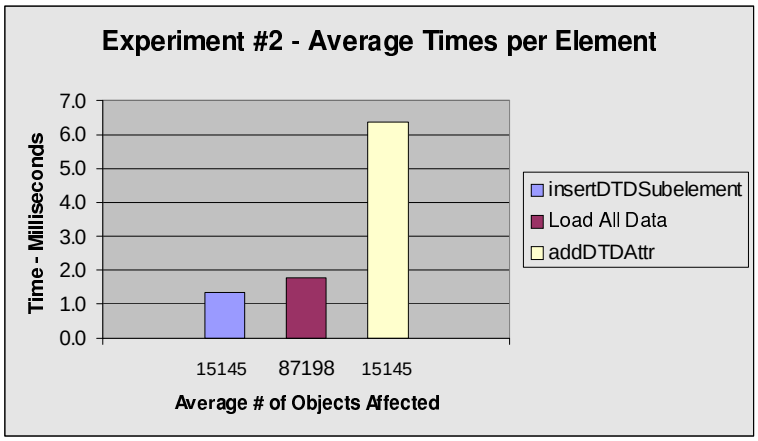


Figure 5.8: Compare Average Load and Primitive Execution Times per Element

Figure 5.8 analyzes the impact of the two primitive operations on a per-element basis,

and compares this result with the average time to load all of the elements from the data set. The numbers across the bottom of the chart along the X axis show the average number of objects affected in each case. Here we sum the numbers from the lines plotted in the chart of Figure 5.7, and divide the sums by 8 to come up with 15,145 and 87,198, the average number of objects affected by the primitives vs. the average number of objects loaded respectively. The numbers along the Y axis indicate the execution times in milliseconds, and we determine the height of each bar by similarly averaging the load and primitive execution times per element. We show averages in this chart rather than individual times for each test because we determined that the cost in terms of execution time per object is independent from the number of objects in the data set. From these numbers we also calculate the percentage of objects affected by the primitive operations out of the total number of data elements, which is approximately 17.5%.

From the chart in Figure 5.8 it can be seen that the first primitive, insertDTDSubelement, is more efficient than reloading the data from scratch, as it takes less time per element than loading does. But the addDTDAttr primitive takes too much time per element to be efficient when compared to how long it takes to reload the same data. Therefore it is possible to conclude that if the user chooses to add or remove attributes, s/he may be better off editing the DTD and XML files manually and reloading the data from scratch. However, this analysis does not consider the time for the user to make manual edits, and there is still an argument to be made for the accuracy of automation. Even though the Exemplar system is not terribly efficient when it comes to adding/removing attributes, a single primitive method call will make the same change to potentially thousands of elements, while a human attempting to do this manually is more prone to making mistakes.

5.2.3 Compare Two Data Change Operations

Now that we have looked at the Exemplar system initialization and examined some schema updates, we next investigate some pure data updates. In this experiment, rather than changing the number of files processed, we change the number of operations performed. These tests were all run on a fixed number of data files (five). Ten different tests were run, each time increasing the number of operations performed, and each test was run ten times to get an accurate measure. The results presented are the averages of the ten runs. The first chart below, Figure 5.9, looks at the addElement primitive, while the second chart, Figure 5.10, investigates the destroyElement primitive. The final chart for this experiment examines the time to execute each of these two operations on a per-element basis.

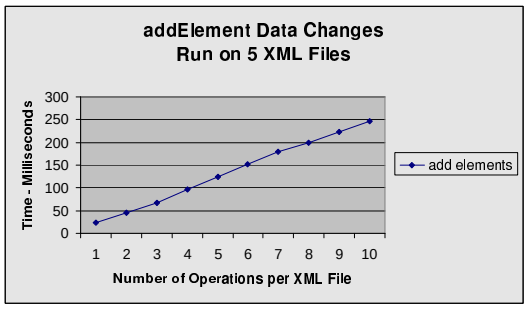


Figure 5.9: Time to Execute addElement Primitive

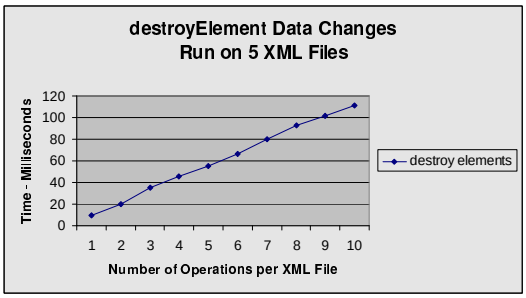


Figure 5.10: Time to Execute destroyElement Primitive

As can be seen in Figures 5.9 and 5.10 based on the time scales along the Y axes, the destroyElement primitive is more efficient than the addElement, although what happens in each case is nearly identical. An analysis of these results determined that the difference comes from the underlying structure storing the data elements. We use a Java Vector to store children subelements. In the case of addElement, the greatest amount of time is spent on the Java call `insertElementAt(Object obj, int index)`, while in the case of destroyElement, the dominant amount of time is spent on the Java call `removeElementAt(int index)`. Both of these method calls operate on an instance

of a Java Vector, specifically, the `children` Vector in class Any. Although it is unknown precisely why removal is more efficient than insertion, one guess is that an insertion may cause more memory to be allocated as the size of the Vector grows, whereas removal does not actually reclaim the freed memory but rather garbage collection will occur at a delayed time.

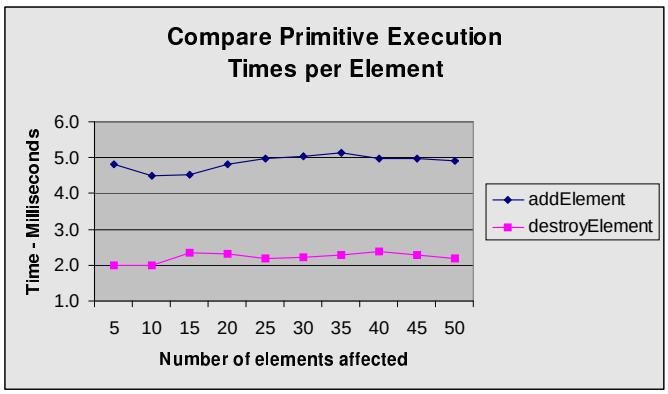


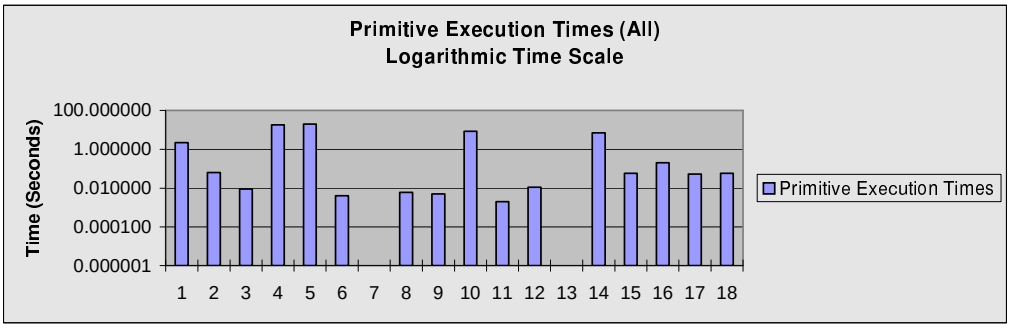
Figure 5.11: Time to Execute addElement Vs. destroyElement

Figure 5.11 examines the data change primitives on a per-element basis. Again, it can be seen from this chart that the destroyElement primitive is more efficient than the addElement (approximately 2 milliseconds as opposed to 5). However, as expected, the time cost for each primitive is fixed, relative to the number of objects affected.

5.2.4 Explore Time Efficiency of Primitives

The final experiment for this thesis examines each of the evolution primitives individually. The purpose of this experiment was to exercise all of the primitive operations to ensure correct operation, and to compare their relative efficiencies. This experiment was run on a fixed number of XML data files (fifteen), and each operation was run ten times for accuracy. The results below show the averages of the ten runs for each operation. Due to space limitations, we cannot show the XML files which resulted after the execution of each primitive to illustrate that the changes were indeed correct. But the developers of

Exemplar conscientiously reviewed the output files between each evolution operation to verify successful execution and correct results.



ID	Primitive Name	Time	ID	Primitive Name	Time
1	createDTDElement	2.181	10	addDTDAttr	8.421
2	destroyDTDElement	0.063	11	changeAttrDefaultVal	0.002
3	renameDTDElement	0.009	12	changeAttrDefaultType	0.011
4	insertDTDSubElement	0.141	13	changeAttrFixedVal	0.0
5	removeDTDSubElement	0.122	14	destroyDTDAttr	7.014
6	changeQuantifier (Element)	0.004	15	changeAttribute	0.057
7	changeQuantifier (Group)	0.0	16	addElement	0.204
8	convertToGroup	0.006	17	destroyElement	0.052
9	flattenGroup	0.005	18	changeElement	0.057

Figure 5.12: Execution Times for Each Primitive Operation

Figure 5.12 shows the results of this experiment. The table beneath the chart shows the primitive operations that correspond to the ID numbers along the X axis of the chart, and the individual execution times in seconds. The chart uses a logarithmic scale in order to show all of the execution times in a single figure. If we had used a linear scale, some of the results would not be visible. Two of the primitives in the chart, `changeQuantifier (Group)` and `changeAttrFixedVal`, took less than one millisecond to run. The results, therefore, for these two operations returned an execution time of zero. It is unknown precisely how long these operations actually took, since the measuring mechanism is not accurate enough to measure times of less than one millisecond.

The intention of this experiment was not to stress the Exemplar system by choosing operations that would effect large amounts of data, because the previous two experiments have already examined the effect of increasing the amount of data affected by certain

operations. Rather, the criteria used to choose what data to run this experiment on was to find simple operations, in order to get close to "best case" results, while still performing some amount of useful work. In other words, we do not attempt to remove an element that does not exist, for example, as such an operation would not represent a particularly useful activity.

Below we indicate the data that was chosen for each primitive and briefly describe what happens during the operation. Most of the element names below (FM and PERSONAE, for example) come from the "play.dtd" file, the DTD for the Shakespeare XML data files. Some, however are made up names, such as FOO and NewAttr1.

1. `createDTDElement:` Create new element definition named FOO. DTD change only; no data changes.

2. `destroyDTDElement:` Destroy element definition named FOO created above. DTD change only; no data changes.

3. `renameDTDElement:` Change name of element P, which occurs four times in each data file. DTD change only; no data changes.

4. `insertDTDSubelement:` Insert existing FM subelement into parent PERSONAE element, which occurs only once in each data file. DTD change plus data change for one element per file.

5. `removeDTDSubelement:` Remove subelement FM from parent PERSONAE element. DTD change plus data change for one element per file.

6. `changeQuantifier (Element):` Change quantifier on subelement LINE in parent SPEECH element from NONE to STAR ("*"). DTD change only; no data changes.

7. `changeQuantifier (Group):` Change quantifier on group inside PERSONAE element from PLUS (“+”) to STAR (“*”). DTD change only; no data changes.

8. `convertToGroup:` Convert subelements 3 through 5 in parent ACT element into a group. DTD change only; no data changes.

9. `flattenGroup:` Remove group node around subelements 3 through 5 in parent ACT element. DTD change only; no data changes.

10. `addDTDAttr:` Create new attribute definition called “NewAttr1”, with IMPLIED default type, and add to parent element PLAY, which occurs only once in each data file. DTD change plus change to Java file for element PLAY; data change for one element per file. The test method which adds “NewAttr1” also creates another attribute “NewAttr2”, with REQUIRED default type, and adds it to parent element TITLE, although this second call was not timed, and its execution time does not appear in the chart. This second attribute was created for use in other primitives mentioned below.

11. `changeAttrDefaultVal:` Change default value for “NewAttr1” created above. DTD change only; no data changes.

12. `changeAttrDefaultType:` Change default type for “NewAttr1” from IMPLIED to FIXED, supplying a fixed value of “val1”. DTD change only; no data changes.

13. `changeAttrFixedVal:` Change fixed value for “NewAttr1” to new fixed value “val2”. DTD change only; no data changes.

14. `destroyDTDAttr:` Destroy attribute definition for “NewAttr1” and remove from parent element PLAY, which occurs only once in each data file. DTD change plus change to Java file for element PLAY; data change for one element per file.

15. `changeAttribute:` Change the value of "NewAttr2" in the first instance of the TITLE element. Data change for one element per file; no DTD changes.

16. `addElement:` Find first instance of LINE element in first instance of SPEECH element, and add LINE again to SPEECH. The result after this primitive executes is that the first LINE in the first SPEECH is duplicated. Data change for one element per file; no DTD changes.

17. `destroyElement:` Remove second instance of LINE element from first instance of SPEECH element. This operation removes the duplication inserted above. Data change for one element per file; no DTD changes.

18. `changeElement:` Change value of first instance of LINE element in first instance of SPEECH element to "*** Line has been changed!". Data change for one element per file; no DTD changes.

In analyzing the results from this experiment, we find that the primitive operations can be grouped into four categories based on the types of changes which occur. These categories are defined as: (1) changes to only the XML data, (2) changes to only the DTD, (3) changes to both the DTD and XML data which behave like pure data updates, and (4) changes to both the DTD and XML data which behave like schema updates. The distinction between categories (3) and (4) is due to our implementation choices, where children subelements are stored in a Java Vector, while attributes are stored as member variables in the associated Java files. In the former case, a change to an element's children, while affecting the DTD, is not technically a schema change, since we are not changing the structure of an element, but only its contents. In the latter case, on the other hand, a change which adds or removes an attribute does correspond to a schema change, since we are truly changing the structure of an element. We group our primitive operations according to these categories as follows.

1. XML data changes only:
   `changeAttribute`
   `addElement`
   `destroyElement`
   `changeElement`

2. DTD changes only:
   `createDTDElement`
   `destroyDTDElement`
   `renameDTDElement`
   `changeQuantifier`[1]
   `convertToGroup`
   `flattenGroup`
   `changeAttrDefaultVal`
   `changeAttrDefaultType`
   `changeAttrFixedVal`

3. DTD and XML data changes (pure data update):
   `insertDTDSubelement`
   `removeDTDSubelement`

4. DTD and XML data changes (schema update):
   `addDTDAttr`
   `destroyDTDAttr`

5.3 Discussion

The results from the first experiment in Section 5.2.1 show that there are some fixed costs associated with the Exemplar system initialization, and other costs which are dependent on the data being operated on. Below is a breakdown of which tasks fit into which categories:

- Fixed Costs: Initializing and shutting down the database are fixed costs which will

[1]This operation would move to category (3) if the quantifier constraint changed from *not required* to *required*, or from *repeatable* to *not repeatable*.

be incurred each time Exemplar is run. These costs are approximately 1.5 and 0.5 seconds respectively.

- DTD Related Costs: Creating the system dictionary classes is dependent on the number of element, group, and attribute definitions in the DTD, plus the number of quantifiers applied to elements and groups, because we create instances of the system dictionary objects for each of these DTD items. Typically, the largest of these costs is associated with the number of element definitions in the DTD, since this number tends to overwhelm the others. If we divide the time to create the system dictionary objects by the number of element definitions in the DTD, we find this cost to be approximately 1.5 seconds per element. Generating the application classes is also dependent on the number of element and attribute definitions in the DTD(s), with the number of elements again being the dominant factor. We create a new Java file for each element definition, and add a member variable to that file for each attribute definition. When we divide the time to generate the application classes by the number of element definitions in the DTD, we find this cost to be approximately 2 seconds per element.
- XML Data Related Costs: Loading and dumping the XML data is obviously dependent on the number of XML files to process and the number of instances of each element in the data files. These costs per element are approximately 1.85 and 1.65 milliseconds respectively.

In our experiments we start each test from scratch, creating a new database, system dictionary and application classes, and loading the data fresh each time. We also dump out new XML files for the entire database each time a change is made, regardless of what changed. In practical use, however, the Exemplar system need not be used in this manner. The majority of the costs listed above might only be incurred once, because after the database, system dictionary and application classes are created, Exemplar may be run

as many times as desired, executing various primitive operations to make changes to the DTD/schema and/or data. In this more realistic scenario, the main cost which remains a factor for each such Exemplar run is only the time to execute the primitive operations. Dumping out new XML files after changes have been made also remains a factor, but this can be done more discriminately, based on those files which have actually changed.

The results from the experiments in Sections 5.2.2 and 5.2.3 show, as expected, that the total primitive execution times increase as the amount of data to process increases, but that the individual operations are performed in a fixed amount of time when viewed on a per-object basis. And finally, the results from our last experiment in Section 5.2.4 show that the amount of time to execute any given primitive varies, depending on the data on which the operation is performed, and depending on the activities involved in the particular operation. Although the addDTDAttr and destroyDTDAttr schema evolution primitives are the least efficient of the lot, the reasons for this are well understood (described in Section 4.6.2), and otherwise the remaining primitive operations are very efficient time-wise, considering the amount of work that may be performed. Based on these results from our experimental study, we conclude that the Exemplar system would prove useful to anyone desiring to maintain DTD and XML data which evolves over time, as it automates changes which would otherwise need to be accomplished by hand, ensures that changes are consistency preserving, and avoids having to reload data with each and every change.

Chapter 6

Related Work

6.1 XML Management Tools

Since XML is primarily used as a data exchange format on the World Wide Web, many research projects dealing with XML have focused on web site management [MMA99, DFS99, FFK+97, CCR00]. These projects attempt to alleviate difficulties associated with managing large amounts of data contained in web sites by representing web pages as XML documents. Although our XEM work does not focus on web site management, research into these projects proved useful in understanding storage and manipulation of XML documents.

Other research on XML focuses on its semi-structured nature [CAW98, Cha99, FS00]. In dealing with semi-structured data, some projects either totally ignore the schema, or just consider it implicated by the actual storage structure and hence to be a "second-class" citizen. They therefore do not deal with schema evolution issues. For example, Object Exchange Model [PMW95] represents semi-structured data, similar in nature to XML, without any associated DTD definition. DOEM [CAW98] is further proposed as a model to represent changes in semi-structured data via temporal annotations. However, it only

deals with the changes at the data level and is schema-blind. All versions of a data item will be stored together over time. Hence it results in an ever-growing complex annotated data structure.

Finally, some XML tools have focused on various language formats as a mechanism for manipulating XML data. For example, Extensible Stylesheet Language Transformations (XSLT) [Gro] is a language designed for transforming individual XML documents. It does not require any DTD and users can specify arbitrary XML data transformation rules. Hence no schema constraints are enforced on the data or on the transformation. Lexus (XML Update Language) [Inf00] is a declarative language proposed by an open source group, Infozone, to update stored documents. However, its primitives also only work on the document level without taking the DTD into account. So neither XSLT nor Lexus can serve in scenarios where a schema or structure is required.

6.2 Schema Evolution

Many database projects have focused on the issue of schema evolution [BKKK87, BMO+89, SZ86, CAW98, Zic91], where the main goal is to develop mechanisms to change not only the schema but also the underlying objects such that they conform to the modified schema. This issue was therefore a high priority in our XEM project. Most commercial database systems today [Inc93, Tec94, Obj93, Tec92] provide support for the restructuring of the application schema by means of a fixed set of simple evolution primitives, as does our XEM system. One issue which sets our project apart however, is that we deal with constraints and invariants in order to preserve system integrity during schema evolution. Recent work has been done to focus on the issues of supporting more complex schema evolution operations [Bré96, Ler96]. These allow the user to string together several primitives to form higher level yet still specific change transformations. Finally,

SERF [CJR98b, CJR98a] is a template-based, extensible schema evolution framework that allows complex user-defined schema transformations in a flexible yet secure fashion.

6.3 XML and Database Systems

A number of projects and tools have emerged to map XML and similar semi-structured data formats to traditional database systems. [FK99] looks at storing and querying XML data using a relational database management system (RDBMS). Both [Koe99] and [MAG+97] investigate semi-structured data in relational databases, while [CACS94] looks at SGML (the predecessor of XML) storage in an object-oriented database management system (OODBMS). Oracle's XML SQL Utility (XSU) [Net00] and IBM's DB2 XML Extender [IBM00a] are well-known commercial relational database products extended with XML support. They mainly provide two methods to manage XML data. The first option is to store XML data as a blob while the second option is to decompose XML data to relational instances. However, if there is any update to the external XML data, for the first storage option, they need to reload the data, and for the second option, they have to first figure out and then make the change on the relational schema level. In other words, the evolution of the data inside or outside of the database are independent from each other. Hence the change propagation from an external XML document to its internal relational storage or schematic structure is not supported. In a related effort at WPI, we have developed the Clock system [ZMLR01] that synchronizes internal relational storage with external XML documents, but this system deals with basic data updates only and does not handle schema changes.

Chapter 7

Conclusions

7.1 Future Work

During the course of our research on the XEM project, a number of issues arose which we did not have time to address. Here we present a number of new research directions which could be undertaken to continue this work.

- **XML Schemas:** The format of an XML Schema includes more powerful features for defining the structure and content of an XML document than a DTD. Our XEM mapping model is currently tied to DTD format, but could be updated to handle XML Schemas instead.

- **Model Mapping:** Our Exemplar implementation is currently tied to the PSE Object Store database. A more generic model mapping, including a database-independent layer, with database-specific drivers would be a more flexible solution.

- **Versioning:** If the Exemplar system were modified such that changes were made to a new copy of DTDs and XML documents, rather than “in place”, or if deltas were stored which could be applied to old documents to produce new ones, our system

could be used to provide revision control and version management services.

- **Scripting:** Currently, calling a primitive in our Exemplar system requires writing Java code, since the primitives are implemented as methods. If we integrated a scripting language into XEM, such as an XML query language like XQL [RLS98] for example, then the user could easily combine primitives into more complex transformations, as most scripting languages are simpler than programming languages.

- **Evolution Templates:** Once we have some form of scripting language in place, then parameterized evolution templates could be introduced, similar to those provided by SERF [CJR98b]. These would give XEM more powerful functionality as users could develop templates for commonly used complex transformations, which are flexible and reusable because their specific behavior in a given circumstance is allowed to vary based on parameters.

- **Web Site Management:** A screen scraping facility which produces XML from HTML would allow us to integrate XEM into a web site restructuring tool, where XML documents represent web pages, and XEM can be used to manage the complexity of data on a web site, since our system is already capable of producing HTML as output via XSLT stylesheets [Gro].

- **Other Applications:** In any environment where data is stored in XML format, applications could be built on top of XEM to provide various data management services. For example, in an environment where DTDs and XML documents are stored in a repository such as Arbortext's Epic [Arb00], an XEM application could be used to manage changes to that data.

7.2 Summary

In this thesis, we present the first of its kind - a taxonomy of XML evolution operations. Using pre- and post-conditions, these primitives assure the integrity of an XML data management system, both when DTD changes are made and XML documents have to change to maintain consistency with the new DTD; and also when individual XML documents are changed to ensure that the changed documents still conform to the corresponding DTD. Our research into XEM is generic for XML data management, independent of any specific implementation.

In our work on the XEM project, we make a number of important contributions in the area of XML data management, including the first approach for addressing evolution in an XML context. We show the motivation behind the need for such support, while identifying the lack of existing support in current XML data management systems. We propose a taxonomy of XML evolution primitives which includes both schema and data updates to fill this gap. We identify various forms of system integrity which a sound XML management system must maintain during evolution. These include the *well-formedness* of DTDs and XML documents, which must conform to the standard language format; the *consistency* of XML documents in terms of their invariants; and the *validity* of XML documents with respect to the constraints specified in the corresponding DTD. We show that our proposed change taxonomy is *complete* in that all valid desired transformations are possible using our primitives, and *sound* in its maintenance of system integrity.

We prove the feasibility of our approach via the functioning Exemplar prototype implementation using the Java programming language and an underlying object-oriented database, and we describe in this thesis the important aspects of that implementation. We conduct experimental studies to verify correct execution of the primitive operations within our prototype system, and present a performance analysis in the form of results from our

experiments. These results show that our prototype indeed provides automated XML evolution management facilities which are superior to making manual edits and then having to reload data from scratch, which would be necessary using other current XML management tools. We conclude that our research into XEM was a fruitful endeavor, with many beneficial contributions to the field of XML data management as a result.

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