Simplifying XML Schema: Effortless Handling of Nondeterministic Regular Expressions

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XML Schema is ...

- A language for defining the structure of XML documents.
- W3C Standard
- Successor of DTD
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- A language for defining the structure of XML documents.
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Why a schema for XML documents?

- Provides semantics to the data
- Very useful for optimization
- Necessary for data integration
- ...
<xsd:element name="store" type="store"/>

<xsd:complexType name="store">
  <xsd:sequence>
    <xsd:element name="order" type="order" minOccurs="0" maxOccurs="unbounded"/>
    <xsd:element name="stock" type="stock"/>
  </xsd:sequence>
</xsd:complexType>

<xsd:complexType name="order">
  <xsd:sequence>
    <xsd:element name="customer" type="customer"/>
    <xsd:element name="item" type="item1" minOccurs="1" maxOccurs="unbounded"/>
  </xsd:sequence>
</xsd:complexType>

\[
\begin{align*}
\text{root} & \rightarrow \text{store} \\
\text{store} & \rightarrow \text{order}^* \text{ stock} \\
\text{order} & \rightarrow \text{customer} \text{ item}^+_1
\end{align*}
\]
XML Schema

XSD

root → store
store → order* stock
order → customer item*

stock → item*
item1 → id price
item2 → id qty

XML Document: Tree

store
  order
    customer
      id price
    item
  order
    customer
      id price
    item
  stock
    item
      id qty
XSD Validation

XSD

root → store
store → order* stock
order → customer item1+
stock → item2
item1 → id price
item2 → id qty

XML Document: Tree
XSD Validation

root → store
store → order* stock
order → customer item₁ +
stock → item₂*

item₁ → id price
item₂ → id qty

XML Document: Tree
XSD Validation

root → store

store → order* stock

order → customer item⁺

stock → item²*

item₁ → id price

total 1 item

item₂ → id qty

item

id price

store

order

customer

item₁

id price

item

id price

item

id price

item

id qty

XML Document: Tree
XSD Validation

root → store
store → order* stock
order → customer item_1+

stock → item_2*
item_1 → id price
item_2 → id qty

XML Document: Tree

```
store
  order
    customer
      id price
      item_1
    item
      id price
      id price
      item
      id price
      id qty

stock
```
XSD Validation

root → store
store → order* stock
order → customer item_1+
stock → item_2
item_1 → id price
item_2 → id qty

XML Document: Tree
XSD Validation

root → store
store → order* stock
order → customer item₁⁺

stock → item₂
item₁ → id price
item₂ → id qty

XML Document: Tree

```
store
  order
    customer
      id price
    item₁
    order
      customer
        id price
    item₁
    item₂
      id qty
```
XML Schema is ...

a simple grammar-based formalism using regular expressions

Regular expressions are great

- Easy to use
- Robust class of languages: closed under union, intersection, complement, …
- Very well understood
Deterministic Regular Expressions

**UPA constraint**
All content models must be **deterministic regular expressions**.

**Definition**
A regular expression $r$ is **deterministic** if when matching any string from left to right against $r$, we can deterministically match every symbol against a position in $r$, **without looking ahead** in the string.
Deterministic Regular Expressions

UPA constraint
All content models must be deterministic regular expressions.

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Example
- \((ab)^*\) is deterministic.
- \((ab)^*a\) is not deterministic.
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A regular expression $r$ is deterministic if when matching any string from left to right against $r$, we can deterministically match every symbol against a position in $r$, without looking ahead in the string.

Example
- $(ab)^*$ is deterministic.
- $(ab)^*a$ is not deterministic. Examples: $aba$ and $a$
Deterministic regular expressions are ugly

- Easy to use
- Robust class of languages: closed under union, intersection, complement, …
- Very well Partially understood
W3C XML Schema Standard

A content model must be formed such that during validation of an element information item sequence, the particle component contained directly, indirectly or implicitly therein with which to attempt to validate each item in the sequence in turn can be uniquely determined without examining the content or attributes of that item, and without any information about the items in the remainder of the sequence.
Scenario

- User writes XML Schema Definition containing non-deterministic expression, say \((a + b)^* a\), and tries to validate it.
- Validator response: **ERROR**: non-deterministic content model \((a + b)^* a\).
User writes XML Schema Definition containing non-deterministic expression, say \((a + b)^*a\), and tries to validate it.

Smart validator response: **PROBLEM:** non-deterministic content model \((a + b)^*a\). However, the content model \(b^*a(b^*a)^*\) describes the same content and is deterministic. Would you like to use it instead?
Theorem: Bruggemann-Klein and Wood

Some regular languages are not definable by a deterministic regular expression.
Theorem: Bruggemann-Klein and Wood

Some regular languages are not definable by a deterministic regular expression.

Scenario

- User writes XML Schema Definition containing expression \((ab)^*a\) and tries to validate it.

- Smart validator response: PROBLEM: non-deterministic content model for \((ab)^*a\). Moreover, there is no deterministic content model describing exactly this content. However, the content model \(a(b?a)^*\) is deterministic and describes the same content plus some additional strings. Would you like to use it instead?
Overall Goal
Develop the tools for a smart schema validator.

Technical goals
Given a non-deterministic regular expression,
- **decide** whether its language can be defined by a deterministic expression
- if possible, **construct equivalent** deterministic expression
- otherwise, **construct** deterministic overapproximation
Overall Goal

Develop the tools for a smart schema validator.

Technical goals

Given a non-deterministic regular expression,

- decide whether its language can be defined by a deterministic expression
- if possible, construct equivalent deterministic expression
- otherwise, construct deterministic overapproximation

Remark

All results apply to DTDs
Deciding Determinism

Deciding Determinism Problem

Given non-deterministic expression $r$, decide whether there exists a deterministic expression $s$, such that $L(r) = L(s)$.
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Bruggemann-Klein and Wood 1998

Deciding Determinism can be done in time exponential in the size of $r$. 
Deciding Determinism

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Given non-deterministic expression $r$, decide whether there exists a deterministic expression $s$, such that $L(r) = L(s)$.

Bruggemann-Klein and Wood 1998
Deciding Determinism can be done in time exponential in the size of $r$.

Theorem
Deciding Determinism is PSPACE-hard.
Problem
Given a non-deterministic expression $r$, construct a deterministic expression $s$, such that $L(r) = L(s)$. 
Construct Deterministic Expressions: BKW

Algorithm Bruggemann-Klein and Wood

- Construct minimal DFA.
- Construct deterministic expression by induction on DFA.
- Note: Added a few optimizations.
Construct Deterministic Expressions: BKW

Algorithm Bruggemann-Klein and Wood
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- Construct deterministic expression by induction on DFA.
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BKW
- + : If possible always return an equivalent deterministic expression.
- - : Can create very big expressions (possibly double exponential)
Example: \((a^*b?c?d?e?f^*g^*h^*i^*j^*k^*a^*)\)
Constructing Deterministic Expressions: GROW

Goal

Find concise deterministic expressions.
Constructing Deterministic Expressions: GROW

**Goal**
Find concise deterministic expressions.

**Glushkov Automata**

\[ a(b^*a)^* \]

KoaToKore (Bex. et. al)
Constructing Deterministic Expressions: GROW

Input Expression

\[ a(a + b)^*a \]
Input Expression

\[ a(a + b)^*a \]

Minimal DFA

KoaToKore: Fail
Constructing Deterministic Expressions: GROW

Input Expression

\[ a(a + b)^*a \]

Minimal DFA

KoaToKore: Fail

Expansion 1

KoaToKore: Fail
Constructing Deterministic Expressions: GROW

Input Expression
\[ a(a + b)^*a \]

Minimal DFA

KoaToKore: Fail

Expansion 1

KoaToKore: Fail

Expansion 2

KoaToKore: \[ a(b^*a)^* \]
Algorithm

- Enumerate all (non-isomorphic) deterministic automata equivalent to $r$, up to a given size.
- Check whether one of these automata is a Glushkov automaton; and construct equivalent expression.
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- Check whether one of these automata is a Glushkov automaton; and construct equivalent expression.

GROW

- + : Returns concise, readable expressions.
- - : Not always returns an expression.
Approximating Deterministic Expressions

Problem

Given a non-deterministic expression $r$, construct a deterministic expression $s$, such that $L(r) \subset L(s)$. 

Optimal Approximations

An approximation $s$ is optimal if there does not exist a deterministic expression $s'$ such that $L(r) \subset L(s') \subset L(s)$. 

Theorem

Let $r$ be an expression such that no equivalent deterministic expression exists. Then, there does not exist an optimal deterministic approximation of $r$. 

W. Gelade (Hasselt University)
Approximating Deterministic Expressions

**Problem**

Given a non-deterministic expression $r$, construct a deterministic expression $s$, such that $L(r) \subset L(s)$.

**Optimal Approximations**

- An approximation $s$ is **optimal** if there does not exist a deterministic expression $s'$ such that $L(r) \subset L(s') \subset L(s)$.
Approximating Deterministic Expressions

Problem
Given a non-deterministic expression \( r \), construct a deterministic expression \( s \), such that \( L(r) \subset L(s) \).

Optimal Approximations
An approximation \( s \) is optimal if there does not exist a deterministic expression \( s' \) such that \( L(r) \subset L(s') \subset L(s) \).

Theorem
Let \( r \) be an expression such that no equivalent deterministic expression exists. Then, there does not exist an optimal deterministic approximation of \( r \).
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Let $r$ be an expression such that no equivalent deterministic expression exists. Then, there does not exist an optimal deterministic approximation of $r$.

Proof
Suppose $s$ is optimal approximation of $r$.
Take $w$ in $L(s)$, not in $L(r)$.
$L(s) \setminus \{w\}$ also definable by deterministic expression $s'$, but better approximation than $s$. 
Algorithm by Ahonen: Ahonen-BKW

1. Given non-deterministic expression $r$, construct its minimal DFA.
2. “Simulate” BKW algorithm. Stuck $\Rightarrow$ merge states and add transitions.
Approximating Deterministic Expressions: Ahonen

Algorithm by Ahonen: Ahonen-BKW

1. Given non-deterministic expression \( r \), construct its minimal DFA.
2. “Simulate” BKW algorithm. Stuck \( \Rightarrow \) merge states and add transitions.
3. Construct deterministic expression using BKW algorithm

Ahonen-GROW

Alternative: apply GROW instead of BKW in step 3.
Approximating Deterministic Expressions: Ahonen

### Ahonen-BKW

- **+**: Always returns an expression.
- **-**: Big expressions.

### Ahonen-GROW

- **+**: Small expressions.
- **-**: Not always returns an expression.
Approximating Deterministic Expressions: SHRINK

Goal

Algorithm that always returns small, readable expression.
Goal
Algorithm that always returns small, readable expression.

KoaToKore (Bex. et. al)
- When automaton is Glushkov automaton, returns corresponding expression (of equal size)
- Can also return overapproximation (of equal size)
Approximating Deterministic Expressions: SHRINK

Input Expression

$a^+ (ba)^* b$?
Approximating Deterministic Expressions: SHRINK

Input Expression

\[ a^+ (ba)^* b? \]

Minimal DFA

KoaToKore: Fail
Approximating Deterministic Expressions: SHRINK

Input Expression
$a^+ (ba)^* b$?

Minimal DFA

KoaToKore: Fail

Merged States

KoaToKore: $(ab)^+$
**Input Expression**

\[ a^+ (ba)^* b? \]

**Minimal DFA**

KoaToKore: Fail

**Merged States**

KoaToKore: \((ab?)^+\)
Approximating Deterministic Expressions: SHRINK

Algorithm

- Shrink minimal DFA by merging states (trying to add as little as possible)
- Each DFA: check whether DFA is glushkov, or let koaToKore overapproximate (by adding transitions)
Experiments: Setup

Expressions

- Randomly generated.
- 2100 non-deterministic expressions.
- Number of alphabet symbols ranging from 5 to 50.

Repeatability and Workability

We participated in the ACM SIGMOD 2009 Repeatability and Workability Evaluation. The reviewers were able to repeat all the experiments presented in our paper, yielding results that match the ones published in our paper, except from insignificant and to be expected variation due to randomness and-or hardware-software differences. The detailed reports will shortly be made publicly available by ACM SIGMOD.
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Deciding Determinism

- Very efficient (up to 50 milliseconds for largest ones)
- Minimal DFAs are small!
## Experiments: Constructing Deterministic Expressions

### Size of output expressions (and success rate)

<table>
<thead>
<tr>
<th>input size</th>
<th>BKW</th>
<th>GROW</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>7</td>
<td>3 (89%)</td>
</tr>
<tr>
<td>10</td>
<td>95</td>
<td>6 (66%)</td>
</tr>
<tr>
<td>15</td>
<td>394</td>
<td>9 (43%)</td>
</tr>
<tr>
<td>20</td>
<td>/</td>
<td>12 (31%)</td>
</tr>
<tr>
<td>25-30</td>
<td>/</td>
<td>13 (21%)</td>
</tr>
<tr>
<td>35-50</td>
<td>/</td>
<td>23 (7%)</td>
</tr>
</tbody>
</table>

### Running times

- GROW and BKW: Less than a second for small expressions.
- GROW: up to 20 seconds for biggest
Experiments: Approximating Deterministic Expressions

Measure of Quality

Ratio of number of strings defined by original expression over number by det. approximation: Close to 1 is good

Quality of Approximations

<table>
<thead>
<tr>
<th>input size</th>
<th>Ahonen-BKW</th>
<th>Ahonen-GROW</th>
<th>SHRINK</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.73 (100%)</td>
<td>0.71 (75%)</td>
<td>0.75 (100%)</td>
</tr>
<tr>
<td>10</td>
<td>0.81 (100%)</td>
<td>0.79 (56%)</td>
<td>0.78 (100%)</td>
</tr>
<tr>
<td>15</td>
<td>0.84 (100%)</td>
<td>0.88 (40%)</td>
<td>0.79 (100%)</td>
</tr>
<tr>
<td>20</td>
<td>/</td>
<td>0.89 (18%)</td>
<td>0.76 (100%)</td>
</tr>
<tr>
<td>25-30</td>
<td>/</td>
<td>0.89 (8%)</td>
<td>0.71 (100%)</td>
</tr>
<tr>
<td>35-50</td>
<td>/</td>
<td>0.75 (4%)</td>
<td>0.68 (100%)</td>
</tr>
</tbody>
</table>
## Experiments: Approximating Deterministic Expressions

### Expression sizes (and success rate)

<table>
<thead>
<tr>
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<th>Ahonen-GROW</th>
<th>SHRINK</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>8 (100%)</td>
<td>3 (75%)</td>
<td>3 (100%)</td>
</tr>
<tr>
<td>10</td>
<td>28 (100%)</td>
<td>6 (56%)</td>
<td>6 (100%)</td>
</tr>
<tr>
<td>15</td>
<td>73 (100%)</td>
<td>8 (40%)</td>
<td>8 (100%)</td>
</tr>
<tr>
<td>20</td>
<td>/</td>
<td>11 (18%)</td>
<td>10 (100%)</td>
</tr>
<tr>
<td>25-30</td>
<td>/</td>
<td>11 (8%)</td>
<td>13 (100%)</td>
</tr>
<tr>
<td>35-50</td>
<td>/</td>
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<td>18 (100%)</td>
</tr>
</tbody>
</table>
Supportive UPA Checker

Input regular expression

1. If \( r \) is deterministic, return \( r \)
2. Else If \( L(r) \) is deterministic
   1. If \( \text{GROW}(r) \) succeeds, return \( \text{GROW}(r) \)
   2. Else return best from \( \text{BKW}(r) \) and \( \text{SHRINK}(r) \)
3. Else return best from \( \text{Ahonen-GROW}(r) \) and \( \text{SHRINK}(r) \)
Future and Current Work

- Minimization of deterministic expressions
- Experiments using real-world expressions
- Take into account counting operator