Beyond .*Script

Implementing A Language For The Web

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A thesis submitted for the degree of
B.Sc. of Applied Computer Science (Fachbereich II)
of the University of Applied Sciences (HTW) Berlin

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Except where otherwise indicated, this thesis is my own original work.

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August 7, 2016

Abstract

This thesis presents and evaluates a port of the zepto programming language to the web. It aims to work as seamlessly with existing technologies as possible and is largely influenced by Revised^5 Report on the Algorithmic Language Scheme (R5RS), a standard of the Lisp derivative Scheme.[1]

It is the result of over a year of independent research on zepto, a new programming language targetting various environments. The prototype described here and implemented for this thesis runs on JavaScript, a language found natively in many web browsers.

The central problem addressed by this thesis is the incoporation of a language runtime into the web ecosystem. This is achieved without the need for extensive code rewrites while supporting most features of the reference implementation of zepto, including large parts of the standard library. This also includes interoperability between the two languages.

It is also discussed in which ways tooling for both JavaScript and zepto, most specifically their respective package managers, interoperate to build larger scale web applications.

[1]A deeper introduction into R5RS can be found in Section 2.2.

Contents

Abbreviations

API Application Programming Interface. 1, 20–22, 24–26, 28

AST Abstract Syntax Tree. 14

BSD Berkeley Software Distribution. 11

CSS Cascading Stylesheets. 8

DOM Document Object Model. 1, 21, 24–26, 28, 29

DSL Domain-Specific Language. 15, 30, 31, 33

EEP Erlang Enhancement Proposal. 10

FFI Foreign Function Interface. 7, 23, 24, 26–28

FRP Functional Reactive Programming. 8

GHC Glasgow Haskell Compiler. 6, 14, 23, 24

GUI Graphical User Interface. 8

HTML Hypertext Markup Language. 8, 20, 21

IR Intermediate Representation. 14

JIT Just In Time Compiler. 6

LLVM Low Level Virtual Machine. 6, 13, 14

PEP Python Enhancement Proposal. 10

R5RS Revised^5 Report on the Algorithmic Language Scheme. ii, 9, 10, 16

REPL Read-Eval-Print Loop. 20, 24

SRFI Scheme Request For Implementation. 10, 18

W3C World Wide Web Consortium. 25, 28

YUI Yahoo User Interface Library. 1

zeps zepto Package System. 11, 18, 19, 29, 33, 34, 39

ZPR zepto Package Registry. 19, 29

1. Introduction

Controlling complexity is the essence of computer programming.

(B. Kernighan)

1.1. Motivation

JavaScript has, since its inception, attracted a lot of controversy. This is rooted in various aspects of its design, from prototypal inheritance and the DOM to its operator precedence. Especially prototypal inheritance has been the cause of a lot of discussion in the Computer Science community. It has the reputation of being counter-intuitive, though it is older than JavaScript, the first commonly known programming language that implemented prototypal objects being Self.

This and a few other design choices have prompted many programmers to develop wrapper libraries around almost anything that constitutes the language. The most widely-used example of this is arguably jQuery, a library that abstracts over the DOM. But more arcane topics have been covered as well: there is, for example, the Yahoo User Interface Library (YUI), a now-abandoned project of Yahoo that aimed to abstract over web APIs but also came with its own inheritance model. This model likened JavaScript prototypes to classical classes by introducing special functions and properties to the objects such as `extend` and `superclass`.

These and other libraries have shaped the way JavaScript has developed. In the upcoming revisions of ECMAScript[1], ECMAScript 6[2] and ECMAScript 7[3], a lot of

[1]ECMAscript is the officially trademarked name of what application developers and browser vendors most commonly refer to as JavaScript.

[2]ECMAScript 6 was renamed to ECMAScript 2015 along the way but for the sake of clarity this thesis uses the more commonly know name of the revision. For an up-to-date version of that revision please refer to (ECMA International, 2015).

[3]Now ECMAScript 2017. For an up-to-date version of the current draft please refer to (ECMA International, 2016).

conveniences from third-party libraries have been adopted by the ”vanilla”[4] JavaScript canon. Among these features is the widely controversial introduction of a class notation for JavaScript that makes prototypes feel more like classes without breaking from existing semantics.

1.1.1. Preprocessors & Transpilers

Classes and other features have been available to JavaScript developers for much longer than the latest iterations of the JavaScript language without them needing to rely on a possibly massive library - provided they use a preprocessor. One of the earliest exemplars of preprocessing for JavaScript, CoffeeScript, included lambdas, a shorthand for anonymous functions; and pattern matching, a technique for destructuring data; and classes, all of which found their way into the latest ECMAScript revisions.

Preprocessing can serve a lot of different purposes apart from providing syntactic commodities to the programmer. Babel, for instance, is a relatively novel library for transpiling JavaScript that adheres to the new standards of ECMAScript back to older revisions, for the sake of backwards-compatibility. It also aims to provide small optimizations before the code reaches the compiler, such as constant hoisting.[5]

Transpilation from a different language is another increasingly popular way to use JavaScript as a platform. One could argue that CoffeScript is nothing short of a transpiler; but one could also argue against this idea, considering its only purpose is to compile to JavaScript. Other general-purpose languages such as Clojure and C++, originally developed to run on other platforms, have the option to compile to JavaScript through ClojureScript (Hickey, 2016) and Emscripten (Zakai, 2013), respectively.

Caveats

This thesis was inspired by the work done in the field of transpilation to JavaScript. Its goal is not to present yet another attempt at transpilation, but rather to rethink the way languages are incorporated into the web of today.

At their heart, all of the preprocessors and transpilers that target JavaScript are JavaScript, even if the syntax and semantics differ radically. There needs to be a clean

[4]A common name for JavaScript that refrains from leveraging paradigm-altering libraries.
[5]Constant hoisting is a compiler optimization technique that eliminates pure functions that always produce the same result in favour of global constants to reduce the overhead of function calls.

mapping of the source language to JavaScript. Because of its flexibility, this is often a doable task, albeit not always desirable.

The value of having the same level of abstraction present at runtime as at compile-time is obvious if the language that is considered places strong emphasis on code mutability, such as in Lisp or Elixir[6]. This thesis aims to equip the programmer with these abstractions by presenting a language that is not a preprocessor, but a genuine runtime system for the frontend.

1.2. Goals of this Thesis

The primary goal of this thesis is to present a novel approach at implementing languages for the Web. This is exemplified by a sample implementation of a non-trivial, pure, and largely feature-complete functional programming language that has been tested in production systems.

There are many reasons to use a procedural or objective-oriented language as a prototype. On one hand, the language itself could be more easily implemented in JavaScript if it is reasonably close to it. Another point that speaks against using a functional — and especially pure — programming language is the possibility of making interoperability harder because JavaScript is intrinsically impure and stateful.

But all of those reasons could also be read as argument *for* the implementation of a functional language. The difference showcases JavaScript's ability to express concepts that are foreign to it. It also serves as a better test bench for more advanced implementation patterns.

This is especially true for those features of the base language that are not present in JavaScript and non-trivial to add to it from a user perspective. The features present in the target language implemented in this thesis but not present in JavaScript most notably include Macros[7] and Continuations[8]. These features were chosen especially because they are extremely foreign to JavaScript programming.

[6]As exemplified by Chris McCord in (McCord, 2015).
[7]The ability to rewrite code at parse or compile time, see Section 3.1.3.
[8]The control state of a program represented as a data structure within the code, see Section 3.1.4.

1.3. Structure of this Thesis

Chapter 2 examines related work in the field of cross-compilation into JavaScript and implementation of interpreters that are directly embeddable into larger systems.

Chapter 3 gives an overview of the concept design and how the features are laid out to match the needs of both the goals of this thesis and the prototype itself.

Chapter 4 presents the system design and how the prototype integrates into existing web components.

Chapter 5 discusses the implementation by picking out different fundamental parts of the system and presenting how they work.

Chapter 6 evaluates the prototype. This includes problems such as how well the integration of the system worked and how it compares to the reference implementation of zepto.

Chapter 7 gives a brief summary of what was done and an outlook as to what might happen with both the desktop and the JavaScript versions of zepto in the future.

2. Related Work

This chapter aims to give a quick overview of work that has already been done in the field of transpilation to and language implementations on top of JavaScript. A few of the most important specimens have already been mentioned briefly in Section 1.1.1.

2.1. Existing Projects

In this section a brief overview of a short, but not necessarily exhaustive list of transpilers to JavaScript shall be presented. The source languages include existing programming languages as well as languages explicitly acting as a layer of abstraction over JavaScript.

The aim of this section is not to present the reader with the syntax and semantics of every single language that is discussed. Rather, the idea is to equip them with a general overview of the ecosystem at the time of writing and how it correlates to the work presented in this thesis.[1]

2.1.1. Transpilers

Transpilers are normally defined as being compilers that translate one high level language into another. They are often referred to as cross-compilers; however, this term is imperfect, as it also refers to compilation from one hardware platform or operating system to another.

Due to this ambiguity, the name *transpiler* was chosen to refer to these kinds of systems in the context of this thesis.

GHCJS

GHCJS — often hyphenated as GHC-JS — is a transpiler from the Haskell language to JavaScript. It is currently maintained by Luite Stegeman. It aims to "solve the JavaScript problem"[2], in that it enables the user to compile any Haskell program to

[1]The programming language that is described in this thesis will be referenced from now on as zepto-js.
[2]A talk given by Stegeman bore this title, see (Stegeman, 2015).

JavaScript. GHCJS does so by insterting a custom compiler backend into the Glasgow Haskell Compiler (GHC) toolchain that emits JavaScript instead of machine code.

GHCJS is the compiler used in this thesis to transpile the existing zepto codebase to JavaScript. Its plug-and-play design, near-complete implementation of the Haskell programming language, and relative maturity all contributed to the decision to use it as a development platform.[3]

Emscripten

Emscripten as discussed in (Zakai, 2013) aims to be a transpiler from Low Level Virtual Machine (LLVM) to JavaScript. Its primary focus is the translation of C and C++ source code to JavaScript.

Emscripten's use case is similar to that of GHC-JS, enabling the user to both

> (1) Compile code directly into LLVM assembly, and then compile that into JavaScript using Emscripten, or (2) Compile a language's entire runtime into LLVM and then JavaScript, as in the previous approach, and then use the compiled runtime to run code written in that language (ibid.).

Translating a runtime into JavaScript for executing foreign code from within JavaScript sounds suspiciously like what zepto-js is trying to achieve.

In fact, there have been efforts to leverage this potential of LLVM in the past. For example, Ryan F. Kelly is trying to make the PyPy Just In Time Compiler (JIT)[4] work in the browser.[5]

As zepto is written in Haskell, though, LLVM was not a viable development platform. If it had been chosen, the goal of reusing the code of the reference implementation would not have been met.

ClojureScript

ClojureScript is a backend for the Clojure programming language that targets JavaScript. Initially developed by Rich Hickey, the author of Clojure, it is now maintained under David Nolen's lead (Hickey, 2016).

[3]Further discussion of the design and decision process can be found in Chapters 3 and 4.

[4]A JIT designed to speed up Python programs by analyzing and compiling them, described in (Bolz et al., 2009).

[5]While this project offers a live demonstration which can be found on its website, accessible under https://pypyjs.org, further documentation on it is sparse and there is seemingly no academically viable source detailing its development and architecture.

Being a Lisp, it has obvious syntactic similarites to zepto. Yet, as it is transpiled rather than interpreted directly in the browser, programming against it is quite difficult. Specifically, the way the FFI works is quite different from zepto-js, as ClojureScript has a lot of syntactic integrations that help embed JavaScript within it. All functions prefixed with a period are assumed to be JavaScript functions on the prototype of the object provided as first argument. JavaScript values can be directly accessed through the `js` namespace. zepto's design is discussed in Section 5.2.2.

```
; ClojureScript provides syntactic abstractions over
; the embedding of foreign code.
(.getElementById js/document "body")

; An equivalent zepto call, with strings
(js "document.getElementById(\"body\")")
; OR, if a variable is accessed
(js (++ "document.getElementById(\"" body "\")"))
```

Listing 1: A comparison of the FFI of JavaScript in zepto and ClojureScript.

2.1.2. Abstraction Languages

The languages mentioned here are languages that abstract purely over JavaScript, choosing it as their primary backend. This differs from the languages discussed in Section 2.1.1, which are general purpose languages with the option to compile to JavaScript if desired by the developer.

CoffeeScript

As mentioned in Section 1.1.1, when it first appeared, CoffeeScript was one of the first transpilers that targeted JavaScript.[6] Many of the constructs, relating both to syntax and semantics, have been adopted by JavaScript. CoffeeScript is similar to JavaScript in that it is a procedural, prototypal language. No semantic features have been added or removed from JavaScript[7], making it relatively dissimilar to the programming system presented in this thesis.

[6]The first git commit dates back to December 13th, 2009 as seen in the commit history of https://github.com/jashkenas/coffeescript. The first public release happened shortly after that.

[7]Although the syntactic abstractions often make it seem as if CoffeeScript offers constructs that are missing from JavaScript.

The biggest deviations from JavaScript can be found in the syntax. The syntax of CoffeeScript is influenced by both Python and Ruby (MacCaw, 2012). For instance, contrary to JavaScript, indentation is significant, and comments start with a pound symbol. These changes are supposed to simplify the development process.

Elm

Elm as it is presented in ”Elm: Concurrent FRP for Functional GUIs” is a language centered around Functional Reactive Programming (FRP)[8] with a special regard to browser-based Graphical User Interfaces (GUIs) (Czaplicki, 2012). It borrows its syntax largely from Haskell and is a pure, functional programming language. Notable features include GUI-centric tooling, such as a ”time-traveling” debugger that caches the state of a program at any given time, allowing for rewinding, forwarding, and jumping.

Elm’s sole similarity to zepto-js is that it is a functional language for the Web. However, unlike zepto-js, it compiles to JavaScript, Hypertext Markup Language (HTML) and Cascading Stylesheets (CSS), and once again falls short of actually getting the code to the browser. It is also very centered around FRP, whereas zepto-js aims to be a general-purpose programming environment. Therefore, Elm’s relation to this thesis is merely tangential, but the advances made by it are important for the context in which zepto-js is placed.

PureScript

PureScript is, much like Elm, a functional, pure programming language that borrows a lot of its syntax from Haskell. It aims to compile into human-readable JavaScript and make possible general purpose programming for the web in a strongly typed, functional style.

It is different from GHCJS in that it does not provide compatibility with Haskell code, although many libraries and functions are relatively similar.[9]

As it shares a lot of features with Elm, it also largely shares its differences to zepto-js.

[8]An in-depth explanation of FRP is outside of the scope of this thesis, but it is a programming style for user-centric programs first described in Paul Hudak’s and Conald Elliott’s 1997 paper ”Functional Reactive Programming” (Elliott and Hudak, 1997).

[9]See Listing 2 for an example.

```haskell
-- | Extract the first element of a list (as implemented in the language standard library).
-- | The Haskell version is unsafe and will throw an error
-- | if it encounters an empty list.
head :: [a] -> a
head (x:_) =  x
head [] =  badHead -- an exception function

-- | the list data type in PureScript is safe by design and
-- | the function returns a Maybe monad.
head :: forall a. List a -> Maybe a
head Nil = Nothing
head (Cons x _) = Just x
```

Listing 2: A juxtaposition of a simple function in Haskell and PureScript.

2.2. Existing Standards

When developing a programming language derived from the Lisp family, one builds on top of almost seventy years of development, formalization, and research. Of course many of the standards formed during this time are now obsolete. Nonetheless, the effort of standardizing the many languages and implementations is still thriving.

Over the years, two main categories of languages have developed: Common Lisp and Scheme. While the syntactic proximity remains, the categories differ widely conceptually. Figure 2.1 shows the differences between those language families.

zepto is a Scheme derivative loosely based on R5RS (Kelsey et al., 1998), the most widely implemented standard of Scheme. It draws from a lot of standard library functions, syntax definitions, and continuations, but aims to introduce custom namespaces to provide a cleaner, more modular way of defining software libraries.[10]

The reason for which a Scheme derivative was chosen over an implementation of Common Lisp can be found in the feature set (see Figure 2.1); hygienic macros and continuations are valuable abstractions that guarantee that components work together.[11] It implements a simple – if a bit contrived – version of binary `or` in Common Lisp and in Scheme. In Common Lisp, the variables defined in regular code will potentially be

[10]This module system will be explained in Chapter 3 in depth.

[11]An example of code that works as expected in Scheme but not in Common Lisp is presented in Listing 3.

	Macro Keyword	Macro Dispatch	Hygienic Macros	Continuations	Standard
Scheme	define-syntax	pattern matching	present	present	ANSI Common Lisp
Common Lisp	defmacro	argument passing	not present	not present	RNRS

Figure 2.1.: A comparison between Common Lisp and Scheme

shadowed by the ones generated during macro expansion, whereas in Scheme they reside in different contexts and are thus hygienic. This renders the system more intuitive and eliminates a class of potential bugs, making it more desirable.

While R5RS is certainly a valuable standard and provided a lot of very useful information for the development for zepto, the language is not as closely tied to the standard as most other implementations. This allowed for the development of zepto-js to progress mostly unencumbered by incompatibilities, although one goal of the development effort was not to break any existing syntactic or semantic ties with R5RS. Disrupting these links could potentially have broken a big part of the standard library, with the library being one of the major arguments for zepto's existence as a language.

2.2.1. Scheme Requests For Implementation (SRFIs)

Scheme Requests For Implementation (SRFIs) comprise an important argument for adhering to the R5RS standard. They are standard library enhancement proposals from the Scheme programmer community that suggest enahcements through the addition of features, much like Python Enhancement Proposals (PEPs) for the Python programming language and Erlang Enhancement Proposals (EEPs) for Erlang. However, the difference that sets SRFIs apart from the latter two is the inclusion of a reference implementation.[12] zepto currently supports five of these requests by default, one of which implements a core feature of the language: descriptive custom data types, better known as smart structs.

In the past, the relative ease of porting the implementation of these requests was a major convenience. By moving even uurther away from the Scheme standards, this process would undoubtedly be affected in a negative manner. Even mere renaming incurs the cost of finding and replacing all occurrences of the affected name, which leads

[12]This is not required, but part of the "good tone" of the community and SRFIs lacking them are relatively rare.

to a new class of potential bugs. Thus, for both the reference implementation and its JavaScript equivalent, a core set of primitives must be available under all circumstances to allow for the cross-fertilization of Scheme and zepto.

```
; the Common Lisp version
(defmacro my-or (x y)
 `(let ((tmp x))
   (if tmp
     x
     y)))

(my-or #f #t)
; works (yields true), expands to:
(let ((tmp #f)) (if #f #f #t))

(let ((tmp #t))
  (my-or #f #t))
; does not work (yields false), expands to:
(let ((tmp #t)) ((tmp #f)) (if #f #f tmp))

; the Scheme version
; it will work as expected in both examples
(define-syntax
  (syntax-rules
    ((my-or x y)
      (let ((tmp x))
        (if tmp
          x
          y)))))
```

Listing 3: Common Lisp Macros vs. Scheme Macros

2.2.2. Unix

While not necessarily a standard, Unix and its guidelines do indirectly affect zepto. Much of zepto's tooling, such as the zeps use Unix utilities and system calls internally. This is expected to change in the future, but so far all of the developers who have worked on or with zepto[13] have used Unix or Unix-like systems such as MacOS X or Berkeley Software Distribution (BSD). This is less of a problem in the browser context because

[13] At least to the knowledge of the author.

many of the packaging and versioning tools are run from the command line before the application is distributed. It is important to keep in mind, though, that some of the tools rely on a specific Operating System when developing zepto programs.

3. Concept Design

Practicality beats purity.

(T. Peters—*The Zen of Python*)

The concept of a version of zepto that would run on JavaScript arose rather naturally from the work done on zepto as a backend-agnostic, run-everywhere concept language. Concurrently to the work on a nanopass compiler that targets LLVM and Erlang but supports pluggable backends by design, efforts have been made to bring the language into the browser setting. After preliminary work on a compiler backend that emits JavaScript was discarded in the early stages of its development for the reasons stated in Section 1.1, the idea presented in this thesis emerged.

In the following, a brief overview of the design of the concepts used in the port and how they impacted the construction of the system will be discussed. A system-based design overview is presented in Chapter 4.

3.1. Construction Design

The value of integrating zepto into existing web infrastructure lies in the addition of a host of new features that are not present natively in JavaScript and hard to implement in a stable manner.[1] The goal of the prototype was thus to expose all of the features that define zepto in the JavaScript implementation as well.

An explanation as to why a Lisp was chosen for this thesis — and specifically zepto — shall be given in the following.

[1]While stability is not guaranteed by the current version of zepto, it is tested and deployed in production systems and shows to function rather reliably.

3.1.1. Lisp

A common saying among programming language designers is that every programmer has written their own implementation of Lisp.[2] There are a lot of different implementations of Lisp in the wild, even ones that compile to JavaScript, such as ClojureScript, the backend for Clojure referenced in Section 2.1.1.

The language's simplicity on a parsing level contributes to its popularity as a language to implement. A simple Lisp can be implemented in fewer than one hundred lines of code if no intermediate representation is generated. This is made possible by Lisp's unique property of enclosing every statement in parentheses, in which the first element within those parentheses is the statement name and the other elements are the arguments. Each of these units is called an S-Expression — a shorthand for "symbolic expression" — and they are often represented as nested lists, although this is an implementation detail. It can be evaluated straight from a textual level, because problems such as operator precedence and statement ambiguity do not exist. In regular Lisp, as specified in the initial paper by John McCarthy, only a of handful special forms are required for Turing-completeness, as well as expressiveness and elegance (McCarthy, 1960).

3.1.2. zepto

As explained in Section 2.2, zepto is a new Scheme implementation. It seeks to be as small as possible, to be able to target a lot of different backends and simplify the process of writing new backend code. Currently, LLVM and Erlang Core[3] bindings are under development. zepto's reference implementation is a simple interpreter that evaluates code directly from the Abstract Syntax Tree (AST). This is slow but ensures a small interpreter size.[4] The compilers are written directly in zepto itself.

The small code base makes zepto a good target for porting it to the web. Furthermore, because it is written in Haskell the code base was expected to be almost entirely compilable to JavaScript using GHCJS[5]. It offers many advanced compilation features such as

[2] The README of the femtolisp project even goes so far as to claim "Some programmers' dogs and cats probably have their own lisp implementations as well." (Bezanson, 2016).

[3] Erlang Core is the Intermediate Representation (IR) of Erlang code before it is complied. Resources and documentation about it are sparse, it mostly seems to exist inside the BEAM's implementation. A small paper (Carlsson, 2001) that describes its' basics was used to implement the compiler from zepto.

[4] The entire codebase is only about 4000 lines of Haskell code.

[5] GHCJS is the transpiler mentioned in Section 2.1.1, a backend for the GHC targetting JavaScript instead of native code.

inlining of JavaScript into the Haskell code base using a technique called quasi-quoting, wherein a special character sequence delimits the inlined code, much like regular quotes. This tool set was expected to simplify the work of porting an existing language to the web.

Of course there are other reasons to use a functional language to demonstrate how to bring a language into the browser. With both syntax and semantics differing greatly from JavaScript, this example enables languages more closely related to JavaScript to eventually make their way into the browser.

3.1.3. Macros

Macros are a mechanism for rewriting code at compile time. As discussed in Section 2.2, zepto's macros are hygienic, which prevents name collisions with code at runtime and eliminates a class of particularly nasty bugs. Macros are evaluated in a step between the parser and the actual compilation of code called macro expansion, in which the compiler rewrites parts of the source code that reference it according to its specifications.

Because Scheme macros leverage pattern matching and argument overloading by default, they allow for syntactic extensions of the language. An example for a simple yet interesting case is made in Listing 4, where a simple syntactic rule set for list comprehensions is defined, not unlike a Domain-Specific Language (DSL), albeit a very small one. This particular list comprehension is syntactically close to the same construct in Haskell, although the semantics should be relatively clear at a close inspection and are, for the sake of example, a bit simpler than in the language by which it is inspired.

```
; this defines a macro of the name listcomp
(define-syntax listcomp ; the name
  (syntax-rules (<- |) ; the set of rules and special tokens to respect
    ((_ expr | elem <- elems) ; the pattern to match where
                              ; the underscore character is a wildcard
      (map (lambda (elem) expr) elems)))) ; the pattern is simply rewritten to a call to the map function

; add1 to every x in the list
(listcomp (add1 x) | x <- [1 2 3 4]) ; rewritten to: (map (lambda (x) (add1 x)) [1 2 3 4])
(listcomp (add1 x) | x <- (range 4)) ; rewritten to: (map (lambda (x) (add1 x)) (range 4))
```

Listing 4: Defining & using a macro in zepto

It should be noted that zepto supports list comprehensions by default and they are both a bit more concise and more powerful — as they allow for the filtering of elements from the source list — than the version defined here.

3.1.4. Continuations

Continuations are a datatype representing the state of a program at the time of request, including environments, definitions, and execution path. By manipulating it and injecting it into different contexts, it becomes a powerful tool to switch back and forth between multiple threads of execution, without actually creating or managing threads. A practical application of coroutines was for instance presented in ”Continuations and Coroutines”, where it was used to implement a fully formed coroutine system that was capable of starting, stopping, and pausing execution of multiple coroutines at once without the need for actual threading (Haynes et al., 1984).

An exhaustive explanation of continuations cannot possibly be given in the scope of this thesis, for further information about this concept refer to ”The discoveries of continuations” (Reynolds, 1993).

3.2. Additional Features

There are features in zepto that are not present in Scheme as specified by R5RS, such as the module system and the extensive standard library. In this section, a brief list of the features and libraries that discriminate zepto from ”regular” Scheme shall be examined.

3.2.1. The module system

zepto implements a custom module system that is completely defined in terms of the language itself. A small code example of different actions in zepto's module space is presented in Listing 5. This allows for namespaced, conditional, and renaming imports, a feature missing from standard Scheme.[6] This approach has a few upsides that all boil down to the module system being available in the user namespace; monkey-patching and mocking objects is possible, simplifying for instance testing and fixing flaws in the program at runtime. The module system is also relatively small and simple, at about 130 lines of macro-backed code, which makes it fairly maintainable.

[6]Although the latest Scheme standard R7RS included such a mechanism (Shinn et al., 2013), it is not widely implemented.

However, this approach comes not without its drawbacks. Most notably, relying on a module system that works at runtime requires more complex compilation and a dispatch system to be present while the program is running. It also requires global data in the form of a special variable — named `*modules*` — holding the mapping of names to values, a concept that is unusual for a functional programming language and might hinder the compilation into other representations. Global data is also normally either not thread-safe or relatively slow to use if it requires some sort of synchronization mechanism — which is not currently a feature that zepto implements.

```
; this defines a module of the name "mathematics"
(module "mathematics"
  (export
    `("add" ,add)
    `("substract" ,substract)
    `("multiply" ,multiply))

  ; the actual worker function (not exposed)
  ; applies a function to a list of arguments
  (doop (op args)
    (apply op args))

  ; the exported functions; essentially just wrappers
  ; around doop
  (add (lambda arguments (doop + arguments)))
  (substract (lambda arguments (doop - arguments)))
  (multiply (lambda arguments (doop * arguments))))

; will return a reference to the function
(import "mathematics:add")
; so that it can be bound to a name
(define add (import "mathematics:add"))
; or called directly
((import "mathematics:add") 1 2)

; import all under the namespace "mathematics"
(import-all "mathematics")
; import all under the namespace "mt"
(import-all "mathematics" "mt")
```

Listing 5: Defining & using a zepto module

This is an acceptable tradeoff for the current version of zepto, as all of the target languages of zepto's compiler support modules. They therefore provide a suitable representation for the semantics of zepto's system.

In the case of JavaScript, this part of zepto's implementation proved not to be a problem and worked without further tweaking.

3.2.2. The standard library

zepto comes with a fairly extensive standard library. It includes a wide variety of utilities spanning such diverse topics as cryptography[7], testing, monads, parsing command line arguments, and a parser combinator.[8]

This is reasonably unusual for Scheme implementations in that many of them come with a fairly minimalistic set of libraries that are often based almost exclusively on SRFIs. Two notable exceptions are Chibi Scheme[9] and Racket, the distributions of which are bundled with an even bigger standard library. This might be due to the fact that Alex Shinn, the main developer behind Chibi Scheme, is very active in the Scheme community and has authored a few SRFIs[10] of his own. He has also served as one of the editors of the upcoming standard of Scheme (Shinn et al., 2013). Additionally, Racket is a language supported by the Computer Science faculties of multiple universities and is the result of over twenty years of research.

The stability of the libraries that come bundled with zepto varies and is not ensured until the reference implementation reaches version 1.0.0. However, many of these libraries have at least been used by other libraries in the zepto ecosystem and are thus the subject of continuous scrutiny.

The standard library as a concept in zepto is designed to be a rather minimal, but usable set of primitives to get the developer started. Once the programmer feels comfortable in the programming environment, starting to work with zeps is suggested.

[7]As found in the rsa module, which implements RSA key generation, signing, validating, and en- and decryption.

[8]An exhaustive list of the modules found in the zepto standard library at the time of writing can be found in appendix A.

[9]The source code for Chibi Scheme and its standard library can be found under https://github.com/ashinn/chibi-scheme.

[10]SRFI 56 (Shinn, 2004) and 115 (Shinn, 2013) were both proposed by him.

3.2.3. zeps

zeps is the package manager for zepto. It is capable of installing and managing packages from Github[11] and the zepto Package Registry (ZPR) through the command line. It is undoubtedly the biggest coherent piece of code written entirely in zepto, and it is capable of intalling and updating itself. At the time of writing, at least forty packages have been published with zeps, including a framework for writing web servers and a Redis database client. It is only able to run on Unix-like systems or systems exposing at least a Unix-like shell.

The authentication system of zeps on the ZPR is RSA-backed[12], which also allows for the signing of packages for the user's convenience. This feature is not available when installing from Github.

The package system aims to be a cohesive, intuitive entity for installing, removing, creating, managing, testing, and updating packages.[13] It includes facilities for creating sandboxed environments, making dependency management of multiple systems with possibly conflicting dependency trees possible. It can also be used to distribute zepto-based command line tools. Furthermore, its ability to bootstrap packages is scriptable, allowing for plugins to decide what files should be generated on the creation of a new package.

It has proven useful in workshops and user feedback sessions, where it helped to ensure that all of the attendees were able to easily manage their first projects.

[11]Github.com, often abbreviated to Github, is a website for hosting Git repositories. Git is a distributed versioning system (Chacon, 2009).

[12]RSA, named after its inventors Ron Rivest, Adi Shamir, and Leonard Ableton, is a public-key cryptosystem that was first described in the article "A Method for Obtaining Digital Signatures and Public-Key Cryptosystems" (Rivest et al., 1978).

[13]A list of all the available commands is given in appendix B.

4. System Design

Practicality beats purity.

*(*T. Peters—*The Zen of Python)*

zepto-js required a few modifications to the way it integrates with its environment, although from a programming language implementation standpoint it is very close to the reference implementation of zepto.

zepto as an interpreter is a closed-off program that does not interact with its surroundings, save for program input. zepto-js, on the other hand, has to integrate with technologies and APIs to make programming a web application not only possible, but also convenient. A solid model of interaction had to be found as a consequence.

4.1. Integration into the Web Ecosystem

To make zepto-js fit into the web and its components, a few design decisions for the interpreter startup had to be done. Rather than make it Read-Eval-Print Loop (REPL) and file-based as in the reference implementation, a tag-based approach was pursued. This means that instead of either launching the interpreter in an interactive mode, where every expression is immediately evaluated after the user enters it, or providing a file to the interpreter to evaluate, the programs are provided to the user through HTML `script` tags, which is the approach taken by JavaScript as well. This ensures that programming in zepto-js would not differ drastically from programming in JavaScript from an application's viewpoint.[1]

There are multiple ways to implement this interface. An initial design idea was to bundle a zepto executable in the form of a browser extension that would parse the HTML code on the page. This would not require the user to download a big JavaScript file every time they visit a page that leverages zepto-js. With the ubiquity of smart caching mechanisms in modern browsers it is, however, unclear how big of a gain this

[1]An example of those tags is given in Listing 6.

would be. On the other hand it would limit the userbase of the website to the set of people who have the extension installed, a major drawback for possible language users.

It was thus determined that the prerequisite for being able to embed zepto code into a website should be to include the zepto-js distribution in the website. To make this more attractive, zepto-js can be loaded asynchronously onto the web page as it is required to also work if the DOM was already built. An explanation of how zepto is loaded and identifies the tags it should interpret is given in Section 5.2.1.

```
<script type="text/zepto">
 (define (fact n) "a tail-recursive version of the factorial function"
    (define (internal acc n)
      (if (<= n 0)
        acc
        (internal (* acc n) (sub1 n))))
    (internal 1 n))
</script>
<script type="text/zepto">
```

Listing 6: The interface of zepto-js within a HTML page.

4.1.1. Integration with Web APIs

TODO

4.1.2. Integration with build tools

A big part of modern web development is the availability of tools that automate the process of shipping JavaScript code. There are tools that cross-compile, minify[2], and optimize JavaScript in a matter of seconds.[3] There are also utilities that simplify the definition of pipelines in which the code is passed through various of those tools for greater composability, such as Grunt[4] or Gulp[5].

[2]Minification is the process of removing extraneous characters from a program that have no syntactic meaning and only add to the readability of the code at hand. In the case of JavaScript, this includes newline characters, comments, and some spaces. The first JavaScript minifier was written by Douglas Crockford (Crockford, 2003).

[3]A few of those tools have been mentioned in the Chapters 1.1 and 2.

[4]Grunt is a JavaScript build tool (Hogan, 2014).

[5]Gulp is a JavaScript build tool akin to Grunt, but younger and, by its own accounts, faster (Baumgartner, 2016).

These tools can be used to write zepto-js-backed websites as well. While many of the optimizations, minifications, and cross-compilers become unusable once the switch from JavaScript to another language is made, the facilities of those tools to collect and merge multiple source files, for instance, can be used without bigger modifications. Furthermore, as those tools are agnostic not only to the types of files they deal with but also to the types of tools they are to run on the source files, zepto-js-specific optimizers can be run on those files should they emerge.

Many of the preprocessed languages discussed in Chapter 2 use these technologies to compile their source files to JavaScript before shipping them. While zepto-js has no regular API that can be plugged into those build tools at the moment, a simple integration with existing tasks is possible as shown in Listing 7.

```
'use strict';

var gulp   = require('gulp');
var concat = require('gulp-concat');

global.buildEnv = 'development';

gulp.task('bundle', function(){
  // Process scripts
  var files = "zepto/*.zp";
  gulp.src(files)
      .pipe(concat('app.zp'))
      .pipe(gulp.dest('build'))
});
// == Register default task
gulp.task('default', ['bundle'], function() {
});
```

Listing 7: A gulp task that collects and merges zepto files.

5. Implementation

It always takes longer than you expect, even when you take into account Hofstadter's Law.

*(*Hofstadter's Law*)*

The implementation philosophy of the prototype of zepto-js has been to reuse as much code from the reference implementation as possible. This guided the flow of design choices down a rather natural path and kept the implementation described here fairly short and trivial.

5.1. Description of the Toolchain

The build infrastructure is centered around GHCJS, the compiler mentioned in Section 2.1.1. This means that the usual build infrastructure for Haskell is supported, which zepto-js partially makes use of, through Cabal and Stackage. Cabal is Haskell's standard package utility system[1], through which zepto-js' dependencies, installation and builds are configured. Stackage is an acronym for *st*able h*ackage*, wherein hackage is the Haskell package registry. It provides lists of packages and their versions that work with each other, making dependency relations more manageable.

GHCJS itself provides zepto-js with aforementioned quasi-quoting[2], which powers the JavaScript FFI.

The management of pure JavaScript sources is another important feature. As in regular GHC, where the management of bits of C code that should interface with Haskell is provided, GHCJS provides management of JavaScript sources. The build file includes a segment called `js-sources`, which ensures that the JavaScript in those sources will be included in the final compilation while still separating them from the rest of the codebase.

[1] It does not claim to be a full-fledged package manager.
[2] A description of quasi-quoting is provided in Section .

The informal convention seems to be to put the files to be included into a directory called jsbits — a hat-tip to the GHC convention of putting C sources into the cbits directory.

The code emitted by GHCJS is conservative in feature use. This is an important feature for older clients with possibly even obsolete browsers wanting to access web pages supported by zepto code, rare as they might be. In these cases, emitting JavaScript that adheres to older standards is a prudent idea.

All these conveniences do not spare the programmer from the actual programming process, of course. While GHCJS seems like a well-maintained project one has to keep in mind that, unlike GHC, it is not backed by a consortium, and the current maintainer seems to do this work completely in his spare time. This leaves the impression that the project could be abandoned at any given moment. Therefore, being too dependent upon its more unusual features could lead to a product that is unnecessarily difficult to maintain.

Taking all of this into consideration, a preliminary analysis revealed two main conditions for the success of this thesis: 1) the code emitted by GHCJS is fast, solid, and reasonably compact, and 2) the newest features of both JavaScript and Haskell were supported.[3]

5.2. Description of the Implementation

As predicted in Section 1.1, the code base of zepto could be reused almost in its entirety. What had to be rewritten was mostly related to the startup of the interpreter, because the regular paths into the code - either via a script being passed into it or launching an interactive REPL[4] — were unavailable in the browser context. Instead, a way of passing the sources from within script tags needed to be found. Further customizations include a FFI to enable better cross-evaluation of JavaScript and the adaptation of existing APIs, such as the DOM.

[3]The newest version of GHC at the time of writing, version 8.0, gained support while this thesis was in the works.

[4]A REPL is an interactive code evaluation environment. Code is typed into a prompt and immediately evaluated. The convenience of such a short feedback loop is often used in the context of scripting languages and shells.

5.2.1. The script tag

Initially, a DOM node walker was considered, but rejected relatively early because of two reasons: firstly, it introduced a layer of complexity from within JavaScript code that would have likely made it brittle and hardly portable. Secondly, it would require a walk of the nodes every time a DOM element is inserted or replaced, which is a common occurence in modern interactive web applications.

```
// the initial observer and the function it takes
zepto.observer = new MutationObserver(zepto.handleMutation);

// this function will get a list of mutations and apply handleDom to them
zepto.handleMutation = function(mutations) {
  mutations.forEach(mutation => {
    mutation.addedNodes.map(zepto.handleDom);
  });
}

// evaluate if it is a text/zepto node
zepto.handleDom = function(node) {
  if (node.nodeName != "SCRIPT" || node.type != "text/zepto") {
    return null;
  }
  return zepto.eval(node.innerHTML);
}

// execute this on startup
window.onload = () => {
  let scripts = document.getElementsByTagName("script");
  scripts.map(zepto.handleDom);
}
// the extra arguments signify recursive listening
zepto.observer.observe(document, {childList: true, subtree: true});
```

Listing 8: The final mutation observer code (simplified)

In November 2015, the World Wide Web Consortium (W3C) released an API that simplified this process for the programmer. Within their specification of the DOM4 (World Wide Web Consortium, 2015) , the fourth specification of APIs for the Web, an object called MutationObserver, which is able to register for notificiations of DOM manipulations, is included. Its main function will be triggered whenever a change occurs within the DOM part to which it is registered to listen.

This simplifies the implementation of a listener to DOM events a great deal. Only minimal programming is required to configure the listener and to filter out all the nodes that are not `script` nodes of the type `text/zepto`.[5]

A problem with this method was that nodes inserted before the listener started were ignored. This was resolved by singling out all the `script` tags present before the listener starts and applying the same filter/evaluation function to all of them. This also ensures that they are executed before any additional — and possibly interdependent — code is passed into the zepto object.

The code was then included in the `zepto` singleton, which is the global interpreter object used for the management and interactivity of the zepto interpreter. A simplified version of this code is presented in Listing 8.

5.2.2. The FFI

The FFI is a central part of the port. If it were unusable, none of the browser's capabilities could be used from within zepto, thus rendering the effort of bringing zepto into the browser effectively useless. The APIs of the Web are a big part of what it means to program for the browser, after all.

An initial sketch of the programming interface was extremely simplistic: a call to the function `js` could be made with a string as argument, representing the code to be run as text. It was piped to the JavaScript function `eval`, and the function always returned an affirmative truth value, regardless of what happened within JavaScript. Quasi-quoting larger blocks of JavaScript was also possible.

This version worked, but was suboptimal. The missing return value renders any effort of talking to an API useless. Oftentimes, it is necessary to chain multiple calls to an API together, as, for instance, when getting and manipulating a node within the DOM. This is highly inconvenient when the option of binding a value to a variable is not available in the FFI. A different kind of return value is needed.

The most obvious solution — albeit the most challenging — would be to infer a fitting zepto type for every return value in JavaScript and return a result depending on these parameters.[6] While is a rather elegant solution, it comes with its own set of caveats and

[5]This was chosen in analogy to the existing `text/javascript` node type.
[6]This approach is shown in Listing 9.

exceptions, as the mapping between JavaScript and zepto values is not always obvious. A JavaScript object has too many properties that get lost in the process of translating it to zepto to make it intuitive, because at least functions do not work in the exact same way.

```
; this would return an integer
(js "1 + 1")

; this would return a hashmap
(js "{key: \"val\"}")

; this is problematic, because it will return an object
(js "new Error()")
```

Listing 9: The ideal FFI

The implementation of JavaScript values in GHCJS is another point of complication. They are opaque datatypes, in this case aliases for addresses and byte vectors. While zepto supports byte vectors and pointers, they are hardly a good representation for semantically rich prototypes as they only offer a glance into the underlying implementation of the JavaScript engine. While it is true that GHCJS itself provides methods for type coercion, these methods are crude and possibly error-prone.

A simpler, but still mostly sensible method arose: returning the string values of all of the values returned.[7] While this places the burden of coercion on the programmer, it also gives the developer the power to make autonomous decisions of how to deserialize values. Functions for deserializing the most common datatypes are included in the standard library of zepto — and, therefore, zepto-js — to aid the programmer in the process of finding the right methods of getting a value out of the FFI.

This still does not solve the problem of helping manage classes. It does, though, empower the programmer to find appropriate ways of serializing on the JavaScript side and deserializing on the zepto side to preserve the information needed in specific programming contexts.

All of this needs an additional layer of abstraction to avoid unnecessary boilerplate, but it is stable enough to support most applications for which zepto-js has yet been used.

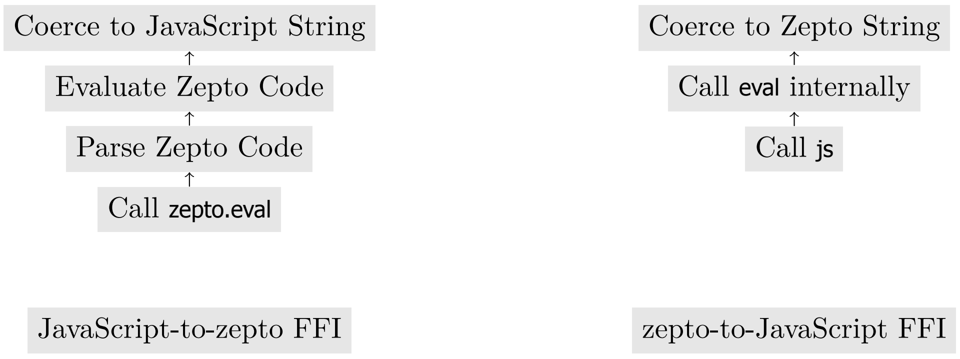
[7]The interface of this version of the FFI is shown in Listing 10.

```
; the function string->number is a standard zepto function
(string->number (js "Math.pow(2, 32)"))

; this is an example of how to resolve the earlier problem:
; override the prototype of the object to return the value that is needed
(js "Error.prototype.toString = function() { return this.message; }")
(error (js "new Error(\"fatal error occured\")"))
```

Listing 10: The final form of the FFI

Implementing the JavaScript-to-zepto FFI was much simpler, as the interpreter is defined within the JavaScript environment. A call to the eval function of the zepto object with a string as argument will return the evaluation's result of that string as zepto code. This result will then be coerced to a text, so that the entirety of the communication between the two languages is string-based. The pipeline of operations is presented in Figure 11.



Listing 11: The FFI stack

5.2.3. The DOM

After building the FFI, it was possible to implement the entire communication with the DOM in terms of calls to foreign functions and the parsing of their return values. This allows for a stable library, because it is unintrusive and does not interfere with existing JavaScript constructs.

While wrapping the entire DOM API would be a big task, making the most integral features of the W3C's specifications work turned out to be rather simple. A minimalistic example of a zepto module that implements the creation, insertion, and retrieval of elements into and from the DOM is presented in Listing 12. A production-ready module would require a host of other features, some of which are already implemented in a library geared toward zepto-js.

```
(module "dom"
 (export
  `("create" ,create)
  `("insert" ,insert)
  `("get" ,get))

 (loads "html")

 (update-dom! (lambda (node contents)
  (js (++ "document.getElementById('" node "').innerHTML = '"
          (create contents)
          "';"))))

 (create (lambda (tree)
  ((import "html:build") tree)))

 (insert (lambda (context tree)
    (update-dom! context tree)))

 (get (lambda (node)
  ((import "html:parse")
    (js (++ "document.getElementById('" node "');"))))))
```

Listing 12: A minimal DOM module.

The DOM module is not included in the standard library of zepto-js, as it was too prototypical to be included in a base set of stable functions. It is, however, available as a third-party zeps package simply called *dom*.[8] Due to its alpha status it had not yet been registered to the ZPR at the time of writing.

5.2.4. Language definitions

One of zepto's most advanced features is language definitions, inspired by the parser macro system in Racket (Flatt, 2011). Language definitions allow for a custom parser to be injected into the loading of source files that replaces zepto's standard parser.

[8]Should zeps be installed on the target system, it can be installed by issuing *zeps install hellerve/dom*.

These parsers are regular functions that take a string representing the program as input and emit regular S-Expressions that can be evaluated as output.[9] This allows for the creation of DSLs and other abstractions. While this is handled fairly differently in zepto than in Racket, the syntax of the resulting language is compatible. zepto handles the custom parser step with a dispatch at the time of file loading, which enabled the system to be implemented without changes to the core language, completely in zepto itself. While this was designed with portability in mind and thought to ease the transition to different backends, it actually proved to complicate matters in the case of the JavaScript port. Here, the module loading system is not present due to the absence of files in the traditional sense, which made determining where to plug in the parser dispatcher a problem.

```
; json-lang.zp
(load "json/json")

(zepto:implements-lang json:parse "json")

; an example for a file that can now be loaded normally
; it will return a hashmap type
#lang json
{
  "hello": "json"
}
```

Listing 13: An example language definition that allows for inlining of JSON code.

As the detection of what to parse is handled from within JavaScript — by the MutationObserver mentioned in Section 5.2.1 — the first implementation of the dispatch mechanism was written entirely in JavaScript. This rendered the dispatch mechanism relatively clumsy, because registering additional languages had to be done in JavaScript, making this feature a JavaScript rather than a zepto feature. While building a parser dispatch mechanism for JavaScript would certainly also make for an interesting experiment, it is outside of the scope of this thesis and would not be a unique feature to zepto.[10]

[9] An example language implementing JSON is presented in Listing 13.

[10] The code for the JavaScript version was salvaged for posteriority and can be found on Github under the name of js-parse-dispatch.

This feature was finally dropped altogether from the initial prototype, as it would either require the impure solution described above or extensive rewrites of the zepto system — at least the `load` statement would require hijacking. Both of these options incurred too high a maintenance cost for a feature that is mostly of importance in the context of file-based systems. At the time of writing it was determined that the implementation of this feature should be deferred to the point where the need for other languages or DSLs within zepto-js arises.

6. Evaluation of the Prototype

When I'm working on a problem, I never think about beauty. I think only how to solve the problem. But when I have finished, if the solution is not beautiful, I know it is wrong.

*(*R. Buckminster Fuller*)*

TODO

6.1. Seamlessness of Integration

6.2. Test Against Standard Implementation of zepto

* added: ffi
  * removed load statement, REPL functionality, language definitions
  * inserting libraries?

7. Summary and Outlook

Part of the inhumanity of the computer is that, once it is competently programmed and working smoothly, it is completely honest.

*(*Isaac Asimov*)*

The prototype presented in this thesis was never expected to be a replacement for technologies that are currently making the web what it is. It is a simple experiment that happens to work well enough to power fewer than a handful of actual production systems, a blessing for the development of zepto. The use cases provided real insight into the discrepancy of how the program works and how it should work. It is also a liability going forward, as users do not generally appreciate breaking changes.

The software system certainly proved that it is possible to make other languages work on the web, an idea that is nascent but, by the hopes of those involved in the production of zepto-js, one that might become a trend going forward.

Other developments in the zepto ecosystem are just as exciting. There have been efforts to port zepto to a few different platforms, all of which are far from finished. Nonetheless, it has been interesting to follow their development. The compiler and parser have both gained language implementations, some of them usable — the aforementioned compiler backends for LLVM and Erlang come to mind, as well as a web server framework that uses a DSL to simplify writing request handlers —, some of them borne purely out of the desire to toy around with the language; parsers and cross-compilers have been written for a handful of esoteric programming languages, including Brainfuck[1], Io, and Iota[2].

The development of zeps has surely contributed to the growth of zepto and fueled the development of zepto-js. It is tested on real systems and has withstood the scrutiny of

[1]Brainfuck is a language that aims to reduce programming to its most minimal and tries to emulate a Turing machine (Müller, 1993).

[2]Io and Iota are conceptually similar to Brainfuck, although they try to reduce programming to the lambda calculus described by Alonzo Church (Barker, 2002).

colleagues and contributors. By the definition of the development team, however, it is not yet ready for a big public release, hence the timid version number of 0.0.7. A stable version might not be as far in the distance as this number suggests, but it certainly is far enough away to merit a healthy dose of defensiveness.

Another big development in the zepto community has certainly been a series of classes and workshops. They too helped route the development of zepto down a path of usability, self-awareness, and constant reevaluation. Targeted at an audience of diverse people with mostly little to no experience with functional programming or Lisp, the workshops have shown to not only awaken an interest in those concepts. They also led to the development of a few projects for zepto and its JavaScript-backed counterpart that now have become part of the standard toolset, such as the plugins for the Atom[3] and Vim[4] editors.

In regard to tooling for zepto-js, a newly formed development team, comprised of people experienced in web development, is building plugins for zepto-js to integrate with Gulp[5] for tasks like minification and dependency resolution. Integration of zeps with Gulp is a subject for the near future too.

All of these developments start to hint at a community in its nascence. It might be too soon to judge whether or not this is true, but it would certainly be a welcome development for zepto and its maintainers.

[3] Atom is an editor that was developed by the Github team as a lightweight, powerful, and pluggable development environment (Jackson, 2014).
[4] Vim is the standard editor for the command line of most Linux distributions (Oualline, 2001).
[5] One of the tools mentioned in Section 4.1.2.

8. Conclusion

There have been voices that have insisted that the web need be fixed since its inception. Most disagreements over its inner workings have been philosophical and are a matter of ongoing dispute. While the web certainly can be improved — like any system, at any time — I do not believe it is fundamentally flawed. The technologies that power the current World Wide Web, from switches and cable technologies to protocols and development frameworks, have shown to be robust enough for a large part of the world to interconnect. We steadily adapt the way we work with it as trends and paradigms emerge and evolve.

One of the major redeeming qualities of the fundamental philosophies of the World Wide Web has certainly been its ability to adapt to changes. Standardization of web technologies has a reputation for being slow, but in terms of design processes on a global scale, it is actually reasonably fast.

zepto is a young language that has adopted this mindset — it changes rapidly and a stable release has yet to be announced. With this thesis, an important step towards reaching a fulfillment of its design goals has been taken.

Many questions addressed by this thesis remain unanswered. Even with that in mind, I hope that my work has asked questions that are worth being asked and that the technologies presented in this thesis will allow for more technologies to come to the web, so that an even more heterogeneous, expressive, and inclusive system can emerge, one that caters to different aesthetics, philosophies, and mindsets.

I would happily welcome any contributions towards that end, both related and unrelated to the technology that is zepto.

A. List of Modules in the zepto Standard Library

Libraries that are loaded by default are denoted by *(dflt.)*.

argparse A command line argument parser

ascii An ASCII art modul

bench A simple benchmarking and timing library

calculus A library that implements combinators of the lambda calculus

char*(dflt.)* A library of functions for working with characters

cl A library that exports standard Common Lisp functions

data A library that exports lazy data types, such as queues, deques and streams

datetime A library for working with and formatting dates and times

delay*(dflt.)* A utility library for delaying computations

infix A library that translates infix mathematical expressions to the appropriate prefix form

io*(dflt.)* A library of functions for Input and Output

json A JSON parser and renderer

keywords*(dflt.)* A library that allows for keyword arguments as found in Python

marsaglia A library of functions for cryptographically strong Pseudo-Random Number Generators

math*(dflt.)* A library of functions for mathematical purposes

minitest A testing library

module*(dflt.)* zepto's module system

monads A library of monads and monadic computations

parsecomb A parser combinator library

pointfree A library for defining functions in point-free style

querystring A querystring parser and renderer

random*(dflt.)* A library of functions for cryptographically insecure random number and data generation

rsa A RSA library

slugify A library for generations slugs

sort*(dflt.)* A sorting library

srfi*(dflt.)* A library of SRFIs

statistics A statistics library

struct*(dflt.)* A library for generating structs with the appropriate functions declaratively

zpbash A BASH library

zpcllections*(dflt.)* A library of functions for defining and working with collections

zpcont*(dflt.)* A library of functions for working with continuations

zpconversion*(dflt.)* A library of functions for converting between datatypes

zperror*(dflt.)* A library of functions for working with errors

zpfile*(dflt.)* A library of functions for working with files

zpgenerics*(dflt.)* A library of functions for defining and working with generic functions

zphash*(dflt.)* A library of functions for working with hash maps

zplist*(dflt.)* A library of functions for working with lists

zpnumbers*(dflt.)* A library of functions for working with numerical values

zpstring*(dflt.)* A library of functions for working with strings

zpvector*(dflt.)* A library of functions for working with vector

zpversion*(dflt.)* A library of functions for working with the current zepto version

B. List of zeps commands

This list can also be found in the README of zeps under https://github.com/zeps-system/zeps.

test Runs the module tests.

t shortcut for test.

search Search for packages matching a search term (on the ZPR).

sandbox Create/destroy a sandboxed zeps environment

run Run the module entry-point, without installing it

repl Launches an interactive shell with a certain module preloaded.

remove Removes a package.

rm shortcut for remove.

register Registers a package.

r shortcut for register.

new Bootstraps a new package.

n Shortcut for new.

keygen Generates a new RSA key for zeps.

install Installs a package.

i Shortcut for install.

help Interactive help on getting started

readme Prints zeps' README

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