Fast XML/HTML for Haskell: XML TypeLift

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Abstract
The paper presents and compares a range of parsers with and without data mapping for conversion between XML and Haskell. The best performing parser competes favorably with the fastest tools available in other languages and is, thus, suitable for use in large-scale data analysis. The best performing parser also allows software developers of intermediate-level Haskell programming skills to start processing large numbers of XML documents soon after finding the relevant XML Schema from a simple internet search, without the need for specialist prior knowledge or skills. We hope that this unique combination of parser performance and usability will provide a new standard for XML mapping to high-level languages.

1 Introduction
XML is the current dominant format for document interchange, being optimized for long-term schema evolution and extensibility[10, 16, 27, 28]. Importantly, XML is based on a number of different data formats, most of which are of practical and commercial interest. That is because they allow system evolution over long time span (in case of PDB[16] since 1976, in case of FixML since 1992[11].)

This report will review the latest developments in the generation of efficient parsers in Haskell. Haskell is a high-level language that incorporates parsing plain XML of unknown format at a speed that is comparable with leading parsers already available in low-level languages. Haskell also automatically generates high-level representations of document content from XML Schema, the current dominant schema description language for XML.

1.1 Use of XML
Having been widely accepted and adopted as the standard for transmission and data storage, XML’s self-descriptive tree structure confers two important user benefits: simplified and standardized data processing. By storing data in plain text format, XML facilitates simple data sharing, transport, and historical storage, without encountering any hardware, software or platform compatibility problems. Importantly, XML offers operational compatibility through its common syntax to enable transfer of messages across communication systems of differing formats.

The generation of significant volumes of XML data has initiated a wealth of active research into rapid parsing[13, 14, 26].

1.2 XML Schema
The overall XML domain is vast, with individual XML file formats being tailored to specific needs and applications. While XML’s self-descriptive structure and file format allows information to be easily ingested, most application areas require strict validation rules to ensure the logical correctness of XML documents.

In 2001, the W3C formally recommended the XML Schema[37] for the description and validation of XML document structure and content by defining document elements, attributes and data types. As extensive-type descriptions, XSDs are helpful for standardizing the large number of XML formats in current use. They do this not only by defining document structure and elements, but also by setting out formal requirements for document validation. Most W3C XML formats have XML Schema definitions that have been developed and standardized by ISO/IEC; the same applies for all ECMA standards, including Microsoft Open-XML and the LibreOffice OpenDocument format.

For newcomers to the field, we now summarize key features of XML Schema. Self-descriptive representation of XML documents encoded with the following: (I) <xs:element> for each XML elements with an option of cardinality constraints, such as minOccurs=0, and maxOccurs=5; (II) an <xs:attribute> for every XML attribute; (III) content representation as regular trees composed of nested (a)<xs:sequence> for a number of elements in a fixed order; (b) <xs:choice> for when any of a number of elements (or (c) <xs:sequence> entries) may be given; (d) <xs:all> for a fixed sequence of elements in any order; (e) mixed="true" for situations where a given sequence of elements may be interwoven with free-form text. It also has rich, named types: (I) number of predefined types with ISO-standards for text representations; (II) xs: any type for when arbitrary XML fragments must be embedded; (III) distinction between xs:text and identifier type xs:token; (IV) syntactic distinction of flat types (<simpleContent>) and tree fragment types (<complexContent>).
Finally it possesses typical programming language facilities for organizing many definitions, including namespaces, comments, and cross-references for data modeling.

Namespaces for element element identifiers and references (ref="id"), so that the same element can be used in different document locations; (I) <xs:group> for groups of elements or attributes that are commonly found together; (II) ability to restrict the value of any type to a subset, implementing <xs:restriction> as a list of values, or a regular expression pattern; (III) ability to form object-oriented hierarchy of types, where xs:extension adds new attributes, and append further content in xs:sequence or provide for alternatives with xs:choice (xs:sequence cannot be extended with xs:choice, and vice-versa); (IV) xs:key and xs:unique constraints that record cross-references within the document, and provide XPath-like expressions for validation.

1.3 Previous work on parsing XML in Haskell

Two current approaches exist for programming XML document processing systems when using functional languages such as Haskell[38]. In the first approach, the XML document takes a tree-like structure that then forms the basis for designing a library of combinators that perform generic XML document processing tasks: selection, generation and transformation of document trees. The second approach uses a type translation framework that is similar to object-relational mapping frameworks; this allows idiomatic XML schemas to be translated into idiomatic Haskell data declarations.

In response to the large number of diverse XML datasets that are in current use, there has, to date, been a wealth of rich research into the efficiency of XML data set ingestion[7, 18–20, 22, 30, 34].

Haskell’s many packages for manipulating XML data sets include

- **xml-conduit** [32]: provides streamed parsing and rendering functions for XML.
- **HaXML** [39]: a collection of utilities that use Haskell for parsing, filtering, transforming and generating XML documents. The utilities include an XML parser and validator, a stream parser for XML events, a combinator library and two translators, one of which translates from DTD to Haskell and another which translates from XML Schema definitions to Haskell data types (both translators include associated parsers and pretty printers).
- **XsdToHaskell** [39]: an HaXML tool to translate valid XML Schema definitions into equivalent Haskell types, together with SchemaType instances.
- **hxt** (Haskell XML Toolbox [31]): a collection of Haskell tools for XML processing whose core component is a domain-specific language with a set of combinators for XML tree processing. Although based on HaXml, hxt uses a generic data model to represent XML documents, including the DTD subset and the document subset, in Haskell.
- **hexml**[25]: a fast, DOM-style XML parser that parses only a subset of the XML. This parser skips entities and does not support <!DOCTYPE-related features.
- **xeno**[8]: a fast, low-memory use, event-based XML parser, written in pure Haskell. A key feature is that it includes an SAX [24]-style parser, which triggers events such as tags and attributes.

1.4 The need for high performance parser generators

Here, we aim to develop a practical, high-performance XML parser, possibly by compromising on strict conformance to XML namespaces, and avoiding strict validation.

Since no pre-existing XML document validation tools exist, our novel parser will enable fast and safe parsing of multiple large XML documents in order to perform analyses, and to update databases. The only existing parsing applications that have similar functionality to our target parser are Protein Databank, which has over 166 thousand depositions [5, 15, 16], and real-time processing of FixML [11] messages.

A secondary aim of our work is that the majority of programmers should not need to consider the complexity of parsing inputs; this will be achieved by abstracting the parser in such a way as to avoid low-level drudgery.

2 Usage

To demonstrate the practical use of xml-typelift, we here give an example of a simplified user.xml document that conforms to the user.xsd XML Schema.

As a test case, we present code that prints the contents of the name element.

Typical XML Schema:

```
<xs:schema
 xmlns:xs="http://www.w3.org/2001/XMLSchema">
 <xs:element name="users">
   <xs:complexType>
     <xs:sequence>
       <xs:element name="user" type="UserType" minOccurs="0" maxOccurs="unbounded"/>
     </xs:sequence>
   </xs:complexType>
 </xs:element>
</xs:schema>
```

```
<xs:complexType name="UserType" mixed="false">
 <xs:sequence>
   <xs:element name="uid" type="xs:int"/>
   <xs:element name="name" type="xs:string"/>
   <xs:element name="bday" type="xs:date"
```
An example document would be:

```xml
<?xml version="1.0" encoding="utf-8"?>
<users>
    <user>
        <uid>123</uid>
        <name>John</name>
        <bday>1990-11-12</bday>
    </user>
</users>
```

### 2.1 Parsing XML with DOM

Here, we present an example program that returns a list of all `<name>` nodes in the input document:

```haskell
import Xeno.DOM
import qualified Data.ByteString as BS

processFile filename = do
    Right result <- BS.readFile filename >>= Xeno.parse.inp
    print $ filter isName $ allNodes result
    where
        isName node = BS.toLower (Xeno.name n) == "name"
```

This code is recommended in circumstances that require an HTML parsing engine that is faster than those commonly available in Python [23].

### 2.2 Parsing XML documents in an event-based manner

The Xeno.SAX parser follows the SAX [24] model of XML parsing, whereby the input is scanned. Rather than returning tokens, Xeno.SAX calls back upon finding a critical point in the input, with pointers to string values.

The callback set can be represented by the following Haskell data structure:

```haskell
data Process a = Process {
    openF :: ByteString -> a,
    attrF :: ByteString -> ByteString -> a,
    endOpenF :: ByteString -> a,
    textF :: ByteString -> a,
    closeF :: ByteString -> a,
    cdataF :: ByteString -> a
}  

process :: (Monad m, VectorizedString str) => Process (m ()) -> str -> m ()
```

This method of processing not only induces inversion of control, but also makes the program more difficult to understand. It does, however, result in faster code, especially when callbacks can be statically inlined, as is usually the case.

In order to simplify the definition of new parsers, we propose reification of the callback set into a record. If our parser needs only to process text nodes, then we can use a default instance that does nothing, and redefine `textF` callback as follows:

```haskell
textPrinter = def { textF = putStrLn }
```

Event-based parsers are based on the concept of passing a function record with callbacks; in practical terms, this mode of parsing is inconvenient.

In the code below, we utilize an ST monad that maintains an imperative state under purely functional wraps [21], thus creating a reference for keeping the current output with `newSTRef`.

```haskell
import Xeno.SAX as Xeno
import qualified Data.ByteString as BS
import qualified Data.ByteString.Lazy as BSL
import Data.Default (def)

processFile filename = do
    input <- BS.readFile filename
    allPres <- stToIO $ do
        results <- newSTRef ([] :: BSL.ByteString)
        current <- newSTRef ([] :: BS.ByteString)
        selected <- newSTRef False
        For each event, we update the partial output reference.
        Note that, in this case, when opening `openF` of a new XML element `<name>`, we are in the selected fragment when closing `closeF` of the XML element `</name>`. Also, note that we are outside the selected fragment for each text node `textF`, and we verify whether we are within the selected fragment, appending it to the results whenever the verification is positive.

        let openF bs@(BS.toLower -> "name") = case bs of
            BS.PS _ start len -> writeSTRef selected True
            BS.PS _ start len -> return ()
        textF t = do
            isSelected <- readSTRef selected
            when isSelected $ modifySTRef current (t:)
            closeF bs@(BS.toLower -> "name") = do
                content <- BSL.fromChunks . reverse <$> readSTRef current
                modifySTRef' results (content:)
                writeSTRef current []
```

Having now built the event handlers, the final step is to call the actual parser with the record of event handlers:
Xeno.process (def {openF, closeF, textF})
input
readSTRef results

After calling the parser, we read the final result using the function readSTRef.

2.3 Obtaining fully typed outputs using parser generators

It is easy to obtain fully typed Haskell representations from XML Schema. The user must first find the XML Schema that describes the input format on the internet standard or from an XML schema repository.

Next, the XML Schema is handed to XML Typelift, which generates a Haskell module that describes both parser and mapping to Haskell ADT:

```
$ xml-typelift-cli --schema InputSchema.xsd
   --output InputSchema.hs
```

We then immediately test the generated parser and examine the output structure:

```
$ runghc InputSchema.hs input.xml
```

The obtained result is then used by the programmer to determine how to access parsed data structure in the specific program. Specifically, XML TypeLift uses a name generation monad [2] to ensure that the resulting code is readable and comprehensible for Haskell programmers of intermediate skill level.

It is easier to process an example generated ADT than an original XML Schema:

```haskell
data Users = Users { users: [User] }
data User = User { uid :: Int, name :: String, bday :: Maybe Date }
```

This ADT is easily read by the standard parser interface from a generated module:

```
parse :: ByteString -> Either String Users
```

We can, therefore, use it to extract the data in an example user program:

```haskell
import UsersSchema(parse, Users(..))
processFile filename = do
  Right users <- BS.readFile filename >>= parse
  print $ map name users
```

This interface is preferable, and we will now explain how to ensure that it’s speed is comparable to the DOM and SAX approaches.

3 Performance techniques

3.1 Code generation as a scalable method of fast parsing

Code generation has an undeserved reputation for producing arcane code that is difficult to read, due to its algorithmic origin; this raises concerns regarding the malicious use of code generation [36]. In this context, we make a specific effort to ensure that our parser generator is easy to read and, thus, properly accessible and customizable. To do this, we first use an abstract interface to the input string; this allows future parser enhancement by vectorization using the VectorizedString class.

Since XML TypeLift originated from Xeno, we now discuss performance techniques for both libraries together; we generate independent code using the same performance techniques as before, before backporting them to Xeno.

3.1.1 Splitting and representing tokens

Conventionally, parsers start by distinguishing tokens and keywords in the input, and then selecting an efficient representation for them. This can be achieved by making an ADT data structure or a hash table that maps each token type to an integer code. Since, in XML, key tokens are identifiers and text fragments, we choose to take advantage of the ByteString library to represent their content as two offsets into the input string.

Capitalizing on the tradition of fast XML parsing in the SAX [24] model, we implicitly represent tokens by distinguishing callback functions that process each token; we expect these functions to be duly inlined by the Haskell compiler.

3.1.2 Performant string representation

Haskell programs use the Bytestring library[4], which examines large input strings efficiently by reducing each object to: (a) a foreign pointer to the input; (b) an offset to the beginning of the string in the input; (c) and an offset to the end of the string in the input.

When using this data structure for fast parsing of a known input, we add a null byte to the end so that it is not necessary to check that no offsets transcend the input end. Additionally, by factoring out a class of string representations that allow efficient scanning, interested programmers can find even more efficient representations that offer a safe interface.

For our specific purposes of parsing source XML documents, we wish to parse both UTF-16 and UTF-8 string representations without needing to write a large library variant to the Bytestring library. An additional benefit of this input representation is its time-saving nature compared to mapping from a file. Whenever this read-only structure is unnecessary, the operating system purges any relevant pages from memory, since the runtime system simply interprets those pages as a large foreign object that has no pointers and, therefore, not worthy of collecting. This turns out to be important, since our benchmarks show that most of our parser prototypes were limited by garbage collector performance.

**Vectorized string interface class** Careful examination reveals that only five operations are necessary for fast XML...
parsing, so that it compiles well to yield fast Low Level Virtual Machine (LLVM) code:

```haskell
class VectorizedString where
    s_index :: str -> Int -> Char
-- | Find the first occurrence
elemIndexFrom :: Char -> str -> Int -> Maybe Int
-- | Extract substring between offsets
substring :: str -> Int -> Int -> str
-- | Move cursor forward
drop :: Int -> str -> str
-- | Is the output exhausted
null :: str -> Bool
```

These operations are easy to define for strings and they provide a fixed minimal interface that allows for easy optimization by the compiler. Regarding encoding, they assume, for optimal implementation, that:

- any given character has a unique representation that does not overlap with the encoding of other characters (possibly multibyte) (for scanning with elemIndexFrom);
- instance is able to perform O(1)-indexing, similar to an array with s_index;
- low-overhead operations on the cursor to the immutable string:
  - shift forward with drop,
  - extract a substring that can be returned to the user with a substring (or alternatively taking prefix with take), and
  - scan rapidly for a token boundary character such as <, >, or ", which can be vectorized by the compiler.

The unique UTF-8\[29\] and UTF-16 \[35\] encodings satisfy this set of assumptions since it is not possible to mistake single word encoding of an ASCII character with words that are parts of multibyte encodings.

We implemented these VectorizedString str type class in Haskell for a number of different string representations:

- UTF-8 with both (i) classical ByteString, and (ii) ByteString with guaranteed termination by \NUL character. Case (ii) is faster than case (i) since it does not check the range of xxx.
- UTF-16, while offering a less memory efficient document representation, allows direct memory-mapping of files stored in UTF-16.

The ease with which these string representations can be implemented offers hope that it is easy to apply SIMD vectorization as a next step.\[5\]

**Null character termination** When considering ByteString efficiency, one should notice that our parsing scans are performed by elemIndexFrom; the interface can, thus, be enhanced by implementing implicit termination. Since we expect most of our input data to be large, adding zero at the end and allocating a single segment of unreadable virtual memory just after the ByteString would offer an acceptable tradeoff to the increased parsing speed for inputs of size in the megabyte to gigabyte range.

Thus, elemIndexFrom starts checking for either a given character or null termination of a given length.

### 3.1.3 Compressed output tree

Large XML documents produce huge data structures that significantly increase garbage collection time. Since the data structures are usually read-only, we opt to take a shortcut, as now described. First, we encode strings as offsets to the input string; this is typical when using the ByteString library. Next, we create a large array of offsets (not pointers) in the original input; these offsets replace all other possible pointers. Therefore, any cell in the offset array encodes one of the following options:

- offset into the ByteString input to represent identifiers, text () nodes, or attribute values;
- a number of sub-elements, to represent a sequence of nodes.

Since Haskell records are created lazily, and they are usually recycled immediately after examination, compressing the output significantly reduces memory use. We consider the creation and interpretation of this offset structure in more detail below.

The offset array structure provides a safe alternative to the PugiXML \[17\] method of inserting pointers inside the parsed structure that is already in place.

### 3.2 Parsing XML Schema

XML Schemas are frequently long and complex, typically using thousands of lines of code. It is, therefore, critical that our parser can be generated automatically from existing sources.
3.2.1 Modeling XML Schema in Haskell

Since we aim to ingest data quickly without validating the document, the current version of XML Typelift ignores the following features: (I) comments, (II) syntactic type distinctions, (III) value restrictions that are not enumerations, and (IV) uniqueness constraints.

We reduce the type representations to those that are modeled within Haskell abstract data types via the following features: (a) $\text{xs:choice}$ is naturally modeled by types with alternative type constructors; (b) $\text{xs:sequence}$ and the set of $\text{xs:attributes}$ are both modeled by record fields within a single constructor; (c) references are modeled as record fields to facilitate code re-use; (d) cardinality constraints are simplified to distinguish between a single value, a, an optional value, Maybe a, and a list [a]; (e) built-in types are translated into Haskell types by predefinition; (f) type restrictions are modeled depending on the constraint: (I) enumerations are modeled as set of nullary constructors, and (II) other constraints are reduced to type aliases.

This is essentially an XML→Haskell mapping similar to Object→Relational and Object→XML mappings, both of which are used for SQL and XML databases, without constraining the realm of XML types on the input.\(^6\)

Automated type generation not only allows us to significantly decrease complexity when writing efficient parsers for existing formats, but it also results in a more convenient API that can be used in Haskell. We propose using the same code generator for other target languages in our future work.

However, since XML Schema’s own schema is very complex, we use an intermediate representation to describe XML document types in sufficient detail to allow parsing, while at the same time omitting most of the details of schema representation.\(^7\)

3.2.2 Schema representation

The entire XML schema can be represented as an environment that holds both simple and complex declared types. In addition to this environment, we also list element types that are allowed to occur in the document root; this uniform representation simplifies a multitude of distinctions that are made by XML Schema between types that are allowed in attributes, and those are allowed only as elements. Thus, further analysis and code generation are both greatly simplified.

\[
\text{data Schema} = \text{Schema} \{ \text{types :: Map String Type}, \text{tops :: [Element]} \}
\]

For each element type, we keep track of its possible multiplicity, name, attributes and content type; note that we ignore name spaces due to limited implementation resources.

Describing element types

\[
\begin{align*}
\text{data Element} = & \text{Element} \{ \text{eType :: Type, minOccurs :: Int -- 0 for no limit, maxOccurs :: Maybe Int -- Nothing for no limit, eName :: String, targetNamespace :: NamespaceName} \}
\end{align*}
\]

Handling of type extensions

Although simple and complex types that have either simple or complex content are one of most complicated aspects of specification, they can be easily modeled by either a ComplexType entry, reference, or modification of another ComplexType.

\[
\begin{align*}
\text{data Type} = & \text{Ref String, Restriction} \{ \text{base :: String, restricted :: Restriction} \, \\
& \text{Extension} \{ \text{base :: String, mixin :: Type} \, \\
& \text{Complex} \{ \text{mixed :: Bool, attrs :: [Attr]}, inner :: TyPart} \}
\end{align*}
\]

Consistent with the principles of data mapping, whereby we seek a common type for shared parts of the data structure, we avoid duplication of fields defined in the base type when generating declarations of extending types.

Type restrictions

Although it is easy to expand restrictions, for the time-being we consider only those that need special mapping to Haskell ADT:

\[
\begin{align*}
\text{data Restriction} = & \text{Enum [String]} \mid \ldots
\end{align*}
\]

For simplicity, we omit treatment of element references and namespaces, which can simply be added to a reference dictionary. Furthermore, complex identifier types can be dealt with in post-parsing analysis to find the namespace of each identifier.

Representing element children

Types are described by regular expression in language whereby letters form child elements. Here again, we use Group as a reference to another TyPart:

\[
\begin{align*}
\text{data TyPart} = & \text{Seq [TyPart]} \mid \text{Choice [TyPart]} \\
& \text{All [TyPart]} \mid \text{Group String} \mid \text{Elt Element}
\end{align*}
\]

Note that, since XML Schema allows Choice, All, and Seq\(^8\) to be nested, the XML data declaration must be broken down into smaller sections.

XML data structure flattening

It is necessary to flatten the XML data structure by breaking types down into sections that can be translated directly into single Haskell data

\(^6\)Except for mixed types, which can be modeled as a list of values with a type that has an added constructor TextValue String. The authors are not currently able to support this.

\(^7\)Indeed, our approach is mirrored by the existence of other schema languages that aim to simplify XML Schema. For example, RelaxNG [17], which aims to describe regular trees inside a document.

\(^8\)Described as: $\text{xs:choice}$, $\text{xs:all}$, and $\text{xs:sequence}$.\]
declarations. This is achieved by grouping the types into the following categories, according to complexity:

1. those that can be implemented as type aliases (newtypes);
2. those that can be implemented as a single Haskell ADT declaration; and
3. those that must be split into multiple types.

As an example of a type that must be split into multiple types, here we consider an element that contains a fixed group of children, and one variant child; for simplicity, element types are omitted.

<xs:element name="person">
  <xs:sequence>
    <xs:element name="firstName"
      minOccurs="1" maxOccurs="1"/>
    <xs:element name="lastName"
      minOccurs="1" maxOccurs="1"/>
  </xs:sequence>
  <xs:choice>
    <xs:element name="residentialAddress"
      minOccurs="1"
      maxOccurs="unbounded"/>
    <xs:element name="phoneNumber"
      minOccurs="1"
      maxOccurs="unbounded"/>
    <xs:element name="imName"/>
  </xs:choice>
</xs:sequence>
</xs:element>

This can be translated into two levels of Haskell ADTs:

data Person = Person {
  firstName :: Text,
  lastName :: Text,
  residentialAddressOr :: ResidentialAddressOr
}

data ResidentialAddressOr = ResidentialAddress Text
  | PhoneNumber Text
  | IMName Text

3.3 Searching for the best parser

Here, we describe and analyze the performance of a variety of generated code types. We keep running prototypes in the repository in the bench/proto directory.9

Parser 1 For Parser 1, we first generate an Xeno.DOM structure, and we convert the resulting tree fragments into Haskell records using a lazy conversion.

Parser 2 A continuation passing monad (ContT) is used for Parser 2. The processor is given as a continuation that receives individual SAX events, and continues processing. Next, a control flow separates out the different generated types, with unfinished elements held in a stack. Data is then passed to the input using an asynchronous queue to allow asynchronous (and possibly chunked) input processing.

Table 1. Speed comparison for generated parser and its prototypes. Columns represent time (in seconds) required to process input file according to file size (in Mb).

| File Size (Mb) | Parser 1 | Parser 2 | Parser 3 | Parser 4 | Parser 5 | Gen.  |
|---------------|----------|----------|----------|----------|----------|-------|
| 1             | 0.99     | 1.97     | 3.78     | 7.61     | 15.31    | 30.67 |
| 3             | 1.19     | 2.39     | 4.79     | 9.66     | 19.30    | 38.28 |
| 4             | 0.79     | 1.58     | 3.17     | 6.38     | 12.88    | 25.37 |
| 5             | 0.93     | 1.85     | 3.68     | 7.46     | 14.89    | 29.80 |
| 6             | 1.28     | 2.56     | 5.03     | 10.31    | 20.71    | 41.15 |
| 7             | 0.76     | 1.52     | 3.02     | 6.07     | 12.28    | 25.21 |
| Gen.          | 0.84     | 1.68     | 3.35     | 6.74     | 13.61    | 27.37 |

Table 2. Allocation comparison for generated parser and its prototypes. Columns represent allocations (in Gb) required to process input file according to file size (in Mb).

| File Size (Mb) | Parser 1 | Parser 2 | Parser 3 | Parser 4 | Parser 5 | Gen.  |
|---------------|----------|----------|----------|----------|----------|-------|
| 1             | 2.71     | 5.43     | 10.88    | 21.83    | 43.76    | 87.63 |
| 3             | 2.88     | 5.77     | 11.56    | 23.20    | 46.50    | 93.10 |
| 4             | 2.13     | 4.26     | 8.55     | 17.18    | 34.46    | 69.02 |
| 5             | 2.25     | 4.51     | 9.04     | 18.15    | 36.41    | 72.92 |
| 6             | 2.94     | 5.89     | 11.80    | 23.68    | 47.46    | 95.02 |
| 7             | 2.23     | 4.46     | 8.95     | 17.98    | 36.05    | 72.21 |
| Gen.          | 2.42     | 4.85     | 9.74     | 19.54    | 39.18    | 78.47 |

9Interested readers are referred to the source repository so that they can compare with their prototypes and preferred optimization.
Table 3. Memory consumption (in Mb) comparison for generated parser and its prototypes. Columns represent memory consumption (in Mb) need to process input file with respective size in header (in Mb).

|   | 0.26 | 0.52 | 1.31 | 2.62 | 5.23 | 10.45 |
|---|------|------|------|------|------|-------|
| 1 | 0.42 | 0.82 | 1.63 | 3.24 | 6.48 | 12.95 |
| 3 | 0.21 | 0.39 | 0.77 | 1.57 | 3.27 | 6.60  |
| 4 | 0.21 | 0.43 | 0.88 | 1.78 | 3.57 | 7.13  |
| 5 | 0.51 | 1.00 | 1.97 | 3.90 | 7.78 | 15.56 |
| 7 | 0.12 | 0.24 | 0.47 | 0.94 | 1.87 | 3.74  |
| gen. | 0.13 | 0.25 | 0.50 | 0.99 | 1.98 | 3.96 |

Table 4. Count of garbage collections of generated parser and prototypes

|   | 2.66 | 5.32 | 10.67 | 21.41 | 42.93 | 85.96 |
|---|------|------|-------|-------|-------|-------|
| 3 | 2.87 | 5.75 | 11.53 | 23.14 | 46.40 | 92.93 |
| 4 | 2.20 | 4.40 | 8.82  | 17.72 | 35.54 | 71.18 |
| 5 | 2.29 | 4.59 | 9.20   | 18.47 | 37.04 | 74.18 |
| 6 | 3.01 | 6.02 | 12.07  | 24.22 | 48.54 | 97.18 |
| 7 | 2.23 | 4.47 | 8.96   | 17.99 | 36.11 | 72.35 |
| gen. | 2.45 | 4.90 | 9.81   | 19.66 | 39.47 | 79.09 |

In order to conserve memory, it then constructs a record only upon element closure.

```
parser :: ByteString -> IO TopLevel
parser str = do
  levelRef <- newIORef (0::Int)
  -- IORef holding each field in the schema
  usersRef <- newIORef Nothing
  userRef <- newIORef Nothing
  -- ... similar code for each field...
  flip Xeno.process str (Process
    { openF = \
          tagName -> do
            level <- readIORef levelRef
            case (level, tagName) of
              -- Here we dive into structure
              (0,"users") -> writeIORef levelRef 1
              (1,"user" ) -> writeIORef levelRef 2
              -- Store nested values
              (2, "uid" ) -> writeTextToRef uidRef
              -- ... similar code skipped...
            , closeF = \tagName -> do
                level <- readIORef levelRef
                case (level, tagName) of
                  (2, "user") -> do
                    let name = Nothing
                    uid <- readIORef uidRef
                    name <- readIORef nameRef
                    "... similar code skipped..."
                    modifyIORef' usersRef (Users {..} : )
                    -- back to previous level
                    writeIORef levelRef 1
                    -- ... similar code skipped...
              }
            )
          (name, "users") -> writeIORef levelRef 1
          (uid, "user") -> writeIORef levelRef 2
          (name, "name") -> writeIORef levelRef 3
          (uid, "bday") -> writeIORef levelRef 4
          -- ... similar code skipped...
          )
    , closeF = \tagName -> do
        level <- readIORef levelRef
        case (level, tagName) of
          (2, "user") -> do
            let name = Nothing
            uid <- readIORef uidRef
            name <- readIORef nameRef
            "... similar code skipped..."
            modifyIORef' usersRef (Users {..} : )
            -- back to previous level
            writeIORef levelRef 1
            -- ... similar code skipped...
    )
  )
  Just users <- readIORef usersRef
  return users
```

Parser 6

Parser 6 uses data reification of event streams (SAXEvent type) and passes the resulting tokens to Parsec ([6]) parser combinators.

```
parser = first errorBundlePretty . parseUsers ""
  . Xeno.process
```

```
type SaxParser a = Parsec Void [SAXEvent] a
```

```
parsers =
  withTag "users" (Users <$> parseUsers)
```

```haskell
tagValue (m,MonadFail) (m,MonadParsec e [SAXEvent] m) => ByteString -> m ByteString
```

```
tagValue tagName = do
  void $ satisfy (=\OpenElt tagName)
  -- ... auxiliary code skipped...
```

Parser 7

Parser 7 uses a single mutable vector, similar to that used by Xeno.DOM offsets (and Parser 3), to add inlined string comparisons (of Parser 4). This parser allows for lazy output extraction.

```
parsers = first errorBundlePretty . parseToArray7
```

```
parseToArray7 bs =
```

```
```
Right $ \text{TopLevelInternal}\ bs\ \text{create}\ $ do
vec <- UMV.unsafeNew $ BS.length bs
_ <- parseUsers vec
return vec

where
-- Some parser just parse tags and
call parser for nested tags
parseUsers vec = do
 UMV.unsafeWrite vec 0 0
 let usersStart = skipHeader bs 0
 if idx bs usersStart == ord '<'
 && idx bs (usersStart + 1) == ord 'u'
 && idx bs (usersStart + 2) == ord 's'
 && idx bs (usersStart + 3) == ord 'e'
 && idx bs (usersStart + 4) == ord 'r'
 && idx bs (usersStart + 5) == ord 's'
 && idx bs (usersStart + 6) == ord '>'
 then do
 (\_, usersEndStart)'
 _ <- parseUser 0
 $ skipSpaces bs (usersStart + 7)
 let usersEndStart =
 skipSpaces bs usersEndStart'
 if idx bs usersEndStart == ord '<'
 && idx bs (usersEndStart + 1) == ord '/'
 && idx bs (usersEndStart + 2) == ord 'u'
 -- ...skip similar code..
 then
 return $ usersEndStart + 8
 else
 failExp "</users>" usersEndStart
 else
 failExp "<users>" usersStart
 -- ...skip similar code...
-- At the end final value parsers store
-- reference to value in result array
parseUid arrayUidStart uidStart' = do
 let uidStart = skipSpaces bs uidStart'
 if idx bs uidStart == ord '<'
 && idx bs (uidStart + 1) == ord 'i'
 && idx bs (uidStart + 2) == ord 'd'
 && idx bs (uidStart + 3) == ord 'a'
 && idx bs (uidStart + 4) == ord '>'
 then do
 let uidStrStart = uidStart + 5
 uidStrEnd = skipToOpenTag bs uidStrStart
 if idx bs uidStrEnd == ord '<'
 && idx bs uidStrEnd == ord '/'
 -- ...skipped...
 then do
 UMV.unsafeWrite vec
 arrayUidStart
 uidStrStart
 UMV.unsafeWrite vec

In order to identify the best implementation, we manually coded seven different parser prototypes. Table tbl. 1
compares the speeds of the generated parsers and their prototypes, while tbl. 2 and tbl. 3 compare memory consumption,
and tbl. 4 counts prototype garbage collections. Since Parser 2 is slow and consumes a large amount of memory, it is
disregarded for the rest of the analysis.
Parser 7 was selected as our code generator template. We here encapsulate operations within combinators to make
the parser code easier to read, and we present a section of example generated code:
parseTopLevelToArray :: ByteString -> Either String TopLevelInternal
parseTopLevelToArray bs =
 Right $ TopLevelInternal bs $ V.create $ do
vec <- V.new $ BS.length bs
 arrayUidStart + 1
 (uidStrEnd - uidStrStart)
 return $ uidStrEnd + 6
 else
 failExp "</uid>" uidStrEnd
 else
 failExp "<uid>" uidStart
 -- ...skip similar code...
extractTopLevel :: TopLevelInternal -> TopLevel
extractTopLevel (TopLevelInternal bs arr) =
 Users extractUsers
 where
 extractUsers =
 let count = arr `UV.unsafeIndex` 0
 in User $ map extractUser
 $ [1, (1 + userSize)
 -- (1 + userSize * (count - 1))]
 -- ...skip similar code...
extractUser ofs = User
 { uid = extractMaybeXmlString ofs
 -- ...skip similar code...
}
return (arrOfs3, strOfs3)
parseusersContent arrStart strStart = do 
  (arrOfs1, strOfs1) <- 
  inManyTags "user" 
    arrStart strStart 
  $ parseUserTypeContent 
  return (arrOfs1, strOfs1)
-- ...auxiliary code skipped...
parseusers vec 
return vec

-- | Extractor of haskell data
-- from internal array
extractTopLevel :: TopLevelInternal -> TopLevel
extractTopLevel (TopLevelInternal bs arr) = 
  fst $ extractUsers1Content 0
  where 
    extractUUserTypeContent ofs = 
      let (uid, ofs1) = extractIntContent ofs in 
      let (name, ofs2) = extractStringContent ofs1 in 
      let (bday, ofs3) = 
          extractMaybe ofs2 extractDayContent 
        in (UserType{..},ofs3)
    extractUsers1Content ofs = 
      let (user, ofs1) = 
          extractMany ofs extractUUserTypeContent 
        in (Users user,ofs1)

3.3.1 Parsing combinators
We next define the combinators that are needed for efficient input parsing:

    ensureTag ::
      Bool -- ˆ Skip attributes 
    -> ByteString -- ˆ Expected tag 
    -> Int -- ˆ Current offset in the input 
    -> Maybe (Int, Bool)
inOneTag, inManyTags, inMaybeTag, inManyTagWithAttrs :: ByteString -- ˆ Expected tag 
    -> Int -- ˆ Current offset 
    -> Int -- ˆ Output array offset 
    -> (Int -> Int -> Parser (Int, Int))
    -- ˆ Nested tag parser
    -> Parser (Int, Int)

To ensure that high-level code does not hinder performance, we first benchmarked an 'intended result' from a small schema code generator.

3.3.2 Final generated code
In the parser generated from the schema, we simply represent them as code flow sites, since this token handling is inlined implicitly by the code generator.

The following example code uses actual parser combinators:

parseUsersContent arrStart strStart = do 
  (arrOfs1, strOfs1) <- 
  inManyTags "user" arrStart strStart 
  $ parseUserTypeContent 
  return (arrOfs1, strOfs1)
parseUserTypeContent arrStart strStart = do 
  (arrOfs1, strOfs1) <- 
  inOneTag "uid" strStart $ parseInt arrStart 
  (arrOfs2, strOfs2) <- 
  inOneTag "name" strOfs1 $ parseString arrOfs1 
  (arrOfs3, strOfs3) <- 
  inMaybeTag "bday" arrOfs2 strOfs2 parseDay 
  return (arrOfs3, strOfs3)

This code does not need to store field offsets within the <user> content structure; this is because both parser and extractor use constant offsets that are consistent with XML Schema. Thus, representation is dictated by the resulting data structure rather than by the original placement of elements within the input structure.10

We now examine how the parser works. As illustrated in fig. 1, the parser meets the node <users>. Since it can contain a sequence of sub-nodes, the parser reserves the current position and starts to analyze the sequence.

Next, the parser ensures that the next node is a <user>, and it then meets with node <uid>42</uid> and writes the offset (50) to string "42", and its length (2) to an offset array. The parser then goes to <name> and writes offset 71 and a string length of 4, "John", to the offset array. The parser does the same for node <bday>, writing offset 95 and length 10.

The parser now switches to the next node: <user>. After processing the <user> node, the parser writes 147, 3 for "777" and 169, 5 for 'Lucky'. Since the node <bday> is optional and not included in this example here, the parser returns 0, 0.

Finally, the parser meets the close tag </users> and writes the sequence length of 2 at its initial place before proceeding to fill the offset array. The resultant data structure can be extracted lazily from the offset structure using extraction combinators:

    extractUserTypeContent ofs = 
      let (uid, ofs1) = extractIntContent ofs in 
      let (name, ofs2) = extractStringContent ofs1 in 
      let (bday, ofs3) = 
          extractMaybe ofs2 extractDayContent 
        in (UserType{..}, ofs3)
    extractUsersContent ofs = 
      let (user, ofs1) = extractMany ofs 

10Although this does not apply to elements with mixed content, it is sufficient for data mapping purposes.
We now consider how extraction of Haskell datatype user extraction (introduced in sec. 2.3) works.

As illustrated in Figure 1, the extractor first reads 2 from the offset array and reads two User objects. In order to read each User object, the extractor first reads the offset to a piece of string as well as the string length and it then parses this information to the appropriate type:

The field \(uid\) of the first User is formed from the 2-byte long string that is extracted from the 50th byte. The field name is them formed from the 4-byte long string that is extracted from 71st byte. If the \(<bday>\) offset is zero, the extractor returns Nothing, and if the offset is non-zero, the extractor will attempt to extract \(<bday>\) from a specified offset and length.

Note that the resulting structure does not use any unsafe pointer operations, since all pointers are encoded as offsets.

4 Benchmarking

Table 5. Speed comparison for generated parser and other tools. Columns represent the time (in seconds) required to process the input file according to the respective header size (in Mb).

| Tool       | 32   | 64   | 128  | 256  | 512  | 1024 |
|------------|------|------|------|------|------|------|
| xeno       | 0.03 | 0.07 | 0.13 | 0.26 | 0.53 | 1.08 |
| pugixml    | 0.05 | 0.09 | 0.20 | 0.40 | 0.81 | 1.63 |
| hexml      | 0.03 | 0.06 | 0.11 | 0.28 | 0.56 | 1.26 |
| hexpat     | 2.71 | 5.45 | 10.94| 21.65| 43.40| 91.73|
| lxml       | 0.35 | 0.70 | 1.40 | 2.81 | 5.64 | 11.30|
| xml-typelift| 0.04 | 0.08 | 0.17 | 0.33 | 0.66 | 1.33 |

Table 6. Allocation comparison (in Mb) for generated parser and other tools. Columns represent allocations (in Gb) required to process input files according to the respective header size (in Mb).

| Tool       | 32   | 64   | 128  | 256  | 512  | 1024 |
|------------|------|------|------|------|------|------|
| xeno       | 0.03 | 0.07 | 0.13 | 0.27 | 0.54 | 1.08 |
| pugixml    | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| hexml      | 0.03 | 0.06 | 0.12 | 0.25 | 0.50 | 1.00 |
| hexpat     | 6.16 | 12.33| 24.66| 49.36| 98.76| 197.56|
| xml-typelift| 2.42 | 4.85 | 9.74 | 19.54| 39.18| 78.47|

4.1 Main alternatives

For benchmarking purposes, we developed a short program that simply generates XML files of similar structures, but with different file sizes and containing random data. Six files of the following sizes (in Mb) were generated: 32, 64, 128, 256, 512, and 1024.

Table 7. Total memory consumption (in Mb) comparison for generated parser and other tools. Columns represent memory consumption (in Mb) required to process input files according to the respective header size (in Mb).

| Tool       | 32   | 64   | 128  | 256  | 512  | 1024 |
|------------|------|------|------|------|------|------|
| xeno       | 0.06 | 0.13 | 0.25 | 0.50 | 1.00 | 1.99 |
| pugixml    | 0.14 | 0.29 | 0.58 | 1.15 | 2.31 | 4.61 |
| hexml      | 0.09 | 0.19 | 0.37 | 0.74 | 1.47 | 2.94 |
| hexpat     | 1.74 | 3.45 | 6.88 | 13.59| 27.07| 52.79|
| py-lxml    | 0.28 | 0.28 | 0.56 | 1.13 | 2.25 | 4.50 |
| xml-typelift| 0.13 | 0.25 | 0.50 | 0.99 | 1.98 | 3.96 |

Table 8. Count of garbage collection cycles for generated parser and other tools using Haskell garbage collection.

| Tool       | 32   | 64   | 128  | 256  | 512  | 1024 |
|------------|------|------|------|------|------|------|
| xeno       | 0.00 | 0.01 | 0.01 | 0.02 | 0.04 | 0.08 |
| hexpat     | 6.32 | 12.65| 25.31| 50.66| 101.36| 202.77|
| xml-typelift| 2.45 | 4.90 | 9.81 | 19.66| 39.47| 79.09|

Our tools seem to show a clear linear scaling according to input size (see tbl. 5). Note that the C-based hexpat tool performs more slowly than any of the other tools that were tested, especially for large files. In particular, the C-based hexpat tool took 91.7 seconds to process the 1 Gb file, while the other tools processed the same file in under two seconds. This result further reinforces our point that clever implementation is more important than language choice when optimizing tool performance; thus, developer skill and expereince are essential to producing high performance solution.

All our tested tools demonstrated linear growth between file size and common allocated memory and GC (see tbls. 6, 7, 8); this growth had a direct correlation with performance.

5 Discussion

This parser contributes to evidence [1] that advanced compilers of high-level languages can have similar performance (speed) to those of low-level languages provided that the software developer is sufficiently well-skilled.

Although parser speed can be improved through innovative implementation and optimization, neither approach is used in the Glasgow Haskell Compiler (GHC) or its LLVM. Given the importance of string processing, it is disappointing that neither GHC or LLVM implement inline keyword matching, and we recommend that this is pursued in future work.

This paper presents techniques for high-level processing of xxx, without compromising memory use or processing speed. Our results confirm that effective use of high-level language libraries enables performance to match that of low-level languages, while at the same time maintaining safety and retaining interface convenience. We expect that
implementation of these techniques will be expanded into high-performance parsers in the future. Offset-based encoding of pointer structures suggests a number of interesting future research directions in GC; region-based GCs would possibly help in this case.

6 Future work

While our goal was to develop a tool suitable for a wide range of uses, implementation of entire XML Schema is beyond the scope of this paper; not all features are currently supported (xs:element references, xs:import), and isolated cases remain untested.

Our future work includes adding new functionality that will be designed to not hamper performance when used in the most common circumstances. In particular, we plan to facilitate incremental data extraction, without building intermediate data structures, by implementing XPath. Provided we secure sufficient funding, we might also implement a monoidal parallelization scheme for the parser, in the spirit of the hPDB parser [1].

Although we have not yet modeled mixed content, it would be relatively easy to map mixed content as a list of sum types (ADT) that contain all allowed elements, and text node constructors. We also plan to add mmap and null termination pre-allocations to the XML Typelift, just as we did with xeno.11

Since VectorizedString operations are only exposed in Xeno.DOM and its generated parser, it would be interesting to formally demonstrate their correctness.

7 Conclusion

While XML documents validated by XML Schema definitions are valid, in order to analyze these formats in a typed programming language, XML data types must be converted from XML Schema into meaningful language data type declarations, and parsers must be generated for these XML documents.

We presented a Haskell tool that converts XML standard data types into Haskell data types, thus making this data available for analysis by Haskell programs. A key advantage of our tool is that it allows easy handling of large XML Schemas, such as Office OpenXML, by Microsoft Office applications.

XML TypeLift avoids the complexities of XML parsing and validation by directly mapping valid input documents into correct Haskell datatypes that represent the intended domain. In a sense, XML mapping to Algebraic Datatypes (XML-ADT mapping), behaves just like object-relational mappings, which are used for interfacing OOP programs to relational databases; this prevents type mismatches (detected at compilation), allowing effective utilization with XML document parsing. Programmers can, thus, use the full power of the type system for conversion of XML Schema data types to Haskell data types, since type validation is performed prior to compilation. Invalid documents that cannot be parsed to Haskell data types return an error message that identifies the error location.

Even though similar parsing solutions exist within other Haskell packages, such as HXT, XML TypeLift offers the following key advantages: (i) It performs online input processing without using system memory. (ii) It has fast, low memory usage and event-based parsing using pure-Haskell xeno parser. (iii) It runs fast for small and large document data processing libraries in other languages [3, 17, 23]

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**Figure 2. Memory consumption comparison for generated parser and prototypes**

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**Appendix**

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Figure 3. Memory consumption comparison for generated parser and other tools.

Figure 4. Count of GC generated parser and prototypes.

Figure 5. Count of GC generated parser and other tools.

Figure 6. Allocations comparison for generated parser and other tools.
Figure 7. Allocations comparison for generated parser and prototypes

Figure 8. Speed comparison for generated parser and its prototypes

Figure 9. Speed comparison for generated parser and other tools