Efficient High-Level Abstractions for Web Programming

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Abstract

Writing large Web applications is known to be difficult. One challenge comes from the fact that the application's logic is scattered into heterogeneous clients and servers, making it difficult to share code between both sides or to move code from one side to the other. Another challenge is performance: while Web applications rely on ever more code on the client-side, they may run on smart phones with limited hardware capabilities. These two challenges raise the following problem: how to benefit from high-level languages and libraries making code complexity easier to manage and abstracting over the clients and servers differences without trading this engineering comfort for performance? This article presents high-level abstractions defined as deep embedded DSLs in Scala, that can (1) generate efficient code leveraging the target platform characteristics, (2) be shared between clients and servers. Though code written with our DSL has a high level of abstraction our benchmark on a real world application reports that it runs as fast as hand tuned low-level JavaScript code.

Categories and Subject Descriptors D.3.3 [*Programming Languages*]: Language Constructs and Features

General Terms Languages, Software Engineering

Keywords Heterogeneous code generation, Domain-specific languages, Scala, Web

1. Introduction

Web applications are attractive because they require no installation or deployment steps on clients and enable large scale collaborative experiences. However, writing large Web applications is known to be difficult [16, 18]. One challenge comes from the fact that the business logic is scattered into heterogeneous client-side and server-side environments [14, 19]. This gives less flexibility in the engineering process and requires a higher maintenance effort: there is no way to move a piece of code targeting the server-side to target the client-side – the code has to be rewritten. Even worse, logic parts that run on both client-side and server-side need to be duplicated. For instance, HTML fragments may be built from the server-side when a page is requested by a client, but they may also be built from the client-side to perform an incremental update subsequent to a user action. How could developers write HTML fragment definitions once and render them on both client-side and server-side?

The more interactive the application is, the more logic needs to be duplicated between the server-side and the client-side, and the higher is the complexity of the client-side code. Developers can use libraries and frameworks to get high-level abstractions on client-side, making their code easier to reason about and to maintain, but also making their code run less efficiently (due to *abstraction penalty*).

Performance is a primary concern in many Web applications, because they are expected to run on a broad range of devices, from the powerful desktop personal computer to the less powerful smart phone [10, 22].

Using the same programming language on both server-side and client-side could improve the software engineering process by enabling code reuse between both sides. Incidentally, the JavaScript language – which is currently the most supported action language on Web clients – can be used on server-side. Conversely, increasing number of programming languages or compiler back-ends can generate JavaScript code (*e.g.* Java/GWT [4], SharpKit[1], Dart [7], Kotlin[2], ClojureScript [15], Fay[3], Haxe [3] or Opa[4]).

However, using the same programming language is not enough because the client and server programming environments are not the same. For instance, DOM fragments can be defined on client-side using the standard DOM API, but this API does not exist on server-side. How to define a common vocabulary for such concepts? And how to make the executable code leverage the native APIs, when possible, for performance reasons?

Generating efficient code for heterogeneous platforms is hard to achieve in an extensible way: the translation of common abstractions like collections into their native counterpart (JavaScript arrays on client-side and standard library's collections on server-side) may be hard-coded in the compiler, but that approach would not scale to handle all the abstractions a complete application may use (*e.g.* HTML fragment definitions, form validation rules, or even some business data type that may be represented differently).

On one hand, for engineering reasons, developers want to write Web applications using a single high-level language, abstracting over the target platforms differences and reducing code complexity. But on the other hand, for performance reasons, they want to keep control on the way their code is compiled to each target platform. We propose to solve this dilemma by providing high-level abstractions in compiled domain-specific embedded languages [6]: they allow the definition of domain-specific languages (DSLs) as libraries on top of a host language, and to compile them to a target platform. The deep embedding gives the opportunity to control the code generation scheme for a given abstraction and target platform.

[1] http://sharpkit.net

[2] http://kotlin.jetbrains.org/

[3] http://fay-lang.org/

[4] http://opalang.org/

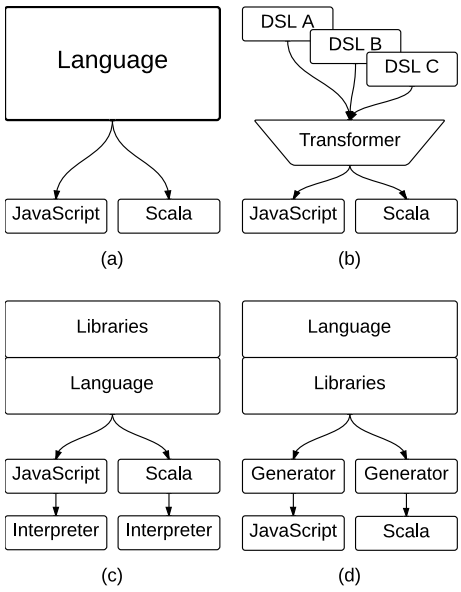

Figure 1. Language engineering processes

Kossakowski *et al.* introduced *js-scala*, a compiled embedded DSL defined in Scala that generates JavaScript code, making it possible to write the client-side code of Web applications using JavaScript [13]. However, Kossakowski *et al.* did not address the engineering dilemma described above. This paper enriches js-scala with the following contributions[5]:

- we define high-level abstractions, typically used in Web programming, that generate low-level code leveraging native Web browser APIs;
- in the case of abstractions shared between servers and clients, we specialize the code generation in order to leverage the target platform native environments.

We validate our approach with a case study implemented with various candidate technologies and discuss the relative pro and cons of them. Though the code written in our DSL is high-level and can be shared between clients and servers, it has the same runtime performances on client-side as hand-tuned low-level JavaScript code.

The remainder of this paper is organized as follows. The next section overviews the existing approaches providing high-level languages for Web programming. Section 3 presents the framework we used to define our DSLs. Section 4 presents our contribution. Section 5 compares our solution to common approaches. Section 6 concludes.

2. Related Work

We classified existing approaches providing high-level abstractions for Web programming in four categories, as shown in figure 1.

Fat Languages The first approach for defining a cross-platform language consists in hard-coding, in the compiler, the code generation scheme of each language feature to each target platform. Figure 1 (a) depicts this process. In order to support a feature related to a specific domain, the whole compiler pipeline (parser, code generator, *etc.*) may have to be adapted. This approach gives *fat* languages because a lot of concepts are defined at the language level: general programming concepts such as naming, functions, classes, as well as more domain-specific concepts such as HTML fragment definition. Thus, implementing a fat language may require a high effort. Examples of such languages for Web programming are Links [5], Opa and Dart [7].

Domain-Specific Languages Another approach consists in defining several independent domain-specific languages [23], each one focusing on concerns specific to a given problem domain, and then to combine all the source artifacts written with these language into one executable program, as shown in figure 1 (b). Defining such languages requires a minimal effort compared to the previous approach because each language has a limited set of features. On the other hand, it is difficult to have interoperability between DSLs. [8] gave an example of such a domain-specific language for defining Web applications.

Thin Languages Alternatively, one can define concepts relative to a specific domain as a library on top of a thin general purpose language (it is also referred to as a domain-specific *embedded* language [11]). Figure 1 (c) depicts this approach. Defining such a library requires minimal effort, though the syntax of the DSL is limited by the syntax flexibility of the host language, and several DSLs interoperate freely within the host language. However, this approach gives no opportunity to efficiently translate a concept according to the target platform characteristics because the compiler has no domain-specific knowledge (though some compilers hard-code the translation of some common abstraction such as arrays to leverage the target platform characteristics). Examples of languages following this approach are Java/GWT, Kotlin, HaXe and SharpKit.

Deeply Embedded Languages The last approach, shown in figure 1 (d), can be seen as a middle-ground between the two previous approaches: DSLs are embedded in a host language but use a code generation process. This approach shares the same benefits and limits as embedded DSLs for defining language units. The code generation process is specific to each DSL and gives the opportunity to perform domain-specific optimizations. In other words deeply embedded DSLs bring domain-specific knowledge to the compiler. Js-scala [13] is an example of deeply embedded DSL in Scala for Web programming.

3. Lightweight Modular Staging

This section gives background material on the framework used to define js-scala.

Lightweight Modular Staging [20, 21] (LMS) is a framework for defining deeply embedded DSLs in Scala. It has been used to define high-performance DSLs for parallel computing [2] and to define JavaScript as an embedded DSL in Scala [13].

LMS is based on staging [12]: a program using LMS is a regular Scala program that evaluates to an intermediate representation (IR) of a final program. This IR is a graph of expressions that can be traversed by code generators to produce the final program code. Expressions evaluated in the initial program and those evaluated in the final program (namely, staged expressions) are distinguished by their type: a `Rep[Int]` value in the initial program is a staged expression that generates code evaluating to an `Int` value in the final program. An `Int` computation in the initial program is evaluated during the initial program evaluation and becomes a constant in the final program.

Defining a DSL with LMS consists in the following steps:

- writing a Scala module providing the DSL vocabulary as an abstract API,
- implementing the API in terms of IR nodes,

[5] The code is available at http://github.com/js-scala

Function	Description
`querySelector(s)`	First element matching the CSS selector `s`
`getElementById(i)`	Element which attribute `id` equals to `i`
`querySelectorAll(s)`	All elements matching the CSS selector `s`
`getElementsByTagName(n)`	All elements of type `n`
`getElementsByClassName(c)`	All elements which **`class`** attribute contains `c`

Figure 2. Standard selectors API. The `querySelector` and `querySelectorAll` are the most general functions while the others handle special cases.

```
function getWords() {
  var form = document.getElementById('add-user');
  var sections =
    form.getElementsByTagName('fieldset');
  var results = [];
  for (var i = 0 ; i < sections.length ; i++) {
    var words = sections[i]
      .getElementsByClassName('word');
    results[i] = words;
  }
  return results
}
```

Listing 1. Searching elements using the native selectors API

```
function getWords() {
  var form = $('#add-user');
  var sections = $('fieldset', form);
  return sections.map(function () {
    return $('.word', this)
  })
}
```

Listing 2. Searching elements in jQuery

- defining a code generator visiting IR nodes and generating the corresponding code.

4. Efficient High-Level Abstractions for Web Programming

4.1 Selectors API

In a Web application, the user interface is defined by a HTML document that can be updated by the JavaScript code. A typical operation consists in searching some "interesting" element in the document, in order to extract its content, replace it or listen to user events triggered on it (such as mouse clicks). The standard API provides several functions to search elements in a HTML document according to their name or attribute values. Figure 2 summarizes the available functions and their differences.

Listing 1 gives an example of use of various functions from the native selectors API to retrieve a list of input fields within a form. The existence of several specialized functions in the API makes it possible to write efficient code, but forces users to think at a low abstraction level.

A high-level abstraction for searching elements in a document could be just one function finding all elements matching a given CSS selector. In fact, most JavaScript developers[6] use the jQuery library [1] that actually provides only one function to search for elements. Listing 2 shows an equivalent JavaScript program as listing 1, but using jQuery. The code is both shorter and simpler, thanks to its higher-level of abstraction. jQuery provides an API that is simpler to master because it has less functions, but this benefit comes at the price of a decrease in runtime performances.

```
def find(selector: Rep[String]) =
  getConstIdCss(selector) match {
    case Some(id) if receiver == document =>
      DocumentGetElementById(Const(id))
    case _ =>
      SelectorFind(receiver, selector)
  }
```

Listing 3. Selectors optimization

```
def getWords() = {
  val form = document.find("#add-user")
  val sections = form.findAll("fieldset")
  sections map (_.findAll(".word"))
}
```

Listing 4. Searching elements in js-scala

Instead, we propose a solution that has a high-level API but generates JavaScript code using the specialized native API, when possible, in order to get both engineering comfort and performances. We are able to achieve this by analyzing, during the first evaluation step, the selector that is passed as parameter and, when appropriate, producing JavaScript code using the specialized API, and otherwise producing code using `querySelector` and `querySelectorAll`.

Our API has two functions: `find` to find the first element matching a selector and `findAll` to find all the matching elements. Listing 3 gives the implementation of the `find` function. It is a Scala function that returns an IR node representing the JavaScript computation that will search the element in the final program. The `getConstIdCss` function analyzes the selector: if it is a constant `String` value containing a CSS ID selector, it returns the value of the identifier. So, if the `find` function is applied to the `document` and to an ID selector, it returns a `DocumentGetElementById` IR node (that is translated to a `document.getElementById` call by the code generator), otherwise it returns a `SelectorFind` IR node (that is translated to a `querySelector` call).

The same applies to the implementation of `findAll`: the selector passed as parameter is analyzed and the function returns a `SelectorGetElementsByClassName` in case of a CSS class name selector, a `SelectorGetElementsByTagName` in case of a CSS tag name selector, and a `SelectorFindAll` otherwise.

Figure 3 shows the IRs returned by the evaluation of

```
document.find("#add-user button")
```

and

```
document.find("#add-user")
```

In the former case, the selector is parsed and does not match an ID selector (it is a composite selector matching button elements within the element having the `add-user` id), so a `SelectorFind` node is returned, then translated into a call to the general `querySelector` function. In the latter case, the selector matches an ID selector so a `DocumentGetElementById` node is returned, then translated into a call to the specialized `getElementById` function.

Finally, listing 4 shows how to implement listing 2 in Scala using js-scala. The code has the same abstraction level as with jQuery, however it generates a JavaScript program identical to listing 1:

[6] According to http://trends.builtwith.com/javascript, jQuery is used by more than 40% of the top million sites.

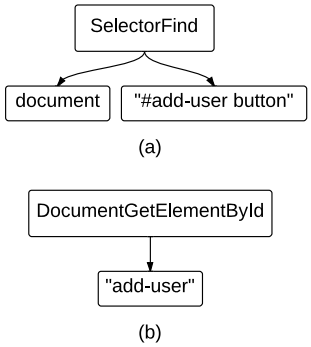

Figure 3. Intermediate representations returned by the evaluation of (a) `document.find("#add-user button")` and (b) `document.find("#add-user")`

```
var loginWidget =
  document.querySelector("div.login");
var loginButton =
  loginWidget.querySelector("button.submit");
loginButton.addEventListener("click", handler);
```

Listing 5. Unsafe code

```
var loginWidget =
  document.querySelector("div.login");
if (loginWidget !== null) {
  var loginButton =
    loginWidget.querySelector("button.submit");
  if (loginButton !== null) {
    loginButton.
      addEventListener("click", handler);
  }
}
```

Listing 6. Defensive programming to handle null references

the high-level abstractions (the `find` and `findAll` functions) exist only in the initial program, not in the final JavaScript program.

4.2 Monads Sequencing

This section presents an abstraction that can be shared between client and server code.

Null references are a known source of problems in programming languages [9, 17]. For example, consider listing 5 finding a particular widget in the page and then a particular button within the widget. The native `querySelector` method returns **`null`** if no node matched the given selector in the document. If we run this code in a page where the widget is not present, it will throw an error and stop further JavaScript execution. Defensive code can be written to handle **`null`** references, but leads to very cumbersome code, as shown in listing 6.

Some programming languages encode optional values with a monad (*e.g.* `Maybe` in Haskell and `Option` in Scala). In that case, sequencing over the monad encodes optional value dereferencing. If the language supports a convenient syntax for monad sequencing, it brings a convenient syntax for optional value dereferencing, alleviating developers from the burden of defensive programming.

In our DSL, we encode an optional value of type `Rep[A]` using a `Rep[Option[A]]` value, which can either be `Rep[Some[A]]` (if there is a value) or a `Rep[None.type]` (if there is no value). An optional value can be dereferenced using the **`for`** notation, as shown in listing 7, that implements in js-scala a program equivalent to listing 6. The `find` function returns a `Rep[Option[Element]]`.

```
for {
  loginWidget <- document.find("div.login")
  loginButton <- loginWidget.find("submit.button")
} loginButton.on(Click)(handler)
```

Listing 7. Handling null references in js-scala

```
override def emitNode(sym: Sym[Any], rhs: Def[Any]) =
  rhs match {
    case OptionIsEmpty(o) =>
      emitValDef(sym, q" $o === null")
    case OptionForeach(o, b) =>
      stream.println(q"if ($o !== null) {")
      emitBlock(b)
      stream.println("}")
    case _ =>
      super.emitNode(sym, rhs)
  }
```

Listing 8. JavaScript code generator for null references handling DSL

The **`for`** expression contains a sequence of statements that are executed in order, as long as the previous statement returned a `Rep[Some[Element]]` value.

Such a monadic API brings both safety and expressiveness to developers manipulating optional values but usually involves the creation of an extra container object holding the optional value. In our case, the monadic API is used in the initial program but generates code that does not wrap values in container objects but instead checks if they are **`null`** or not when dereferenced. So the extra container object exists only in the initial program and is removed during code generation: listing 7 produces a code equivalent to listing 6.

Listing 8 shows the JavaScript code generator for methods `isEmpty` (that checks if the optional value contains a value) and `foreach` (that is called when the **`for`** notation is used, as in listing 7). The `emitNode` method handles `OptionIsEmpty` and `OptionForeach` nodes returned by the implementations of `isEmpty` and `foreach`, respectively. In the case of the `OptionIsEmpty` node, it simply generates an expression testing if the value is **`null`**. In the case of the `OptionForeach` node, it wraps the code block dereferencing the value within a **`if`** checking that the value is not **`null`**.

The IR nodes are not tied to the JavaScript code generator, so we are able to make this abstraction available on server-side by writing a code generator similar to the JavaScript code generator, but targeting Scala. So the same abstraction is efficiently translated on both server and client sides.

4.3 DOM Fragments Definition

This section shows how we define an abstraction shared between clients and servers, as in the previous section, but that has different native counterparts on client and server sides. The challenge is to define an API providing a common vocabulary that generates code using the target platform native APIs.

A common task in Web applications consists in computing HTML fragments representing a part of the page content. This task can be performed either from the server-side (to initially respond to a request) or from the client-side (to update the current page). As an example, listing 9 defines a JavaScript function `articleUi` that builds a DOM tree containing an article description, and listing 10 shows how one could implement a similar function on server-side using the standard Scala XML library. The reader may notice that the client-side and server-side APIs are very different and that the client-side API is very low-level and inconvenient to use.

```
var articleUi = function (article) {
  var div = document.createElement('div');
  div.setAttribute('class', 'article');
  var span = document.createElement('span');
  var name =
    document.createTextNode(article.name + ': ');
  span.appendChild(name);
  div.appendChild(span);
  var strong = document.createElement('strong');
  var price = document.createTextNode(article.price);
  strong.appendChild(price);
  div.appendChild(strong);
  return div
};
```

Listing 9. JavaScript DOM API

```
def articleUi(article: Article) =
  <div class="article">
    <span>{ article.name + ": " }</span>
    <strong>{ article.price }</strong>
  </div>
```

Listing 10. Scala XML API

```
def articleUi(article: Rep[Article]) =
    el('div, 'class -> 'article)(
        el('span)(article.name + ": "),
        el('strong)(article.price)
    )
```

Listing 11. DOM definition DSL

```
def articlesUi(articles: Rep[Seq[Article]]) =
    el('ul)(
        for (article <- articles)
        yield el('li)(articleUi(article))
    )
```

Listing 12. Using loops

Our first step consists in capturing, in a high-level API, the concepts common to the JavaScript and Scala APIs. Though they are different, both APIs define HTML elements with attributes and content. We define an `el` function to define an HTML element, eventually containing attributes and children elements. Any children of an element that is not an element itself is converted into a text node. Listing 11 shows how to implement our example with our DSL. The children elements of an element can also be obtained dynamically from a collection, as shown in listing 12.

The `el` function returns an `Element` IR node that is a tree composed of other `Element` and `Text` nodes. The JavaScript and Scala code generators traverse this tree and produce code building an equivalent DOM tree and XML fragment, respectively. When the children of an element are constant values (as in listing 11) rather than dynamically computed (as in listing 12), the code generators unroll the loop that adds children to their parent, for better performance. As a result, listing 11 generates a code equivalent to listing 9 on client-side and equivalent to 10 on server-side.

Listings 13 and 14 show the relevant parts of the code generators for this DSL. They basically follow the same pattern: they visit `Tag` and `Text` IR nodes and produce the corresponding elements in the target language.

5. Evaluation

Our goal is to evaluate the level of abstraction provided by our solution and its performances, by comparing it with common approaches. We take the number of lines of code as an inverse approximation of the level of abstraction. We also evaluate the ability to share code between client and server sides.

```
case Tag(name, children, attrs) =>
  emitValDef(sym, q"document.createElement('$name')")
  for ((n, v) <- attrs) {
    stream.println(q"$sym.setAttribute('$n', $v);")
  }
  children match {
    case Left(children) =>
      for (child <- children) {
        stream.println(q"$sym.appendChild($child);")
      }
    case Right(children) =>
      val x = fresh[Int]
      stream.println(q"for (var $x = 0; $x < $children.length; $x++) {")
      stream.println(q"$sym.appendChild($children[$x]);")
      stream.println("}")
  }
case Text(content) =>
  emitValDef(sym, q"document.createTextNode($content)")
```

Listing 13. JavaScript code generator for the DOM fragment definition DSL

```
case Tag(name, children, attrs) =>
  val attrsFormatted =
    (for ((name, value) <- attrs)
     yield q" $name={ $value }").mkString
  children match {
    case Left(children) =>
      if (children.isEmpty) {
        emitValDef(sym, q"<$name$attrsFormatted />")
      } else {
        emitValDef(sym,
          q"<name$attrsFormatted>{ ${children.map(quote)} }</$name>"
        )
      }
    case Right(children) =>
      emitValDef(sym, q"<$name$attrsFormatted>{ $children }</$name>")
  }
case Text(content) =>
  emitValDef(sym, q"{xml.Text(content)}")
```

Listing 14. Scala code generator for the DOM fragment definition DSL

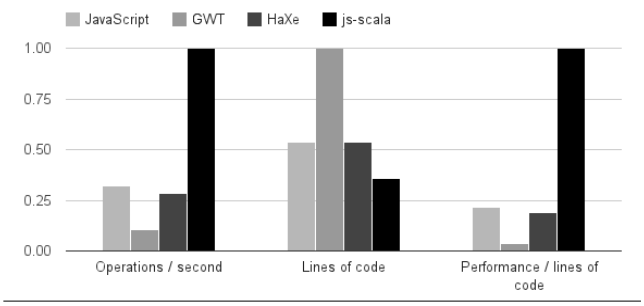

Figure 4. Micro-benchmark on the optional values abstraction

We realized a micro-benchmark involving a program using essentially the optional value DSL, and we benchmarked a real world program. In each case we have written several implementations of the program, using plain JavaScript, Java/GWT, HaXe and js-scala (in each case we tried to write the application in an idiomatic way). The performance benchmarks measured the execution time of the generated JavaScript code. The tests were run on a DELL Latitude E6430 laptop with 8 GB of RAM, on the Google Chrome v27 Web browser.

5.1 Micro-Benchmark

The micro-benchmark focuses on the optional value abstraction. We reimplemented this abstraction in plain JavaScript, Java and HaXe and wrote a small program manipulating optional values.

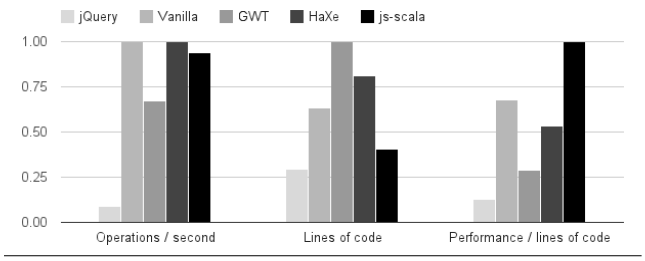

Figure 5. Benchmarks on a real application

Figure 4 shows the micro-benchmark results. The js-scala version of the program runs between 3 to 10 times faster than other approaches. This version also takes less lines of code than others (this result is almost due to the special **for** notation, that has no equivalent in other benchmarked languages). Finally, the js-scala program has a performance to lines of code ratio more than 4 times higher than others.

5.2 Real World Application

Chooze [7] is an existing complete application for making polls. It allows users to create a poll, define the choice alternatives, share the poll, vote and look at the results. It contains JavaScript code to handle the dynamic behavior of the application: double-posting prevention, dynamic form update and rich interaction with the document.

The application was initially written using jQuery. We rewrote it in vanilla JavaScript (low-level hand-tuned code without third-party library), js-scala, GWT and HaXe.

5.2.1 Performance

The benchmark code simulates user actions on a Web page (2000 clicks on buttons, triggering a dynamic update of the page and involving the use of the optional value monad, the selectors API and the HTML fragment definition API). Figure 5 shows the benchmark results.

The runtime performances of the vanilla JavaScript, HaXe and js-scala versions are similar (though the js-scala version is slightly slower by 6%). It is worth noting that the vanilla JavaScript and the HaXe versions use low-level code compared to js-scala, as shown in the middle of the figure (lines of code): the js-scala version needs only 74 lines of code while the vanilla JavaScript version needs 116 lines of code (57% bigger) and the HaXe version needs 148 lines of code (100% bigger). The jQuery JavaScript version, which code is high-level (54 lines of code, 27% less than js-scala) runs 10 times slower than the js-scala version.

The last part of the figure compares the runtime performance to lines of code ratio. Js-scala shows the best score, being 1.48 times better than the vanilla JavaScript version, 1.88 times better than the HaXe version, 3.45 times better than the GWT version and 7.82 times better than the jQuery JavaScript version.

5.2.2 Code Reuse

We were able to share HTML DOM fragment definitions between server-side and client-side only in the js-scala version.

6. Conclusion

We were able to provide high-level abstractions for Web programming, decreasing code complexity and improving code reuse between client and server sides, while generating efficient low-level code leveraging both target environments.

[7] Source code is available at http://github.com/julienrf/chooze

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