A Benchmark Collection of Deterministic Automata for XPath Queries

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Abstract. We provide a benchmark collection of deterministic automata for regular XPath queries. For this, we select the subcollection of forward navigational XPath queries from a corpus that Lick and Schmitz extracted from real-world XSLT and XQuery programs, compile them to stepwise hedge automata (SHAs), and determinize them. Large blowups by automata determinization are avoided by using schema-based determinization. The schema captures the *XML* data model and the fact that any answer of a path query must return a single node. Our collection also provides deterministic nested word automata that we obtain by compilation from deterministic SHAs.

Keywords: *XML*, regular path queries, automata, nested words, trees, hedges. `docbook/Latex`

1 Introduction

XML is one of the most used standardized formats for representing exchanging structured data between various tools and applications. *XML* documents form unranked data trees. Processing *XML* documents in both in-memory and streaming modes are widely studied for many years [15] [16] [14] [13] [11]. The most frequent tasks are validating, querying and transforming *XML* documents. In the *XML* technology, this is done with standardized languages based on XPath queries, such as Xslt and XQuery.

Automata-based algorithms are not only relevant for validating *XML* documents with respect to a schema (as with RelaxNG) but also for querying *XML* streams [23] [7] [22] [12]. The problem with syntax-oriented approaches for answering XPath queries on *XML* streams yield only low coverage. Automata approaches, in contrast, can deal with all of XPath 3.0 as shown by Sebastian, Niehren, and Debarbieux [7]. When applying automata, however, it is natural to abstract *XML* documents to nested words [2], which generalize on unranked data trees and sequences thereof that are also called forests or hedges. Automata for nested words are also relevant for enumerating query answers of document spanners in in-memory mode [8] [28], and for enumerating query answers on data trees [20] [3] [6].

Deterministic automata are relevant to keep the computational complexity of various problems tractable. In particular it enables automata minimization in polynomial time and universality testing in linear time. In contrast, universality becoming EXP-complete for nondeterministic automata on trees or nested words

[5] [29]. Note that universality testing can be used as a stopping condition for automata algorithms. More concretely, determinism is required for the streaming algorithms of [23] and [12] but also for the inmemory algorithm of [28]. Therefore, deterministic automata on nested words need to be produced for regular path queries [17] [21] [9] for benchmarking these algorithms.

Compiling regular path queries to automata is less problematic, but their determinization may blowup the automata sizes exponentially. This also happens in practice. For the XPath query `//a[following- sibling::b[.//c][./d]]/e` for instance, [7] construct a nested word automaton (Nwa) with 38 states of overall size 7338. The determinization of this automaton has more than 5000 states and 20 million transition rules. It is so big that it cannot be computed an a standard laptop. This shows that the usual determinization algorithm for Nwa*s* [4] [1] [26] quickly leads to a size explosion.

Niehren and Sakho [24] improved this situation by using the determinization algorithm for stepwise hedge automata (Shas), which in turn can be compiled to deterministic Nwa*s*. In this way deterministic Shas and Nwa*s* of decent size could be obtained for the 10 forward navigational XPath queries for the XPathMark benchmark [10]. But even the determinization of Shas may lead to unreasonably large automata for pratically relevant XPath queries. For the XPath query `/a/b//(* | @* | comment() | text())`, for instance, a deterministic Sha with 145 states and size 348 got reported, whose determinization has 10 005 states and overall size 1 634 123 [25].

Niehren, Sakho, and Al Serhali showed recently [25] that this determinization problem for Shas can be solved by using schemas, i.e., deterministic automata that model which nested words are valid inputs of the automaton. In the case of XPath queries, the schema captures the *XML* data model, and that each query answer must return a unique node of the *XML* document.

The first schema-based approach is to determinize the product of the query automaton with the schema automaton. For the above XPath query, this yields a deterministic Sha with 92 states and size 417, which after minimization goes down to 27 states and size 98. Nevertheless, this approach may seem surprising at first sight, since the schema-product is usually bigger than the query automaton itself. But indeed it works quite nicely in practice. The intuition is that the deterministic schema reduces the number of subsets of states that are to be considered during determinization since all states in such subsets must be aligned to the same schema state.

The second schema-based approach is to clean the determinized automaton with respect to the schema. This means removing all states and transitions that cannot be aligned to the schema. Schema-based cleaning has the advantage of always yielding smaller automata. Unfortunately, however, it is not always computationally feasible in practice, since the automaton produced by determinization is often too large for being schema-cleaned.

The third schema-based approach is schema-based determinization, an algorithm proposed in [25]. The idea is integrate schema-based cleaning directly into the determinization algorithm, in order to avoid large blowups from the beginning, while producing the same result as with the second approach. The automata obtained by schema-based determinization are usually smaller than

by determinizing the schema-product, also after minimization, since they do not recognize the same language.

We applied the implementations of all three approaches to show that small deterministic SHAs and NWA*s* can be obtained for all the regular XPATH queries in the benchmark corpus that Lick and Schmitz [19] [18] harvested from XSLT and XQUERY programs available online (docbook, teixml, htmlbook, ...). The third solution based on schema-based determinization followed by minimization yields the best results. The largest SHA obtained in this way for the whole benchmark collection has 58 states. In average there are 22 states and 71 transition rules per automaton. All automata are published in the software heritage archive at `https://archive.softwareheritage.org/browse/origin/?origin_url=https://gitlab.inria.fr/aalserha/xpath-benchmark`.

The fact that we can indeed determinize the automata of most if not all practical XPATH queries with a mild size increase, gives new hope to improve the situation on *XML* streaming in the near future, building on approaches requiring deterministic automata [23] [12] [27].

1.1 Outline

We present our selection of regular XPATH benchmark queries from the corpus of Lick and Schmitz [19] in in Section 2. Nested words and their relationship to *XML* documents are recalled in in Section 3. A deterministic stepwise hedge automata defining the schema of valid *XML* documents is given in in Section 3.2. A formal definition of stepwise hedge automata follows for the sake of self-containedness in in Section 4. In in Section 5 we discuss our compiler from XPath expressions to deterministic automata, and illustrate it by example automata from our benchmark collection. In in Section 6 we discuss how we tested our automata for correctness on a sample of annotated *XML* documents produced from the XPATH query based on Saxon XSLT. The sizes of automata in our benchmark collection of SHAs are discussed in in Section 7. We conclude in in Section 8. Some complementary information can be found in in Appendix A.

2 XPath Benchmark Queries

We start with the collection of 21000 XPATH queries that Lick and Schmitz [19] extracted from real-world XQUERY and XSLT programs available on the Web. The purpose of this corpus is to reflect the form and distribution of XPATH queries in practical applications. The much smaller XPathMark benchmark [10], in contrast, focuses on functionality testing.

We then filter the subclass of around 4500 forward navigational XPATH queries of Lick's and Schmitz's corpus. The other queries contain comparisons of data values, arithmetics, and functions, including higher-order functions to iterate over sequences, which may be nonregular. We also removed boolean queries and kept only node selection queries. We then selected the 180 largest queries of this subcorpus.

Finally, we removed duplicates of queries up to renaming of *XML* namespace prefixes and local names, and syntactical details, such as `.//author` or

`descendant-or-self::author` or `descendant-or-self::corpauthor`. This leads us to the collection of 79 queries. The first 10 queries are shown in in Table 1.

Id	XPath Query
18330	/descendant-or-self::node()/child::parts-of-speech
17914	/descendant-or-self::node()/child::tei:back/descendant-or-self::node()/child::tei:interpGrp
10745	*//tei:imprint/tei:date[@type='access']
02091	* | .//refentry
00744	.//@id | .//@xml:id
12060	.//attDef
02762	.//authorgroup/author | .//author
06027	.//authorinitials | .//author
02909	.//bibliomisc[@role='serie']
06415	.//email | address/otheraddr/ulink

Table 1: The first 10 of the 79 queries of the benchmark collection (see Table 3).

We note that the XPath query 18339 is considered as large since it contains the recursive axis `descendant-or-self`. Other queries are considered as large since having a parse tree with more than 15 nodes, for instance 05684 and 05684.

3 Nested Words for XML Documents

We use nested words to abstract from XML documents since automata can be defined more easily for nested words.

3.1 Nested Words

Nested words generalize on words by adding parenthesis that must be well-nested. Nested words also generalize on unranked trees and over sequences thereof that are often called hedges. We restrict ourselves to nested words with a single pair of opening and closing parenthesis $\langle$ and $\rangle$ since named parenthesis can be encoded easily. Let Σ be a set that we call the alphabet. Nested words in $\mathcal{N}_\Sigma$ have the following abstract syntax.

$$w, w' \in \mathcal{N}_\Sigma ::= \varepsilon \mid a \mid \langle w \rangle \mid w \cdot w' \qquad \text{where } a \in \Sigma.$$

We assume that concatentation $\cdot$ is associative, and that the empty word ε is a neutral element, that is $w \cdot (w' \cdot w'') = (w \cdot w') \cdot w''$ and $\varepsilon \cdot w = w = w \cdot \varepsilon$. Nested words can be identified with hedges, i.e., sequences of unranked trees and letters, that is $\mathcal{N}_\Sigma = (\Sigma \cup \langle \mathcal{N}_\Sigma \rangle)^*$.

3.2 XML Documents

XML documents are labeled unranked trees that can be serialized into a text, such as for instance:

```
<s:a name="uff"> <s:b> gaga <s:d/> <s:b/> <s:c/> <s:a>
```

We represent XML documents as nested words over the signature Σ_{XML} that contains 4 disjoint types of letters: the *XML* node-types $\{elem, attr, text, comment\}$, the *XML* namespaces of the document $\{s\}$, the *XML* names of the document $\{a, \ldots, d, name\}$, and the characters of the data values, say UTF8. For the above example, we get the nested word:

$$\langle elem \cdot s \cdot a \cdot \langle attr \cdot name \cdot u \cdot f \cdot f \rangle \langle elem \cdot s \cdot b \cdot \langle text \cdot g \cdot a \cdot g \cdot a \rangle \langle elem \cdot s \cdot d \rangle \rangle \langle elem \cdot s \cdot c \rangle \rangle$$

4 Automata for Nested Words

Stepwise hedge automata (SHAs) [24] extend on classical finite state automata (NFAs) from words to nested words. They provide a graphical way to define regular languages of nested words, and thus regular languages of *XML* documents. SHAs are often easier to read that the better-known nested word automata (NWA*s*) and help us to avoid large size blowups coming with NWA determinization. In this section we recall the definition of SHAs based on the definition of NFAs and discuss their relationship NWA*s*.

4.1 Finite State Automata (NFAs)

We consider finite state automata with else rules and possibly infinite alphabets.

Definition 1. *An* NFA (with else rules) *is a tuple* $A=(\Sigma, \mathcal{Q}, \Delta, I, F)$ *such that alphabet* Σ *is a possibly infinite set,* $\Delta = \Delta' \uplus \_^{\Delta}$ *contains a subset of transition rules for letters* $\Delta' \subseteq (\mathcal{Q} \times \Sigma) \times \mathcal{Q}$ *and a subset of else rules* $\_^{\Delta} \subseteq \mathcal{Q} \times \mathcal{Q}$*. We call* NFA A deterministic *or equivalently a* DFA *if* Δ' *and* $\_^{\Delta}$ *are partial function.*

As usual when using automata, we draw NFAs as graphs whose nodes are the states. A state $q \in \mathcal{Q}$ is drawn with a circle (q), an initial state $q \in I$ with an incoming arrow $\rightarrow(q)$, and a final state with a double circle $((q))$. A letter transition rule $(q_1, a, q_2) \in \Delta'$ is drawn as a black edge $(q_1) \xrightarrow{a} (q_2)$ that is labeled by a letter $a \in \Sigma$. An else rule $(q, q') \in \_^{\Delta}$ is drawn as $(q) \dashrightarrow (q')$. It permits that the automaton in state q can go to state q' when reading any letter $a \in \Sigma$ such that there exists no q'' with $q \xrightarrow{a} q'' \in \Delta$. Any else rule can be expanded to a set of letter transitions rules as follows:

$$\frac{q \dashrightarrow q' \in \Delta \quad a \in \Sigma \quad \neg \exists q'' \in \mathcal{Q}.\ q \xrightarrow{a} q'' \in \Delta}{q \xrightarrow{a} q' \in \Delta^{exp}} \qquad \frac{q \xrightarrow{a} q' \in \Delta}{q \xrightarrow{a} q' \in \Delta^{exp}}$$

4.2 Stepwise Hedge Automata (SHAs)

We extend NFAs to SHAs by adding adding apply rules that read states of subtrees rather than letters from the alphabet.

Definition 2. *An* SHA (with else rules) *is a tuple* $A = (\Sigma, \mathcal{Q}, \mathcal{P}, \Delta, I, F)$ *where* $\Delta = \Delta' \uplus \Delta''$ *so that* $A' = (\Sigma, \mathcal{Q}, \Delta', I, F)$ *is a* NFA. *Furthermore,* $\mathcal{P}$ *is a finite set of tree states and* $\Delta'' = (\langle\rangle^\Delta, @^\Delta, {\longrightarrow}^\Delta)$ *such that* $\langle\rangle^\Delta \subseteq \mathcal{Q}$ *is a subset of tree initial states,* $@^\Delta \subseteq (\mathcal{Q} \times \mathcal{P}) \times \mathcal{Q}$ *a set of apply rules, and* ${\longrightarrow}^\Delta \subseteq \mathcal{Q} \times \mathcal{P}$ *a set of tree final rules.*

We draw SHAs as graphs extending on the graphs of NFAs. A tree state $p \in \mathcal{P}$ is drawn in gray (p). A tree initial state $q \in \langle\rangle^\Delta$ is a hedge state is drawn as $\xrightarrow{\langle\rangle}(q)$ with an incoming tree arrow. An apply rule $(q_1, p, q_2) \in @^\Delta$ is drawn by a blue edge $(q_1) \xrightarrow{p} (q_2)$ carrying a state $p \in \mathcal{P}$ rather than a letter $a \in \Sigma$. It states that a nested word in state $q_1 \in \mathcal{Q}$ can be extended by a tree in state $p \in \mathcal{P}$ and go into state $q_2 \in \mathcal{Q}$. A tree final rule $(q, p) \in {\longrightarrow}^\Delta$ is drawn as $(q) \longrightarrow (p)$. It states that if w is a nested word in state $q \in \mathcal{Q}$ then $\langle w \rangle$ is a tree in state $p \in \mathcal{P}$.

Transitions of SHAs have the form $q \xrightarrow{w} q'$ wrt Δ where $w \in \mathcal{N}_\Sigma$ and $q, q' \in \mathcal{Q}$. They are defined by the inference rules:

$$\frac{q \in \mathcal{Q}}{q \xrightarrow{\varepsilon} q \text{ wrt } \Delta} \qquad \frac{q \xrightarrow{a} q' \in \Delta^{exp}}{q \xrightarrow{a} q' \text{ wrt } \Delta} \qquad \frac{q_0 \xrightarrow{w_1} q_1 \text{ wrt } \Delta \qquad q_1 \xrightarrow{w_2} q_2 \text{ wrt } \Delta}{q_0 \xrightarrow{w_1 \cdot w_2} q_2 \text{ wrt } \Delta}$$

$$\frac{q' \in \langle\rangle^\Delta \qquad q' \xrightarrow{w} q \text{ wrt } \Delta \qquad q \longrightarrow p \in \Delta \qquad q_1 \xrightarrow{p} q_2 \in \Delta}{q_1 \xrightarrow{\langle w \rangle} q_2 \text{ wrt } \Delta}$$

The last inference rule says that when reading a tree $\langle w \rangle$ the automaton can transit from a state q_1 to a state q_2 if with w it can transit from some tree initial state q' to q, so that there is some tree final rule $q \longrightarrow p \in \Delta$ and some apply rule $q_1 \xrightarrow{p} q_2 \in \Delta$. The language $\mathcal{L}(A)$ of a SHA is defined as usual for NFAs except that nested words may be recognized too:

$$\mathcal{L}(A) = \{w \in \mathcal{N}_\Sigma \mid q \xrightarrow{w} q' \text{ wrt } \Delta,\ q \in I,\ q' \in F\}$$

The notion of determinism for SHAs extends on the notion of left-to-right determinism of NFAs and on the notion of bottom-up determinism of tree automata.

Definition 3. *We call an* SHA A deterministic *or equivalently a* dSHA, *if the contained finite automaton* A' *is a* DFA, *there is at most one tree initial state in* $\langle\rangle^\Delta$, *and* $@^\Delta$ *and* ${\longrightarrow}^\Delta$ *are partial functions.*

4.3 Adding Typed Else Rules

Suppose that the alphabet Σ is typed, in that any letter $a \in \Sigma$ can be given some types in some type set T. We can then add typed else rules $(q, \tau, q') \in \Delta \times T \times \Delta$ that we draw as $(q) \xrightarrow{-\tau} (q')$. In contrast to untyped else rules, a typed else rule cannot be expanded with all letters from Σ, but only with those that can be given the type τ.

4.4 A Schema for XML Documents

The most frequent type of XPath queries select nodes of *XML* documents. For referring to selected nodes, we fix a single selection variable `x`. We call an *XML* document or subdocument, in which a single node is annotated by `x`, an *`x`-annotated example*. An `x`-annotated example is called *positive* for a query if the query selects the `x`-annotated node in the *XML* document, and *negative* otherwise.

The dSha *xml&one*^{x}: a schema for x-annotated *XML* documents in Fig. 1 recognizes the set of all `x`-annotated examples. These must satisfy the *XML* data model and contain exactly one occurence of `x`.

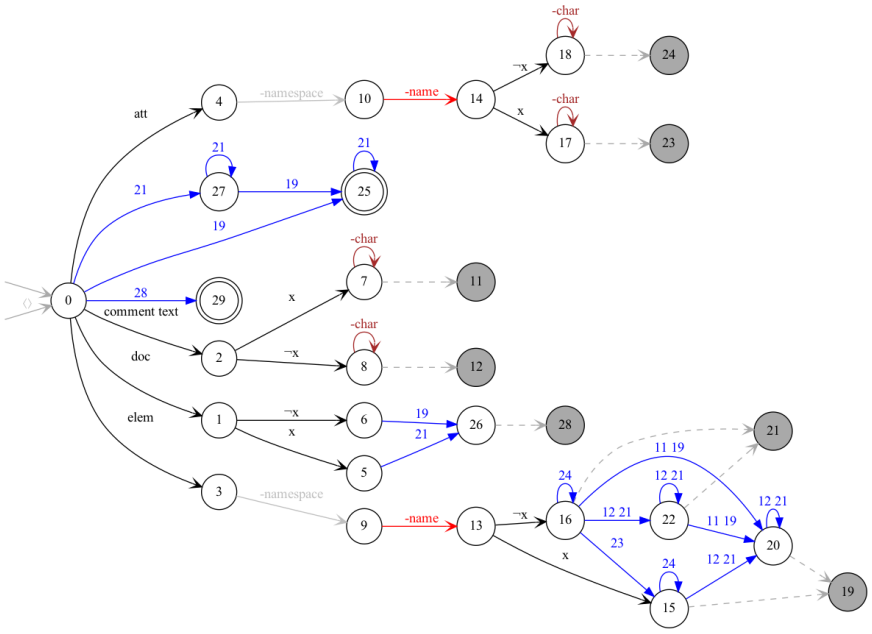

Fig. 1: The dSha *xml&one*^{x}: a schema for x-annotated *XML* documents.

The automaton starts in hedge state 0 where it expects to read a nested word $\langle w \rangle$, that can be evaluated to tree state 28, in order to go to the final state 29, where it accepts. The sequence of children w of the tree must be evaluated form

the tree initial state, which is equally the hedge state `0`. If w starts with letter `doc` indicating an *XML* document node at the root, the automaton moves from state `0` to state `5`. There it may either read the variable `x` and go to state `5`, where it expects a subtree in state `21`, i.e. an *XML* element of which no node is annotated by `x`. Or it may read the symbol ¬`x` and move to state `6`, where it expects a subtree in state `19`, i.e. an *XML* element of which exactely one node is annotated by `x`. In both cases it can go to the hedge state `26` and from there to the tree state `28`. The automaton also states the relationships of elements, attributes, text and comment nodes according to the *XML* data model.

The alphabets of names and namespaces of *XML* documents are infinite. In order to represent infinite sets of transition rule symbolically in a finite manner, the automaton use type else rules. The typed else rule in state `3`, for instance, is labeled by `-namespace`, permitting to read any namespace and to go to state `9`. State `9` in turn has an else rule labeled by `-name` which permits to read any (local) name and move to state `13`.

4.5 Nested Word Automata (NWAs)

Nested word automata (NWA*s*) [26][1] are well known pushdown machines for defining regular languages of nested words. They can process nested words in a streaming manner: top-down, left-to-right, and bottom-up manner. SHAs in contrast operate bottom-up and left-to right only. They avoid any top-down processing, since it quickly leads to huge size increases during NWA determinization.

Any SHA can be compiled in linear time to an NWA such that determinism is preserved. There also exists an inverse translation in quadratic time (but not preserving determinisim), so both automata classes have the same expressiveness, also when restricted by determinism. We omit the details, but provide deterministic NWA*s* in our collection. See for instance: The *d*NWA $nwa(det(A_2))$ obtained from the dSHA $det(A_2)$ in Fig. 4.

5 Compiler to Automata

We extended on the compilation chain for regular XPATH queries to automata from [24]. As a running example, we consider the following query:

$$Q_2: \qquad \texttt{h:body[@lang != '']}$$

Query Q_2 selects a node if it has a child named `body` in namespace `h`, that has the attribute node named `lang` containing a nonempty text.

5.1 Parser

Our parser for XPATH expressions computes a parse tree following the grammar of XPATH 3.1 from the W3C. In addition, it returns for any forward regular XPATH expression a logical formula in the language FXP [7]. For the XPATH example Q_2, we obtain the following FXP formula:

$$child(lab_{elem:type} \wedge lab_{h:namespace} \wedge lab_{body:name} \wedge lab_{x:var} \wedge \\ child(lab_{att:type} \wedge cand_{default:namespace} \wedge lab_{lang:name} \wedge string \neq ''))$$

Our previous parser needed considerable improvement in order to be able to cover the large variety of queries from the corpus of Lick and Schmitz [19].

5.2 Nested Regular Expressions

We next compile Fxp formulas to nested regular expressions, which extend on standard regular expressions from words to nested words. Again, considerable work was needed to enable a sufficiently large coverage. For the query Q_2 our compiler yields the nested regular expression:

$$\langle (elem{:}type._) + doc{:}type).\_.\top. \\ \langle elem{:}type.h{:}namespace.body{:}name.x{:}var. \\ \langle att.type.default{:}namespace.lang{:}name.\_.(\_char.(\_char)^*\rangle.\top\rangle.\top\rangle.\top$$

Note that the test for a nonempty string got translated by the regular expression $\_char.(\_char)^*$. It should also be noticed that this expression matches some x-annotated nested words, that are not x-annotated examples, i.e. not belonging to the language $\mathcal{L}(xml\&one^x)$ of the schema. This is since the nested subwords matching universal expression $\top$ are completely unconstrained.

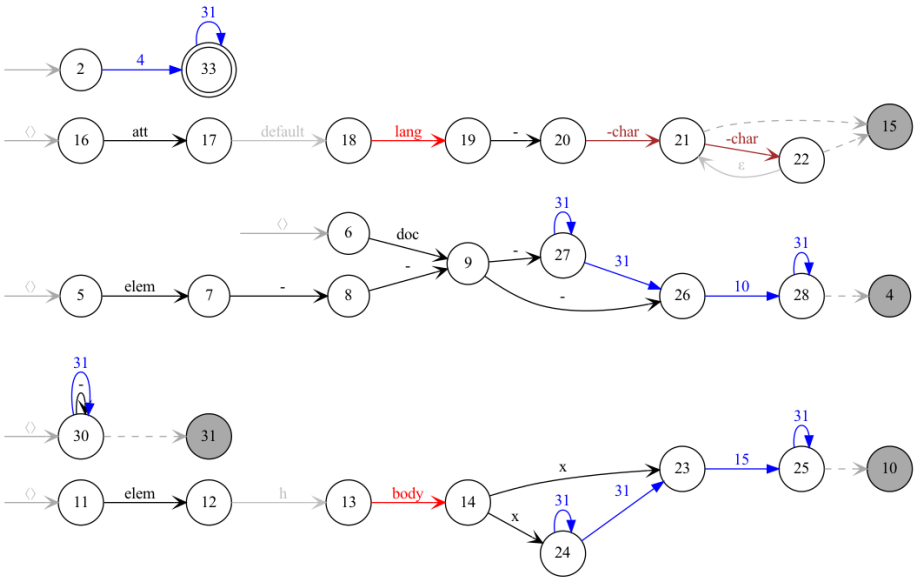

Fig. 2: The nondeterministic Sha $A_2 = sha(Q_2)$. .

5.3 Compiler to SHAs

The compiler then converts nested regular expressions into SHAs. This is done by extending a usual compiler from regular expressions to NFAs. The interaction of recursion and nesting leads to some nasty issues, that are discussed and resolved in [24]. For developping the present benchmark, we needed to add a treatment of typed wildcards such as `-char`. This is done by introducing typed else rules. For the query Q_2 we obtain: SHA in The nondeterministic SHA $A_2 = sha(Q_2)$. in Fig. 2. Similarly to the nested regular expression, this SHA may recognize some annotated nested words, that are not x-annotated examples, i.e., that do not belong to the language of the schema $L(xml\&one^x)$.

5.4 Determinization

The usual determinization algorithms for NFAs and tree automata can be lifted to a determinization algorithm for SHAs. When applied to query Q_2 however, we obtain a SHA with 25 states and 183 transition rules, which is much larger than one might expect. It is given in The determinization $\det(A_2)$ of the SHA A_2 in Fig. 5 of the appendix. Even worse, in some cases, the determinization algorithm does not finish after some hours.

5.5 Determinizing the Schema Product

Determinization applied to the product of the queries' automaton and the schema $xml\&one^x$ permits to compute deterministic automata for all queries of our benchmark within a timeout of 100 seconds. The result for Q_2 is a dSHA with 53 states and 110 transition rules, see automaton The determinization of the schema product $\det(A_2 \times xml\&one^x)$ in Fig. 6 of the appendix. The overall size is smaller, and the automaton is much easier to understand, but the number of states increased.

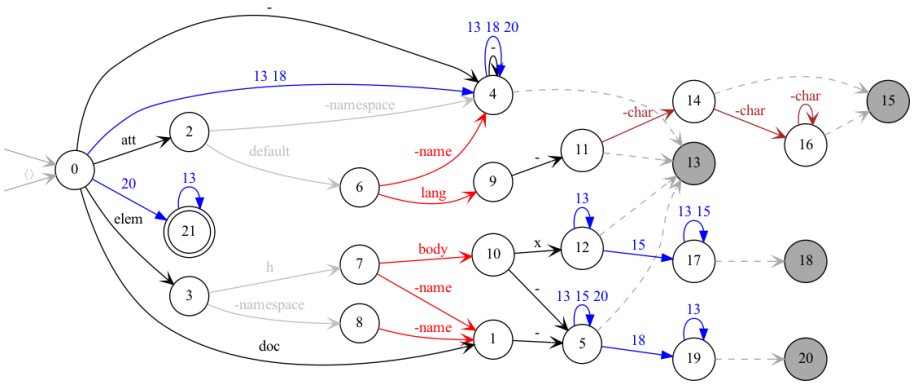

Fig. 3: The schema-based determinization $det_S(A_2)$ where $S = xml\&one^x$.

5.6 Schema-Based Determinization

Schema-based determinization as proposed in [25] improves the situation further. For query Q_2 it yields: SHA in The schema-based determinization $det_S(A_2)$ where $S = xml\&one^x$ in Fig. 3 which has only 22 states and 45 transitions. The size is roughly devided by 2 compared to: The determinization of the schema product $\det(A_2 \times xml\&one^x)$ in Fig. 6.

5.7 Minimization

We then minimize the dSHA from The schema-based determinization $det_S(A_2)$ where $S = xml\&one^x$ in Fig. 3. This often reduces the size and the number of states in an important manner and often makes it easy to see how the automaton is functioning. Exceptionally in the case of Q_2, no states are fusioned when minimizing the dSHA obtained by schema-based determinization.

It should be noticed that minimizing the determinization of the schema product usually yields a different result then minimizing the schema-based determinization. This is since both automata may recognize different languages. Some nested words outside the schema may be accepted after schema-based determinization, but not by the schema product.

5.8 Compiler to NWAs

The compiler finally maps SHAs to NWA*s* in linear time, while preserving determinism. For instance the minimal dSHA in The schema-based determinization $det_S(A_2)$ where $S = xml\&one^x$ in Fig. 3 is converted to: The dNWA $nwa(det(A_2))$ obtained from the dSHA $det(A_2)$ in Fig. 4.

6 Testing Automata on Samples

For testing the stepwise hedge automata, we created a sample with positive and negative x-annotated examples for each of the queries. Please contact the authors if you are interested in the test samples. They can be provided without problem.

For this we produced an *XML* document for each of the XSLT programs from which the XPATH queries of Lick and Schmitz were extracted. We did this in such a way that each of the queries has at least one answer on one of the subdocuments of the document of its collection. Subdocuments are important here, since the XPATH queries of an XSLT program will be applied to subdocumens naturally.

By using Saxon XSLT, we computed the answer set of all the queries on all the subdocument of the produced *XML* documents. For this, we exported query answers in Dewey notation, similarly to the way that nodes are returned by Schematron: The Dewey noation of a node is its relative address from the root, i.e., by the list of child steps leading to the node. Such lists can be easily encoded in *XML* format.

Each query query answer yields a positive x-annotated examples for the query, that is obtained by annotating the *XML* document by x at the selected position. Negative x-annotated examples are obtained from the answers of the

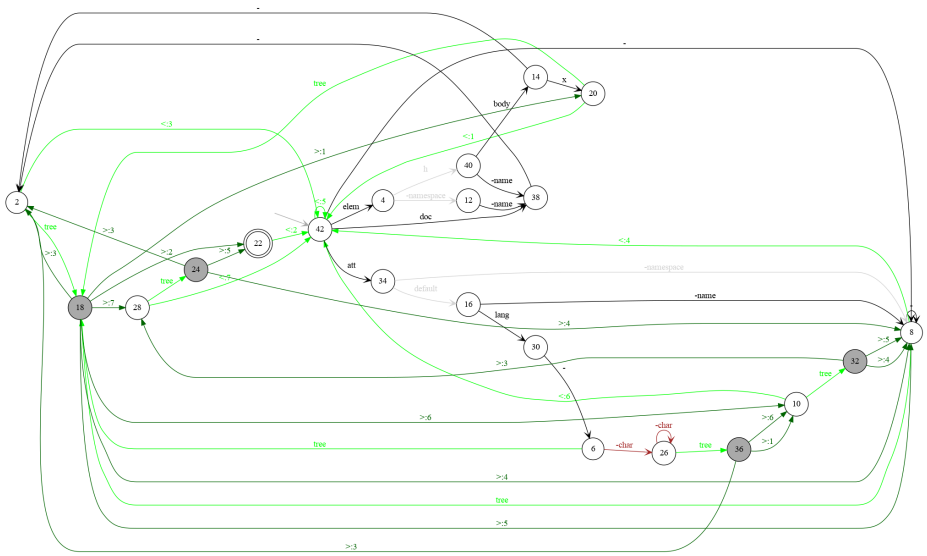

Fig. 4: The dNWA $nwa(det(A_2))$ obtained from the dSHA $det(A_2)$.

other queries on the same document. The annotation of the *XML* document is done by yet another XSLT stylesheet that we wrote for this purpose. Here we use the fact that query answers are also represented in *XML* format.

By testing the automaton on these samples, we could fix various problems that arised on the way to our final collection. Currently, no test failures are remaining, except for the query 13896 below that we removed from the corpus for the current version. The problem here is raised by the blank symbol in the attribute value `'evans citation'`:

```
//HEADER//IDNO[@TYPE='evans citation']
```

7 Statistics of the Benchmark Automata

We compiled all of our 79 XPATH queries to deterministic automata using the compilation chain described in in Section 5. Here we present the statistics of the benchmark automata that we obtained. The summary is given in in Table 2. We show for each automaton two numbers `size(#states)` where `size` is the overall size of the automaton and `#states` the number of its states.

The nondetermnistic SHAs compiled from the nested regular expressions was cleaned using the schema $xml\&one^x$: The dSHA $xml\&one^x$: a schema for x-annotated *XML* documents in Fig. 1. The result is called $A = sha(Q)$ leading to the statistics in the second column of in Table 2.

We note that 37% of the SHAs original stepwise hedge automata for the queries $A = sha(Q)$ have more than 100 states, so they are sometimes bigger than one might expect. The biggest is for query 06176 with 630 states and an overall size of 1391. The reason is that this query is selecting a union of 20 subqueries, all with descendant-or-self axis. Foe each subquery, we have 4 construsts of

respective state sizes: 2, 6, 10 and 13, making a subtotal of $31 * 20 = 620$. With an additional 8 states for one subquery that select all descendants with an attribute named *id* and another 2 for reading any tree, we end up with our total 630 states.

Table 2: Experiment results on the XPath subcorpus from Lick and Schmitz in Table 3. For each automaton we present: size(number-of-states).

query Q of id	A	det(A)	$B =$ det($A \times S$)	$C =$ $det_S(A)$	$B' =$ $mini(B)$	$C' =$ $mini(C)$	$nwa(C')$
18330	99 (41)	465 (43)	145 (44)	74 (22)	128 (39)	61 (18)	73 (18)
17914	179 (75)	2740 (141)	265 (69)	150 (44)	152 (43)	82 (24)	98 (24)
10745	187 (76)	939 (68)	275 (72)	141 (38)	218 (57)	130 (34)	150 (34)
02091	100 (42)	555 (45)	182 (57)	81 (24)	146 (44)	61 (17)	75 (17)
00744	109 (46)	335 (37)	169 (54)	80 (24)	128 (41)	54 (15)	64 (15)
12060	64 (25)	162 (22)	139 (44)	56 (16)	121 (39)	44 (12)	54 (12)
02762	121 (50)	564 (53)	222 (63)	97 (28)	123 (39)	46 (12)	56 (12)
06027	115 (48)	1101 (79)	184 (57)	82 (24)	123 (39)	46 (12)	56 (12)
02909	96 (38)	311 (36)	213 (62)	100 (27)	167 (49)	91 (24)	105 (24)
06415	139 (58)	1793 (93)	300 (74)	135 (36)	229 (55)	101 (25)	123 (25)
03257	130 (53)	1310 (92)	445 (85)	224 (46)	210 (49)	87 (20)	105 (20)
05122	83 (33)	292 (33)	221 (55)	92 (23)	161 (44)	63 (16)	77 (16)
09138	269 (117)		323 (97)	164 (49)	133 (40)	56 (13)	66 (13)
05460	232 (98)	3468 (174)	509 (127)	269 (77)	156 (44)	62 (16)	76 (16)
12404	84 (33)	258 (31)	170 (52)	77 (22)	143 (44)	68 (19)	82 (19)
10337	92 (36)	291 (34)	197 (58)	92 (25)	159 (47)	83 (22)	97 (22)
06639	123 (50)	516 (49)	237 (65)	106 (30)	154 (44)	60 (16)	74 (16)
14340	79 (33)	231 (29)	126 (40)	58 (18)	110 (36)	45 (14)	55 (14)
13804	70 (29)	155 (21)	128 (41)	63 (20)	124 (40)	60 (19)	70 (19)
02194	81 (33)	253 (31)	135 (42)	66 (20)	119 (38)	53 (16)	63 (16)
06726	149 (64)	2806 (149)	176 (53)	97 (30)	121 (38)	55 (16)	65 (16)
13640	100 (41)	364 (40)	165 (50)	86 (26)	140 (43)	76 (23)	90 (23)
05735	111 (45)	412 (44)	201 (58)	106 (30)	161 (47)	96 (27)	110 (27)
15766	144 (58)	669 (60)	300 (77)	155 (41)	219 (57)	135 (35)	151 (35)
15539	217 (88)	1709 (121)	402 (98)	213 (58)	228 (57)	144 (38)	164 (38)
15809	197 (84)	3795 (188)	230 (67)	129 (39)	145 (43)	82 (24)	96 (24)
15524	125 (50)	471 (49)	245 (68)	130 (35)	185 (52)	120 (32)	134 (32)
06512	135 (56)	583 (58)	218 (60)	117 (35)	152 (43)	77 (23)	91 (23)
06176	1391 (630)		1661 (448)	1203 (386)	176 (43)	113 (23)	127 (23)
12539	179 (76)	3479 (174)	243 (69)	138 (40)	166 (48)	101 (28)	115 (28)

11780	205 (88)	3832 (190)	254 (71)	143 (41)	164 (47)	99 (27)	113 (27)
11478	101 (41)	365 (40)	166 (50)	87 (26)	141 (43)	77 (23)	91 (23)
11227	153 (62)	583 (53)	334 (81)	163 (42)	244 (59)	144 (37)	166 (37)
05684	1348 (616)		1068 (284)	719 (226)	193 (39)	124 (16)	134 (16)
06947	744 (342)		828 (232)	444 (129)	151 (41)	71 (14)	83 (14)
06794	270 (121)		354 (102)	178 (51)	144 (42)	64 (15)	76 (15)
06169	346 (155)		427 (121)	219 (62)	147 (41)	67 (14)	79 (14)
06924	598 (274)		682 (192)	362 (105)	147 (41)	67 (14)	79 (14)
11958	109 (44)	348 (35)	213 (57)	90 (24)	178 (48)	76 (20)	94 (20)
01705	772 (350)		1308 (279)	746 (172)	221 (48)	113 (19)	129 (19)
02086	809 (367)		1366 (291)	781 (180)	223 (48)	115 (19)	131 (19)
02000	642 (291)		723 (201)	387 (110)	163 (41)	83 (14)	95 (14)
02697	383 (172)		464 (131)	240 (68)	149 (41)	69 (14)	81 (14)
14183	110 (44)	362 (36)	217 (58)	94 (25)	182 (49)	80 (21)	98 (21)
07106	457 (206)		538 (151)	282 (80)	153 (41)	73 (14)	85 (14)
05824	62 (25)	150 (21)	130 (42)	50 (15)	112 (37)	38 (11)	48 (11)
11368	102 (41)	458 (44)	247 (62)	104 (28)	191 (49)	78 (20)	96 (20)
15848	124 (49)	303 (35)	221 (63)	103 (27)	179 (51)	100 (26)	114 (26)
15462	127 (50)	325 (37)	237 (67)	112 (29)	191 (54)	109 (28)	123 (28)
04267	87 (34)	146 (20)	137 (43)	54 (15)	131 (41)	51 (14)	63 (14)
07113	695 (296)		2409 (456)	1527 (302)	311 (73)	229 (48)	241 (48)
03864	272 (121)		353 (101)	177 (50)	143 (41)	63 (14)	75 (14)
15484	181 (71)	657 (62)	394 (96)	189 (47)	277 (68)	174 (42)	194 (42)
15461	146 (58)	628 (54)	651 (109)	283 (51)	241 (59)	140 (33)	160 (33)
11160	309 (138)		390 (111)	198 (56)	145 (41)	65 (14)	77 (14)
06856	306 (138)		390 (112)	198 (57)	139 (41)	59 (14)	71 (14)
06458	827 (376)		908 (251)	492 (140)	173 (41)	93 (14)	105 (14)
13710	420 (189)		501 (141)	261 (74)	151 (41)	71 (14)	83 (14)
06808	525 (240)		609 (172)	321 (93)	145 (41)	65 (14)	77 (14)
04338	470 (206)		1066 (207)	563 (135)	213 (51)	95 (22)	115 (22)
04358	1006 (444)		3580 (559)	2021 (433)	757 (99)	345 (58)	401 (58)
13632	132 (58)	339 (33)	248 (66)	113 (33)	128 (36)	47 (9)	55 (9)
01847	559 (252)		1013 (223)	543 (137)	194 (48)	92 (19)	108 (19)
05219	698 (315)		1192 (260)	651 (164)	196 (48)	94 (19)	110 (19)
05226	920 (417)		1558 (338)	867 (218)	208 (48)	106 (19)	122 (19)
03325	753 (342)		834 (231)	450 (128)	169 (41)	89 (14)	101 (14)
03410	938 (427)		1019 (281)	555 (158)	179 (41)	99 (14)	111 (14)
03407	716 (325)		797 (221)	429 (122)	167 (41)	87 (14)	99 (14)

04245	901 (410)		982 (271)	534 (152)	177 (41)	97 (14)	109 (14)
04953	938 (427)		1019 (281)	555 (158)	179 (41)	99 (14)	111 (14)
05463	204 (86)	1180 (70)	332 (77)	152 (38)	180 (48)	78 (20)	96 (20)
12960	167 (68)	1340 (81)	421 (88)	190 (46)	317 (64)	146 (33)	176 (33)
12961	166 (68)	1318 (80)	417 (87)	186 (45)	313 (63)	142 (32)	172 (32)
09123	164 (64)	705 (59)	358 (90)	175 (43)	265 (66)	164 (40)	186 (40)
12514	182 (77)	2734 (112)	320 (77)	146 (38)	247 (57)	114 (28)	140 (28)
12964	128 (52)	560 (48)	277 (67)	120 (31)	219 (53)	96 (24)	118 (24)
08632	128 (52)	629 (51)	277 (67)	120 (31)	219 (53)	96 (24)	118 (24)
12962	129 (52)	576 (49)	281 (68)	124 (32)	223 (54)	100 (25)	122 (25)

The column for $\det(A)$ contains the statistics for the determinization of A. No schema is used there. We use a timeout of 100 seconds. Whenever this is not enough, the cell in the table is left blank. Indeed, the determinization fails with this timeout for 37% of the queries of our corpus. Roughly, the determinization fails for all SHAs with more than 100 states. For instance, for query 11780 the SHA A has has size 205 (88), while the dSHA $\det(A)$ has size 3832 (190).

The column for $B = \det(A \times S)$ contains the determinization of the product of A and the schema $S = xml\&one^x$. Even though $A \times S$ is always larger than A, we were able to always determinize $A \times S$ within the timeout, in contrast to A. The largest dSHA B obtained is for for query 04358: it has size 3580 (559). This show that B may still be quite big, but often a big improvement in size over $\det(A)$.

The next column reports on $C = det_S(A)$ obtained by schema-based determinization with schema $S = xml\&one^x$. Again, the computation succeeds in all cases within the timeout of 100 seconds. The size of C for query 04358 is 2021 (433), which improves in size over B.

In the next two columns, we respectively minimize the determinized SHAs B and C, using a naïve minimization algorithm. All automata can be minimized within the timeout of 100 seconds. We note that $C' = mini(C)$ is always smaller than $B' = mini(B)$, showing that schema-based determinization yields smaller minimal automata than determinizing the schema-product. The maximal number of states of the minimal dSHAs $C' = mini(C)$ is 58 for query 04358. In average the number of states decreases by 55%.

In the last column, we compiled the minimized dSHAs of C' to the dNWA $nwa(C')$. It has the same number of states than C' for all queries and a minor increase is the number of transitions. All these results, including the automata of the intermediate steps, generated during the whole compilation chain are available at in the software heritage archive at the following url: `https://archive.softwareheritage.org/browse/origin/?origin_url=https://gitlab.inria.fr/aalserha/xpath-benchmark`.

8 Conclusion

We provide a benchmark of deterministic automata for regular XPath queries obtained with an algorithm for schema-based determinization of symbolic SHAs that we presented. Our benchmark is compiled from forward navigational XPath queries: the 79 largest queries modulo renaming of the 4500 forward navigational XPath queries of the corpus of Lick and Schmitz [19]. From the SHAs of these 79 queries, 37% cannot be determinized in less then 100 seconds by schema-less determinization. Schema-based determinization, in contrast, succeeds for 100% of them. Furthermore, all dSHAs obtained by schema-based determinization are sufficiently small so that they can be minimized with the naïve quadratic algorithm. This leads us to a collection of minimal dSHAs with an average number of states of 22, and 71 as the average number of transition rules.

We hope that the automata of our collection will be used for experimenting with algorithms for XPath queries in the near future and for developing and comparing the performance of algorithms for answering XPath queries on *XML* streams in particular.

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A Complementary Information

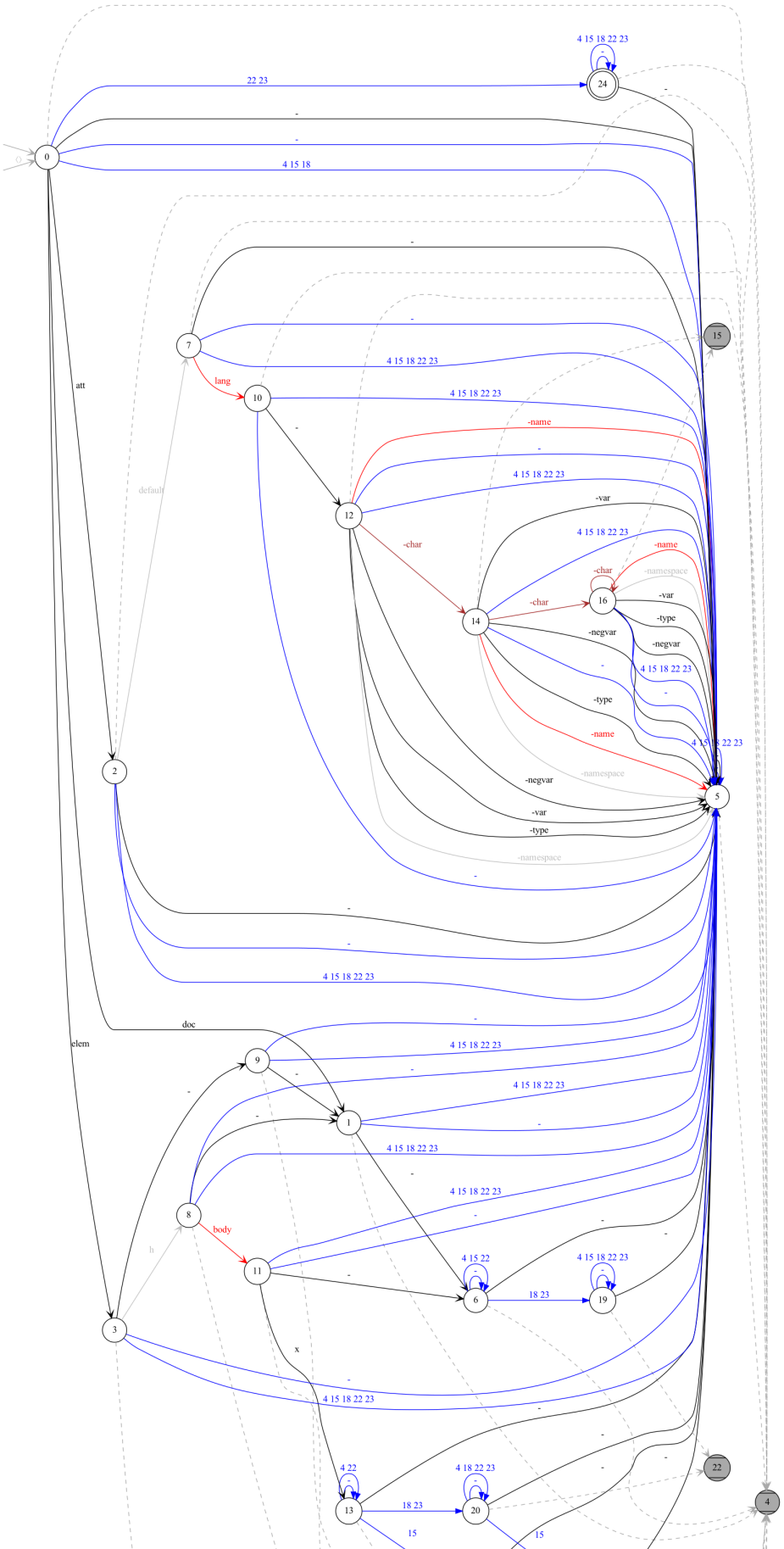
Table 3: The 79 largest forward navigational queries of the XPath corpus of Lick and Schmitz without dublicates up to renaming.

Id	XPath Query
18330	/ descendant-or-self::node()/child::parts-of-speech
17914	/ descendant-or-self::node()/child::tei:back/descendant-or-self::node()/child::tei:interpGrp
10745	*//tei:imprint/tei:date[@type='access']
02091	* | .//refentry
00744	.//@id | .//@xml:id
12060	.//attDef
02762	.//authorgroup/author | .//author
06027	.//authorinitials | .//author
02909	.//bibliomisc[@role='serie']
06415	.//email | address/otheraddr/ulink
03257	.//equation[title or info/title]
05122	.//procedure[title]
09138	.//rng:ref | .//tei:elementRef | .//tei:classRef | .//tei:macroRef | .//tei:dataRef
05460	.//table//footnote | .//informaltable//footnote
12404	.//tei:dataRef[@name]
10337	.//tei:note[@place='end']
06639	.//tgroup//footnote
14340	//*
13804	//GAP/@DISP
13896	//HEADER//IDNO[@TYPE='evans citation']
02194	//annotation
06726	//doc:table | //doc:informaltable
13640	//equiv[@filter]
05735	//glossary[@role='auto']
15766	//h:body/h:section[@data-type='titlepage']
15524	//h:section[@data-type='titlepage']
06512	//refentry//text()
06176	//set | //book | //part | //reference | //preface | //chapter | //appendix | //article | //colophon | //refentry | //section | //sect1 | //sect2 | //sect3 | //sect4 | //sect5 | //indexterm | //glossary | //bibliography | //*[@id]
12539	//tei:elementSpec | //tei:classSpec[@type='atts']
11780	//tei:ref[@type='cite'] | //tei:ptr[@type='cite']

11478	//xhtml:p[@class]
11227	/tei:TEI/tei:text//tei:note[@type='action']
05684	@abbr | @align | @axis | @bgcolor | @border | @cellpadding | @cellspacing | @char | @charoff | @class | @dir | @frame | @headers | @height | @id | @lang | @nowrap | @onclick | @ondblclick | @onkeydown | @onkeypress | @onkeyup | @onmousedown | @onmousemove | @onmouseout | @onmouseover | @onmouseup | @rules | @scope | @style | @summary | @title | @valign | @valign | @width | @xml:id | @xml:lang
06947	anchor | areaset | audiodata | audioobject | beginpage | constraint | indexterm | itermset | keywordset | msg | doc:anchor | doc:areaset | doc:audiodata | doc:audioobject | doc:beginpage | doc:constraint | doc:indexterm | doc:itermset | doc:keywordset | doc:msg
06794	articleinfo | chapterinfo | bookinfo | doc:info | doc:articleinfo | doc:chapterinfo | doc:bookinfo
06169	article | preface | chapter | appendix | refentry | section | sect1 | glossary | bibliography
06924	authorblurb | formalpara | legalnotice | note | caution | warning | important | tip | doc:authorblurb | doc:formalpara | doc:legalnotice | doc:note | doc:caution | doc:warning | doc:important | doc:tip
11958	biblStruct//note
01705	book | article | part | reference | preface | chapter | bibliography | appendix | glossary | section | sect1 | sect2 | sect3 | sect4 | sect5 | refentry | colophon | bibliodiv[title] | setindex | index
02086	book | article | topic | part | reference | preface | chapter | bibliography | appendix | glossary | section | sect1 | sect2 | sect3 | sect4 | sect5 | refentry | colophon | bibliodiv[title] | setindex | index
02000	chapter | appendix | epigraph | warning | preface | index | colophon | glossary | biblioentry | bibliography | dedication | sidebar | footnote | glossterm | glossdef | bridgehead | part
02697	chapter | appendix | preface | reference | refentry | article | topic | index | glossary | bibliography
14183	content//rng:ref
07106	dbk:appendix | dbk:article | dbk:book | dbk:chapter | dbk:part | dbk:preface | dbk:section | dbk:sect1 | dbk:sect2 | dbk:sect3 | dbk:sect4 | dbk:sect5
05824	descendant-or-self::*
11368	descendant-or-self::tei:TEI/tei:text/tei:back
15848	descendant::*[@class='refname']
15462	descendant::h:span[@data-type='footnote']
04267	descendant::label

07113	following-sibling::*[self::dbk:appendix | self::dbk:article | self::dbk:book | self::dbk:chapter | self::dbk:part | self::dbk:preface | self::dbk:section | self::dbk:sect1 | self::dbk:sect2 | self::dbk:sect3 | self::dbk:sect4 | self::dbk:sect5] | following-sibling::dbk:para[@rnd:style = 'bibliography' or @rnd:style = 'bibliography-title' or @rnd:style = 'glossary' or @rnd:style = 'glossary-title' or @rnd:style = 'qandaset' or @rnd:style = 'qandaset-title']
03864	guibutton | guiicon | guilabel | guimenu | guimenuitem | guisubmenu | interface
15484	h:pre[@data-type='programlisting']//text()
15461	h:table[descendant::h:span[@data-type='footnote']]
11160	html:table | html:tr | html:thead | html:tbody | html:td | html:th | html:caption | html:li
06856	imageobject | imageobjectco | audioobject | videoobject | doc:imageobject | doc:imageobjectco | doc:audioobject | doc:videoobject
06458	info | refentryinfo | referenceinfo | refsynopsisdivinfo | refsectioninfo | refsect1info | refsect2info | refsect3info | setinfo | bookinfo | articleinfo | chapterinfo | sectioninfo | sect1info | sect2info | sect3info | sect4info | sect5info | partinfo | prefaceinfo | appendixinfo | docinfo
13710	persName | orgName | addName | nameLink | roleName | forename | surname | genName | country | placeName | geogName
06808	personname | surname | firstname | honorific | lineage | othername | contrib | doc:personname | doc:surname | doc:firstname | doc:honorific | doc:lineage | doc:othername | doc:contrib
04338	refsynopsisdiv/title | refsection/title | refsect1/title | refsect2/title | refsect3/title | refsynopsisdiv/info/title | refsection/info/title | refsect1/info/title | refsect2/info/title | refsect3/info/title
04358	section/title | simplesect/title | sect1/title | sect2/title | sect3/title | sect4/title | sect5/title | section/info/title | simplesect/info/title | sect1/info/title | sect2/info/title | sect3/info/title | sect4/info/title | sect5/info/title | section/sectioninfo/title | sect1/sect1info/title | sect2/sect2info/title | sect3/sect3info/title | sect4/sect4info/title | sect5/sect5info/title
13632	self::placeName | self::persName | self::district | self::settlement | self::region | self::country | self::bloc
01847	set | book | part | preface | chapter | appendix | article | reference | refentry | book/glossary | article/glossary | part/glossary | bibliography | colophon
05219	set | book | part | preface | chapter | appendix | article | topic | reference | refentry | book/glossary | article/glossary | part/glossary | book/bibliography | article/bibliography | part/bibliography | colophon

05226	set | book | part | preface | chapter | appendix | article | topic | reference | refentry | sect1 | sect2 | sect3 | sect4 | sect5 | section | book/glossary | article/glossary | part/glossary | book/bibliography | article/bibliography | part/bibliography | colophon
03325	set | book | part | reference | preface | chapter | appendix | article | topic | glossary | bibliography | index | setindex | refentry | sect1 | sect2 | sect3 | sect4 | sect5 | section
03410	set | book | part | reference | preface | chapter | appendix | article | topic | glossary | bibliography | index | setindex | refentry | refsynopsisdiv | refsect1 | refsect2 | refsect3 | refsection | sect1 | sect2 | sect3 | sect4 | sect5 | section
03407	set | book | part | reference | preface | chapter | appendix | article | glossary | bibliography | index | setindex | refentry | sect1 | sect2 | sect3 | sect4 | sect5 | section
04245	set | book | part | reference | preface | chapter | appendix | article | glossary | bibliography | index | setindex | refentry | refsynopsisdiv | refsect1 | refsect2 | refsect3 | refsection | sect1 | sect2 | sect3 | sect4 | sect5 | section
04953	set | book | part | reference | preface | chapter | appendix | article | glossary | bibliography | index | setindex | topic | refentry | refsynopsisdiv | refsect1 | refsect2 | refsect3 | refsection | sect1 | sect2 | sect3 | sect4 | sect5 | section
07095	sf:stylesheet | sf:stylesheet-ref | sf:container-hint | sf:page-start | sf:br | sf:selection-start | sf:selection-end | sf:insertion-point | sf:ghost-text | sf:attachments
05463	table//footnote | informaltable//footnote
12960	tei:classSpec/tei:attList//tei:attDef/tei:datatype/rng:ref
12961	tei:classSpec/tei:attList//tei:attDef/tei:datatype/tei:dataRef
09123	tei:content//rng:ref[@name = 'macro.anyXML']
12514	tei:content/tei:classRef | tei:content//tei:sequence/tei:classRef
12964	tei:dataSpec/tei:content//tei:dataRef
08632	tei:front//tei:titlePart/tei:title
10595	tei:label | tei:figure | tei:table | tei:item | tei:p | tei:title | tei:bibl | tei:anchor | tei:cell | tei:lg | tei:list | tei:sp
12962	tei:macroSpec/tei:content//rng:ref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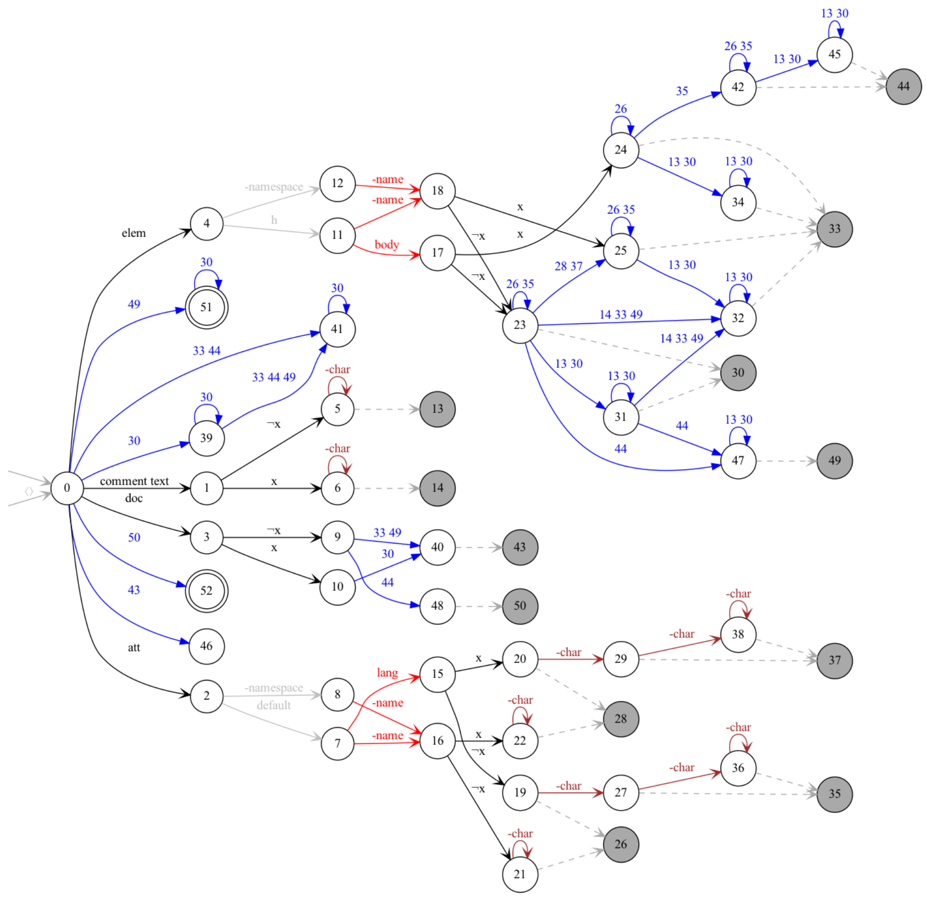

Fig. 6: The determinization of the schema product $\det(A_2 \times xml\&one^x)$.