A Multitier Debugger for Web Applications

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Abstract: Debugging Web applications is difficult because of their distributed nature but also because of the programming languages and tools commonly used to develop them. Taking benefit of the multitier aspect of the Hop programming language, we have built a new debugger for Web applications that copes with the server-side and the client-side of the executions. Its advantage over most debuggers for the Web is that it reports the full stack trace containing all the server-side and client-side frames that have conducted to an error. An error is reported on its actual position on the source code, wherever it occurs on the server or on the client.
To help detecting errors as early as possible, the Hop debugger is accompanied with a debugging execution mode where types are checked before data structures are accessed, argument numbers are verified before functions are called, and array bounds are checked before vectors are accessed. Combining the debugger and the debugging mode makes errors of Web applications easier to understand and easier to localize. Hopefully they also become easier to fix.

1 INTRODUCTION

The distributed nature of Web applications makes debugging difficult. The programming languages and tools commonly used make it even more complex. Generally the server-side and the client-side are implemented in different settings and the debugging is treated as two separated tasks: on the one hand, the debugging of the server, on the other hand, the debugging of the client. Most studies and tools focus on this latter aspect. They concentrate on the debugging of JavaScript in the browser. Although useful, this only addresses one half of the problem. Considering the debugging of Web applications as a whole raises the following difficulties:

- As the server-side and the client-side are generally implemented in different languages, debuggers for the Web do not capture the whole execution of the application. Programming the server and the client in the same language helps but is not sufficient to let the debugger expose a coherent view of the whole execution as this also demands a runtime environment that enforces consistent representations of data structures and execution traces.
- The JavaScript tolerant semantics tends to defer errors raising. For instance, calling a function with an insufficient number of arguments may lead to filling a data structure with the unexpected `undefined` value which, in turn, may raise a type error when accessed. The *distance* between the error and its actual cause may be arbitrarily long, which can make the relation between the two difficult to establish.
- The JavaScript event loop used for the GUI splits the execution into unrelated callback procedures which get called upon event receipts. When an error occurs, the active stack trace only contains elements relative to the current callback invocation. It is oblivious of the context of the callback. Understanding the cause of the error is then uneasy.

Pursuing our research on multitier programming for the Web, we have built a programming environment that eliminates most of these problems.

- When an error is raised, the full stack trace is reported. This stack trace may contain server stack frames, client stack frames, or both. We call this a *multitier stack trace*.
- When an error occurs, either on the client or on the server, its source location is reported by the debugger.
- In *debugging mode*, types, arities, and array bounds, are strictly enforced on the server and on

the client. Hence, when the execution of the program deviates from the formal semantics of the language, an error is raised immediately.

This paper presents this debugger and exposes the salient aspects of its implementation.

1.1 Debugging Web Applications

Most studies of the debugging of Web applications consider the client-side of the applications. Beside an early debugger for CGI applications by Vckovski (Vckovski, 1998), most efforts concentrate on creating JavaScript debuggers for the Web browsers. Feldman and Sharma have both developed a remote debugger for WebKit (Feldman, 2011; Sharma, 2012). Mickens has developed a browser-agnostic JavaScript debugger (Mickens, 2012). These tools offer facilities for inspecting the JavaScript stack frame and for breakpointing. They do not address the problem of debugging Web applications globally. These studies are complementary with our effort as Hop can use them to step inside the client side execution, provided they support the *source map* specification (Lenz and Fitzgerald, 2011).

A previous study by E. Schrock (Schrock, 2009) has identified many difficulties posed by JavaScript when debugging Web applications. *"In the early days, the [JavaScript]'s ability to handle failure silently was seen as a benefit. If an image rollover failed, it was better to preserve a seamless Web experience than to present the user with unsightly error dialogs.*

This tolerance of failure has become a central design principle of modern browsers, where errors are silently logged to a hidden error console... Now, at best, script execution failure results in an awkward experience. At worst, the application ceases to work or corrupts server-side state. Tacitly accepting script errors is no longer appropriate, nor is a one-line number and message sufficient to identify a failure in a complex AJAX application. Accordingly, the lack of robust error messages and native stack traces has become one of the major difficulties with AJAX development today... Ideally, we would like to be able to obtain a complete dump of the JavaScript execution context[.]". This is exactly what Hop brings. In addition to offering multitier execution stacks that reflect the states of the server and the client, the Hop-to-JavaScript compiler (Loitsch and Serrano, 2007) generates codes which enable early error detection. It also generates `ECMA-262-5` *strict mode* (ECMA, 2009) code which helps detecting undeclared variables and functions that can be located inside JavaScript code linked against Hop applications.

1.2 The Hop Programming Language

Hop has been presented in several publications (Serrano et al., 2006; Boudol et al., 2012; Serrano and Berry, 2012). We only remind its essential aspects and show some examples that should be sufficient to understand the rest of the paper.

Hop is a Scheme-based multitier functional language. The application server-side and client-side are both implemented within a single Hop program. Client code is distinguished from server code by prefixing it with the syntactic annotation '`~`'. Server-side values can be injected inside a client-side expression using a second syntactic annotation: the '`$`' mark. On the server, the client-side code is extracted, compiled on-the-fly into standard JavaScript, and shipped to the client. This enables Hop clients to be executed by unmodified Web browsers.

Except for multitier programming, the standard Web programming model is used by Hop. A server-side Hop program builds an HTML tree that creates the GUI and embeds client-side code into scripts, then ships it to the client. AJAX-like service-based programming is made available by service definitions, a service being a server-side function associated with a URL. The `with-hop` form triggers execution of a service. Communication between clients and servers is automatically performed by the Hop runtime system, with no additional user code needed.

The Hop Web application `fib-html` below consists of a server-built Web page displaying a three-rows table whose cells enumerate positive integers. When a cell is clicked, the corresponding Fibonacci value is computed on the client and displayed in a popup window. Note the '`~`' signs used in lines *3*, *8*, *9*, and *10* which mark client-side expressions.

```
 1:(define-service (fib-html)
 2:  (<HTML>
 3:   ~(define (fib x) ;; client code
 4:      (if (< x 2)
 5:          1
 6:          (+ (fib (- x 1)) (fib (- x 2)))))
 7:   (<TABLE>
 8:    (<TR> (<TD> "fib(1)" :onclick ~(alert (fib 1))))
 9:    (<TR> (<TD> "fib(2)" :onclick ~(alert (fib 2))))
10:    (<TR> (<TD> "fib(3)" :onclick ~(alert (fib 3)))))))
11:
```

Let us modify the example to illustrate some Hop niceties. Instead of building the rows by hand, we let Hop compute them. The new Hop program uses the `(iota 3)` expression (line *9*) that evaluates to the list (1, 2, 3) and the `map` functional operator that applies a function to all the elements of a list. The `$i` expression (line *8*) denotes the value of `i` on the server at HTML document elaboration time.

```
(define-service (fib-html)
  (<HTML>
     ~(define (fib x) ...)
    (<TABLE>
       (map (lambda (i)
              (<TR>
                 (<TD> "fib(" i ")"
                    :onclick ~(alert (fib $i)))))
         (iota 3)))))
```

Before delivery to a client, the server-side document is compiled on the server into regular HTML and JavaScript. This produces the following document [1]:

```
<!DOCTYPE HTML>
<html>
  <head> <meta ...>
    <script src='/usr/local/share/hop/hop_s.js'>
  </head>
  <script>
    function fib(x) {if(x<2) return 1; else ...}}
  </script>
  <table>
    <tr><td onclick="alert(fib(1))">fib(1)</td></tr>
    <tr><td onclick="alert(fib(2))">fib(2)</td></tr>
    <tr><td onclick="alert(fib(3))">fib(3)</td></tr>
  </table>
</html>
```

This program can then be executed by all standard browsers.

If for some reason, the programmer wants the `fib` calls to be evaluated on the server, three modifications are needed: *i)* a service must be defined as the client cannot access directly server-side functions, *ii)* the definition of the `fib` function must be migrated to the server, and *iii)* a `with-hop` remote call must be introduced:

```
(define-service (fib-html)
  (<HTML>
    (<TABLE>
      (map (lambda (i)
             (<TR>
                (<TD> "fib(" i ")"
                   :onclick ~(with-hop ($fib-svc $i)
                                alert))))
        (iota 3)))))

(define-service (fib-svc n)
  (define (fib x) ...)
  (fib n))
```

These examples illustrate the flavor of Web programming with Hop. Many more are available on the Hop web site[2].

In *debugging* mode, Hop generates JavaScript code that enforces types consistency, arity correctness, and array bounds. In this mode, all functions must be called with a number of arguments compatible with their declaration, all accesses to the data structures and to the arrays are verified by the runtime system. By experience, we have found strict checking an effective method for correcting errors that are otherwise difficult to understand. Since preventing runtime errors has a cost, Hop also supports a *production* mode where types, arities, and bounds are not enforced at runtime. This yields faster but *unsafe* executions. In production mode, executions are not guaranteed to comply with the Hop's formal semantics (Boudol et al., 2012).

1.3 Organization of the paper

The paper is organized as follows. Section 2 presents some debugging scenarios. Section 3 sketches the implementation of the debugger and the debugging mode. A comparison of the performance between the *debugging* and *production* modes is then presented. Section 4 presents the related work.

2 DEBUGGING SCENARIOS

In this section we show the error reports produced by the Hop *debugging* mode in typical erroneous situations. The reports are accessible on the client, *i.e.*, the Web browser, and on the server, which prints them on its console.

2.1 Client-side error

Let us first consider a type error that involves client-side and server-side computations. The server-side program elaborates a single-button Web page which invokes the client-side function `my-callback` when clicked (line *10*).

```
 1:(module bug1_server
 2:   ~(import bug1_client)
 3:   (export bug1-svc))
 4:
 5:(define-service (bug1)
 6:   (<HTML>
 7:      (<HEAD>
 8:         :jscript (service-resource bug1 "bug1.scm"))
 9:      (<BUTTON> :id "my-button"
10:         :onclick ~(my-callback)
11:         "click me to raise the error")))
12:
13:(define-service (bug1-svc a b)
14:   (vector a b))
```

The function `my-callback` is implemented in a separate client-side module.

[1] Some generated programs have been manually modified to fit the paper layout constraints.

[2] http://hop.inria.fr

```
 1: (module bug1_client
 2:    $(import bug1_server)
 3:    (export (my-callback)))
 4:
 5: (define (my-callback)
 6:    (with-hop ($bug1-svc 11 12)
 7:       my-type-error))
 8:
 9: (define (my-type-error l)
10:    (car l))
```

The client-side function `my-callback` (line *5*) calls the server service `bug1-svc`. When the service completes, the execution resumes on the client by invoking the function `my-type-error`. This function is called with the vector its receives from the service. This is wrong because its wants a pair. The vector/list type mismatch is reported as:

```
File "bug1.scm", line 10, character 3:
#   (car l))
#   ^
*** CLIENT ERROR: http://localhost:8888/hop/bug1, car:
Type "pair" expected, "vector" provided -- #(11 12)
   1. ~my-type-error@bug1_client, bug1.scm:9
With-Hop trace:
   2. ~(with-hop (bug1-svc...) ...), bug1.scm:6
   3. ~my-callback@bug1_client, bug1.scm:5
   4. ~button#my-button.onclick, bug1.hop:10
```

The error report shows the position in the source file of the error and the complete stack trace. Client-side frames are prefixed with the ~ sign. (Here, all stack frames are client frames.) When the type error is raised in the client-side function `my-type-error` the active stack trace only contains one frame denoting the invocation of the function `my-type-error`. However, the report also shows the context from which `my-type-error` has been called. It shows that a click on the button defined line *9* of `bug1_server` module has called the client-side function `my-callback` which, in turn, has invoked the remote service `bug1-svc`.

The call trace makes explicit the whole execution flow which has conducted to the error on the client. As it also makes explicit the network traversal (frame #2) that took place before `my-type-error` is called, it is easier to understand which actual computation conducted to the type error.

This scenario also illustrates an important difference between Hop and JavaScript. In JavaScript a function equivalent to `my-type-error` would silently return the `undefined` value. In Hop *debugging* mode, the type error is signaled as soon as the illegal access gets executed.

2.2 Server-side error

Let us modify the definition of the previous service to introduce a server-side error:

```
13: (define-service (bug2-svc a b)
14:    (vector (car a) b))
```

This is wrong as the service `bug2-svc` is passed an integer for the argument `a` while it expects a pair. The new error report is as follows:

```
File "bug2.hop", line 14, character 301:
#   (vector (car a) b))
#           ^
*** SERVER ERROR:car
Type "pair" expected, "int" provided -- 11
   1. \@bug2-svc, bug2.hop:13
   2. &pool-scheduler1965,
With-Hop trace:
   3. ~(with-hop (bug2-svc...) ...), bug2.scm:6
   4. ~my-callback@bug2_client, bug2.scm:5
   5. ~button#my-button.onclick, bug2.hop:10
```

The report locates the error inside the `bug2-svc` service (services are prefixed with `\@` to distinguish them from regular functions). The stack trace shows server-side stack frames and the client-side context that has yielded the service invocation. This time again the error is easy to follow and to understand as the complete trace before the error is exposed. The computation started with a user click on the client. The click action has been followed by a service invocation, which has raised the server-side error.

2.3 Putting together

The Hop debugger keeps track of all the callbacks of the client-side program. Let the callback be associated with a service invocation as seen before, with a GUI event (mouse move, key press, ...), with a server side event (a high level facility supported by Hop built on top of websockets), or with a timer, Hop generates a dedicated entry in the stack trace. Callback traces can be combined without restriction. For instance, suppose a service call wrapped in an `after` expression (a mere JavaScript `setInterval` wrapper) as follows:

```
5: (define (my-callback)
6:    (after 1000
7:       (lambda ()
8:          (with-hop ($bug2-svc 11 12)
9:             my-type-error))))
```

The new error trace shows a *with-hop* trace preceded by an *after* trace:

```
File "bug2.hop", line 14, character 295:
#   (vector (car a) b))
#           ^
*** SERVER ERROR:car
Type "pair" expected, "bint" provided -- 11
   1. \@bug2-svc, bug2.hop:13
   2. &pool-scheduler1926,
With-Hop trace:
   3. ~(with-hop (bug2-svc...) ...), bug3.scm:8
   4. ~lambda, bug3.scm:7
After trace:
   5. ~after, /usr/local/share/hop/hop_s.js:8254
   6. ~my-callback@bug3_client, bug3.scm:5
   7. ~button#my-button.onclick, bug2.hop:10
```

A Hop stack trace may also contain JavaScript frames as JavaScript functions are treated as Hop functions. This can be observed in the previous stack trace with the `after` function (frame #5) which is a plain JavaScript function implemented in the Hop standard client library (the file `hop_s.js`).

Beside full stack traces, the Hop debugger also supports stepping. In the current version, the server-side stepper and client-side stepper work separately and only the client-side stepper is fully operational. The server-side is in progress, being developed using the techniques presented in (Kellomäki, 1993). The implementation of the client-side stepper is briefly discussed in Section 3.1.

3 IMPLEMENTATION

The Hop debugger relies on three elements: *i)* stepper, *ii)* construction the stack traces, and *iii) debugging mode* where types, array bounds, and function arities are verified at runtime. These are presented in this section.

3.1 Implementing the stepper

The server-side stepper is currently being developed using the techniques established for Lisp-like languages (Kellomäki, 1993). The client-side stepper reuses the native stepper available in modern browsers. The Hop-to-JavaScript compiler produces *Source Map* tables (Lenz and Fitzgerald, 2011) that let browsers step in the client side code using the original Hop source code instead of the generated JavaScript one. Figure 2 shows a screenshot of Chrome being used to step the example of Section 2.1.

3.2 Constructing stack traces

Hop client-side programs are compiled into *natural* JavaScript programs, namely, Hop functions are mapped into JavaScript functions, and Hop variables are mapped into JavaScript variables. Hence, obtaining the client-side part of the Hop stack frames is similar to obtaining a plain JavaScript stack frames, whose technique is well known (Schrock, 2009; Mickens, 2012; Sharma, 2012). It relies on two observations: first, JavaScript exception objects contain stack information; second, there are four different contexts in which codes get executed:

1. the global context while loading the page;
2. event listeners (GUI or server events);
3. timeouts and intervals;
4. remote service callbacks (XmlHTTPRequest).

To obtain a stack trace, the runtime environment installs exception handlers on these four contexts, it intercepts exceptions, and extracts their stack information. Older techniques based on the two special JavaScript variables `caller` and `callee` are now impractical as JavaScript *strict mode* used by Hop does not support these variables.

3.2.1 Constructing multitier stack traces

The *multitier stack trace* describes the current computation and the context in which it has been initiated. Contexts are computed as follows:

1. The context of a global top-level JavaScript evaluation is empty.
2. The context of a DOM listener specified as an attribute of an HTML node consists of a description of the node and a description of the event the listener is attached to.
3. The context of an event listener dynamically attached to a DOM event consists of a description of the DOM node plus the stack trace active at the moment the listener is attached.
4. The context of a timeout consists of the concatenation of the context and the stack trace active when the callback is registered, and a description of the timeout itself.
5. The context of a service call (`with-hop`) consists of the concatenation of the context and the stack trace active when the remote call is spawn and a description of the called service.

Hop stores the active context in the JavaScript global variable `hop_current_stack_context`, which is updated each time a new callback is registered. This approach is correct because JavaScript execution is single-threaded and because callbacks always run up to completion (*i.e.*, they are never preempted).

Let us illustrate the construction of the multitier stack trace on two actual examples. First, let us show the compilation of an HTML button declaration as found in the examples of section 2.1.

```
(<BUTTON> :id "my-button" :onclick ~(my-callback)
   "click me to raise the error")
```

The *production mode* compilation merely consists in mangling the Hop identifier to map it into the JavaScript identifiers space:

```
<button id='my-button'
  onclick='BGl_myzd2callbackzd2zzbug3_clientz00()'>
  click me to raise the error
</button>
```

The possibility to change the compilation schema according to external configuration is a benefit of the Hop approach where the JavaScript code is generated on demand by an on-the-fly compiler. Switching from production mode to debugging mode and *vice versa* merely requires switching on and off a Hop compiler flag. In *debugging mode*, the compilation of the button is changed for:

```
1: <button id='my-button'
2:   onclick='hop_callback(
3:     function () {BGl_myzd2callbackzd2zzbug3_clientz00()},
4:     hop_callback_html_context_handler(
5:       "button#my-button.onclick", "bug2.hop", 205))
6:   .call(this)'>
7:    click me to raise the error
8: </button>
```

This code constructs an HTML context that stores the source location of the button (line *4*). It calls the library the library function hop_callback (line *2*). The wrapped callback returned from hop_callback is then called with the this parameter of the HTML statement (line *6*).

The hop_callback function sets the global exception context (line *2*) and it wraps the user callback (proc) into a context aware callback (line *3*). This wrapped callback installs an error handler (line *4*) which signals potential errors in the context that was active when the callback has been installed (the variable ctx line *7*).

```
 1: function hop_callback( proc, ctx ) {
 2:    hop_current_stack_context = ctx;
 3:    return function() {
 4:       try {
 5:          return proc.apply( this, arguments );
 6:       } catch( e ) {
 7:          hop_callback_handler( e, ctx );
 8:       }
 9:    }
10: }
```

The function hop_callback_handler, which is invoked when an error is raised at execution time, simply extracts the stack trace it finds in the exception and the stack trace is builds from the callback context:

```
function hop_callback_handler( e, ctx ) {
   var estk = hop_get_exception_stack( e );
   var cstk = hop_get_context_stack( ctx );
   report_stack_frame( estck );
   report_stack_frame( cstck );
}
```

To show how contexts are accumulated, let us study the implementation of the Hop after function. It works similarly to with-hop but it is simpler to understand as with-hop carries its own complexity independently of stack contexts. The base implementation of after is as follows:

```
function after( timeout, proc ) {
   if( hop_debug() >= 0 ) { /* debugging code */ }
   var i = setInterval(
      function() { clearInterval( i ); proc() },
      timeout );
}
```

When debugging is enabled (hop_debug() >= 0 is true), the extra following code is executed:

```
 1: /* debugging code */
 2: if( !sc_isNumber( timeout ) )
 3:    sc_typeError( "after", "integer", timeout, 1 );
 4: if( !("apply" in proc) )
 5:    sc_typeError( "after", "procedure", proc, 1 );
 6: try {
 7:    throw new Error( "after" );
 8: } catch( e ) {
 9:    var ctx = sc_cons( "After trace:",
10:       hop_append_context(
11:          hop_get_exception_stack( e ),
12:          hop_current_stack_context ) );
13:    proc = hop_callback(hop_arity_check(proc, 0), ctx);
14: }
```

First, initial type tests (lines *2* and *4*) are executed. Then, before calling the setInterval JavaScript function, an exception is raised to capture the current execution trace (the function hop_get_exception_stack.) This stack trace is concatenated to the context active when the function after is called. Line *13*, the call to the function hop_arity_check checks if the callback provided on the call site has a correct arity. If not, it throws an exception.

The proposed implementation of after breaks tail recursions. Programming patterns as:

```
(let loop ()
   (after delay
      (lambda () ... (loop))))
```

blow the memory because the contextual stack is augmented each time a new iteration of the loop is executed. Several *ad-hoc* solutions are possible to workaround this problem. The one implemented in Hop consists in checking the top of the contextual stack. If it is already an *after* frame, nothing is pushed on the stack. Otherwise a new frame is pushed as already described. Although simplistic, we have found this solution sufficient and convenient to debug tail-recursive programs. If needed in the future, smarter solutions will be envisioned.

Handling the context stack on the server is simpler. When a client invokes a service, it serializes the context stack and ships it along the service arguments. The server protects the execution of its service with a handler that appends the execution trace of the exception to the client-side context. This augmented context is returned to the client if a server-side error occurs.

3.2.2 Pretty-printing the stack trace

Pretty printing stack traces requires the debugger to identify correctly Hop stack frames and to map the actual locations of the generated JavaScript file into the user source codes. In this process, a stack frame such as:

```
at BGl_myzd2callbackzd2zzbug1_clientz00 (bug1.js:4:60)
```

is translated into:

```
at my-callback@bug1_client, bug1.scm:10
```

The mapping of identifiers is straightforward. It merely uses the standard Hop functions for mangling/demangling identifiers. The Hop mangling is also used to separate stack frames corresponding to Hop function calls and to JavaScript function calls.

Actual source locations are reconstructed by the Hop client runtime system using the extra informations produced by the Hop-to-JavaScript compiler. It relies on the *source map* tables (Lenz and Fitzgerald, 2011) the compiler generates for the JavaScript steppers. These tables contain all the informations needed to map JavaScript source positions into Hop source positions. To make the source tables explicitly available from standard JavaScript code, the Hop-to-JavaScript compiler generates the extra call at the end of each generated file:

```
hop_source_mapping_url( "bug1.js", "bug1.js.map" );
```

This merely registers that a source map table is available for the file `bug1.js`. When a stack frame referring `bug1.js` has to be translated, the table is actually downloaded from the server, and a JavaScript client library translates the JavaScript location translated into a Hop location.

3.3 Enforcing types and arity

JavaScript tolerates many user errors. A function can be called with less or extra parameters than required. An unbound variable can be set or an undeclared data structure field accessed without raising errors. The arithmetic operators never raise exceptions whatever the type of the arguments they receive. Many other examples can be found on the Web. As a consequence of this tolerant semantics, Hop cannot delegate to JavaScript the dynamic checking of the programs it compiles. Rather, it must checks types, function arities, and array bounds by itself.

Former studies of the compilation of strict functional languages have shown that for Hop-like languages, despite functions being first class citizen, the compiler knows the very function that is invoked on most call sites (Shivers, 1988; Rozas, 1992). Hence, most arity checks can be resolved statically by the compiler. It is then sensible not to instrument the function bodies which would penalize all the executions of the functions but to instrument only the calls to unknown functions instead. For a call site such as:

```
(fun a0 a1)
```

when the compiler knows that `fun` is a function waiting two parameters, it generates the following JavaScript code:

```
fun( a0, a1 )
```

Otherwise, it generates:

```
hop_check_arity( fun, 2 )( a0, a1 )
```

The arity of the Hop compiled functions is stored in a field called `hop_arity`, the function `hop_check_arity` merely compares the value of this field to the actual number of arguments. For hand-written JavaScript functions the field does not exist and the test always succeeds. The library function `hop_check_arity` is implemented as follows (for simplicity only fixed arity functions are considered in the paper):

```
function hop_check_arity( fun, arity ) {
   if( "hop_arity" in fun ) {
      if( fun.hop_arity == arity ) {
         return fun;
      } else {
         throw new ArityError( fun, arity );
      }
   } else { /* a plain JavaScript function */
      return fun;
   }
}
```

Checking the types and the array bounds is a different matter as in general actual types and array bounds are unknown at compile-time. Hence, before accessing any data structure or any array, a check must be executed. To avoid code size expansion of the generated JavaScript codes, Hop instruments the getters and setters defined in its standard library instead of adding extra tests in the user code it generates.

Checking types at runtime slows down the execution for two reasons. First, it requires to fetch the dynamic types of the objects and compare them against global values. Second, it prevents the compiler from inlining operators which contain type tests as it would enlarge generated code size too much.

Fortunately, these costs can be significantly reduced using JavaScript dynamic properties which are available since ECMAScript 5. A dynamic property is syntactically used as a regular property but the actual access goes through a user defined function. Let us illustrate how Hop uses this feature with pairs objects which are used to represent list elements. In production mode, pairs are defined as:

```
function sc_Pair(car, cdr) {
   this.__hop_car = car;
   this.__hop_cdr = cdr;
}
```

In debugging mode, the implementation is changed for:

```
function sc_Pair(car, cdr) {
   this._safe__hop_car = car;
   this._safe__hop_cdr = cdr;
}
Object.defineProperty( Object.prototype, "__hop_car", {
   /* type errors for non pair objects */
   get: function() {typeError("car", "pair", this);},
   set: function(v) {typeError("set-car!", "pair", this);}
} );
Object.defineProperty( sc_Pair.prototype, "__hop_car", {
   get: function() { return this._safe__hop_car; },
   set: function(v) { this._safe__hop_car = v; }
} );
```

Using JavaScript getters lets the compiler generate the same inlined code for accessing the first and second elements of pairs. In debugging mode, these accesses now go through the JavaScript *getters* and *setters* which transparently enforce type consistency. This technique has several advantages over inserting extra type checks in the generated code. First, the code of the compiler is unchanged. Second, the generated code is no larger in debug mode than in production mode. Third, even pairs accessed from JavaScript are type checked.

We have evaluated the performance of this technique on four browsers: Firefox 23, Chromium 29, Safari 7, and IE11. Firefox and Chromium have been executed on the GNU-Linux 3.10.10 running on an Intel Xeon E5-1660, 3.3GHz. Safari has been executed on a 2.6GHz core i7 running MacOS 10.9.1, and IE on a core 2.7GHz i5 running Windows 7. We have compared the performance of unsafe access, explicitly type check, and property verified access[3].

[3]Note that it would make few sense to compare the raw performances of the browsers as the hardware running them differs.

	unsafe	check	property
Chromium	44ms	209ms	44ms
Firefox	45ms	177ms	296ms
Safari	39ms	665ms	4678ms
IE	91ms	458ms	1305ms

This experiment shows a contradictory result. On the one hand, there is a huge benefit in using dynamic properties instead of using explicit type checks on Chromium. On the other hand, there is a drawback in using them on other browsers. As the techniques for implementing properties efficiently is now well known because published (Schneider, 2012), we foresee that all browsers will implement them efficiently too in a close future. Since properties have the advantages of their own mentioned earlier we have opted for using them, although they currently penalize non V8-based browsers.

Type checking numerical operators is also required in debugging mode as JavaScript replaces silently all non numeral values with `0` or `NaN`. For that, a prelude is added to each operation which enforces the types of the arguments. For instance, the '`-`' function is defined as:

```
function sc_minux2( x, y ) {
   if( typeof x !== "number" )
      sc_typeError( "-", "number", x, 3 );
   if( typeof y !== "number" )
      sc_typeError( "-", "number", y, 3 );
   return = x - y;
}
```

This slows down dramatically the performance because it adds two extra tests and it disables inlining for avoiding code size explosion. We have tried to improved the implementation by testing only the result of the operation as:

```
function sc_minux2( x, y ) {
   var res = x - y;
   if( isNaN( res ) ) {
      if( typeof x !== "number" )
         sc_typeError( "-", "number", x, 3 );
      else
         sc_typeError( "-", "number", y, 3 );
   }
   return res;
}
```

The JavaScript function `isNaN` is a property of the global object. It is then difficult for a compiler, to implement it as efficiently as a simple operator. As suggested by the ECMA-262-5 specification (ECMA, 2009) (see Section 15.1.2.4), calling `isNaN(`*v*`)` can be replaced with the more efficient expression *v*`!==`*v*. We have compared the three methods on the `fib` benchmark which uses extensively additions, subtractions, and integer comparisons.

	type-*based*	isNaN-*based*	!==-*based*
Chromium	71ms	101ms	71ms
Firefox	19ms	101ms	54ms
Safari	48ms	100ms	55ms
IE	129ms	261ms	136ms

This experiment has contradicted our intuition as it clearly shows the benefit of using the explicit type checking approach on all browsers, even if it executes more tests at runtime.

3.4 Global Performance Evaluation

For constructing the contextual stack, an exception is raised each time a callback is registered. Whatever the speed of raising and catching JavaScript exceptions, this has a minor impact on the overall performance as callbacks are installed when pure JavaScript performance does not matter: the network times dominate the preparation of the evaluation of a `with-hop` call; the setup time of a timeout is unimportant as its purpose is to slow down the execution or to yield the processor. The parsing of the string denoting the execution stack and the mapping the JavaScript source locations to the actual Hop source locations would have a much significant impact as it allocates many temporary data structures. This takes time and this exercises the garbage collector. Hopefully it can be delayed until a stack must be actually displayed. In the fast path where no error is raised, the parsing of the stack is never executed.

Performance of arity checking and type checking is a different matter as these require extra tests that get executed frequently. We have measured their impact on a set of representative benchmarks. As we have already established that the performances of Hop client-side programs is on par with similar hand-written JavaScript programs (Loitsch and Serrano, 2007), the results presented here also give an intuition of how JavaScript would be impacted if it was supporting an equivalent debug mode.

For each benchmark, we have measured the raw speed obtain in production mode, the speed of the instrumented version where only the arity is checked, and the fully instrumented version where types are also systematically checked. The results of this experiment are presented Figure 1.

Measuring the performance of browser-hosted JavaScript execution engines is not easy. Profiling tools are unusable as they introduce a bias of their own. Measuring the CPU or system time is impossible as the JavaScript library lacks accesses to the system information. The only possibility we have consists in measuring the user observable execution times. To make performance evaluation even more complex, JavaScript usually stops programs that run more than 5 seconds. We then have to measure short lasting executions, which is subject to a lot of variations depending on the system state (cache, JIT information, etc.). In this context, we have found relevant to run a benchmark several times, collecting all the execution times. When the sum of these times reaches or exceeds 10 seconds, the benchmark is stopped and the mean time is reported. This methodology is not totally accurate but it gives a decently correct idea of the actual raw speed of a benchmark.

The first observation is that degradation varies significantly from one benchmark to another but on Chromium and Firefox, the two most popular portable browsers, we deem it acceptable. In general, Chromium is the less impacted browser. This probably is a consequence of its dynamic properties implementation observed in Section 3.3 that lets it enforce types efficiently.

The second observation is that degradations seem not to depend on the benchmark themselves. For instance, in debug mode, Fib behaves poorly on Chromium and decently on Firefox. An opposite situation is observed for Earley. Probably, for a reason or another, enforcing types on these benchmarks defeats the JIT compilers differently. As we consider a worse ratio of 4 or 5 for debugging acceptable, we have not investigated any further in order to minimize the impact of type checking on performance.

The third observation is that arity checking is unnoticeable but on the two benchmarks Beval and Conform. These two benchmarks use higher order functions extensively. This programming style imposes arity verification at runtime. The overhead is then expected.

4 RELATED WORK

Multitier programming for the Web has been pioneered by GWT from Google, Links from the University of Edinburgh (Cooper et al., 2006), and Hop. The three languages have appeared almost simultaneously in 2006. Other languages have then followed such as Ocsigen (Vouillon and Balat, 2013), iTask3, or Opa (Binsztok et al., 2013). Among the Hop competitors, only GWT considers the problem of debugging Web applications. GWT supports debugging of multitier applications but cannot debug JavaScript components. GWT has nothing similar to the Hop multitier stack.

Nodejs is a platform built on top of V8, the JavaScript runtime used by Chrome. Nodejs is used for building fast, scalable network applications, such as Web servers. Nodejs is an effective way of supporting JavaScript on both ends of the application. How-

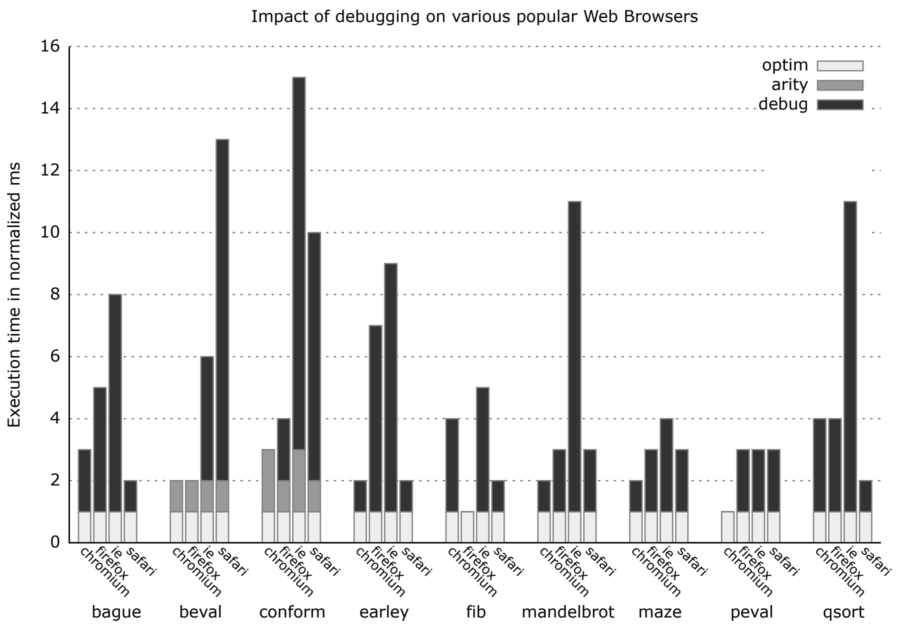

Figure 1: This experiment reports about the impact of debugging on client-side speed. For each benchmark and for each browser, the optimized speed is used as a base value for that benchmark. The experiment presents the slowdowns imposed by the debugging mode. For instance, on the Bague benchmark, arity checking incurs no performance penalty to Chromium and Firefox but type checking slows down Chromium by a factor of 3 and Firefox by a factor of 5.

ever a Nodejs Web application is still conceived as two separated software components and debugging is also separated.

The following example mimics the server error example of Section 2.2.

```
var http = require("http");
var url = require("url");

http.createServer(function(request, response) {
  var url_parts = url.parse(request.url, true);
  var query = url_parts.query;

  response.writeHead(200, {"Content-Type": "text/html"});
  response.write("<html>"+query["x"]["car"]+"</html>");
  response.end();
}).listen(8888);
```

When executed, it produces the following trace.

```
node1.js:10
              + query["x"]["car"]
                          ^
TypeError: Cannot read property 'car' of undefined
 at Server.<anonymous> (node1.js:10:40)
 at Server.EventEmitter.emit (events.js:98:17)
 at HTTPParser.parser.onIncoming (http.js:2056:12)
 at HTTPParser.parserOnHeadersComplete (http.js:120:23)
 at Socket.socket.ondata (http.js:1946:22)
 at TCP.onread (net.js:525:27)
```

The error is correctly located in the server source file but the stack trace is oblivious of the client-side execution that has preceded the server computation. It merely reports that the error as occurred in the context of answering an HTTP request but without much details. Running Nodejs in debug mode could give access to extra informations about the nature of the HTTP request but it will still lack informations about the client state. The techniques proposed in this paper could improve this situation.

Popular modern JavaScript frameworks raise the abstraction level of client-side programs by offering facilities for generating client-side programs at runtime and for communicating with the server more easily. This makes developing applications easier but as of the current versions, it also makes debugging more difficult because the code automatically generated by the runtime system shows up when an error is raised. Let us illustrates this with the Google's Angularjs framework (Google, 2013). Let us consider the tutorial available on the framework Web page which illustrates Ajax programming with the following example:

```
var catApp = angular.module('catApp', []);
catApp.controller('PhoneListCtrl', ['$scope', '$http',
   function ($scope, $http) {
      $http.get('phones.json').success( function(data) {
      $scope.phones = data; });
  $scope.orderProp = 'age'; }]);
```

Introducing a syntax error in `phones.json` produces:

```
SyntaxError: Unexpected token }
    at Object.parse (native)
    at fromJson (angular.js:1035:14)
    at $HttpProvider.defaults.defaults.transformResponse
       (angular.js:6926:18)
    at angular.js:6901:12
    at Array.forEach (native)
    at forEach (angular.js:302:11)
    at transformData (angular.js:6900:3)
    at transformResponse (angular.js:7570:17)
    at wrappedCallback (angular.js:10905:81)
    at angular.js:10991:26
```

As it can be seen, the whole execution trace is only populated with Angularjs entries which none is explicitly mentioned in the user program. Even more important, the stack trace it totally silent about the `controller`'s code and the HTTP request. The techniques presented in this paper could help presenting less obscure stack traces to the programmer.

The tolerant semantics of JavaScript makes it inconvenient to be used as the target of the compiler of another programming language. The checks executed at runtime by JavaScript are likely to be either insufficient if the source language is safe, or superfluous if the source language is unsafe. In Hop debugging mode, each access is double-checked. Once by Hop and once by JavaScript which ensures that the execution does not corrupt the memory. Of course, this double checking slows down executions. In this respect, the `asm.js` endeavor (Herman et al., 2013) is promising. It could become an interesting target for the Hop client-side compiler.

There is a whole line of research which consists in typing JavaScript. Some focus on inferring static types of JavaScript programs (Jensen et al., 2009), some such as TypeScript (Microsoft, 2013) extend the language to support type annotations. The shared objective is to enable JavaScript errors detection at compile-time. This is orthogonal to our effort as our purpose is to detect unexpected behaviors at runtime.

5 CONCLUSION & PERSPECTIVES

The lack of complete debugging information is acknowledged as a major difficulty when developing Web applications (Schrock, 2009). Using the Hop multitier setting we have solved this problem by creating a debugger which reports full stack traces. When an error is raised, the programmer is presented with the complete execution trace composed of server-side and client-side frames that have conducted to the error. The Hop runtime environment supports a debugging mode where types, arity, and bounds are strictly enforced. Combining the debugger and the debug mode makes error easier to localize and to understand.

The presented debugger exposes a unified execution stack that reflects both ends of the application but it uses two separate steppers that cannot collaborate. In a further step, we will create a global stepper that will be able to traverse the network. Stepping forward seems easy to obtain because it will just require the implementation of a collaboration layer between two existing tools. Inspecting the execution stack backward is more hypothetical since it requires to save execution traces potentially infinitely.

The presented techniques rely on the multitier paradigm to expose a global and coherent view of the execution between the server and the client. They also rely on code generation to instrument the code actually executed on the browser. In Hop this is implemented in a single runtime environment whose main element is a custom bootstrapped web server embedding compilers for generating HTML and JavaScript on-the-fly. In addition to supporting better debugging, this approach also enables fast dynamic HTTP responses servers (Serrano, 2009). This approach also has drawbacks: as it is does not rely on mainstream tools and techniques, it attracts few developers. In consequence, Hop offers less libraries and support than popular languages. Our response to this problem consists in supporting a deep compatibility between Hop and the standard Web technologies in order to make HTML, CSS, third party JavaScript programs, and Web services as easy to use in Hop as they are in JavaScript, PHP, or any other standard tool (Serrano and Berry, 2012). It remains that Hop relying on the Scheme programming language, an academic programming language, is unlikely to get massive adoption. As this is our objective, we now consider a radical evolution. We are then considering transposing the Hop principles to JavaScript. The recent evolutions of JavaScript such as the EcmaScript 6 quasiliteral extensions (ECMA, 2013) that offers a standard mean for expressing client- and server-side code within a single JavaScript source file and the fast V8-based server-side environments are paving the road to new Web development environments for which the contributions presented in this paper might be useful.

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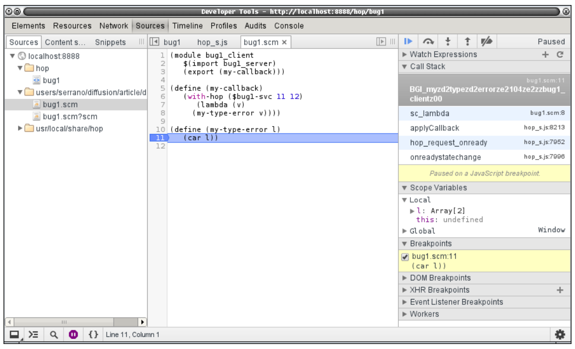
6 APPENDIX



```
(module bug1_client
   $(import bug1_server)
   (export (my-callback)))

(define (my-callback)
   (with-hop ($bug1-svc 11 12)
      (lambda (v)
     (my-type-error v))))

(define (my-type-error l)
   (car l))
```

```
bug1.scm:11
BGl_myzd2typezd2errorze2104ze2zzbug1_clientz00
sc_lambda                       bug1.scm:8
applyCallback                   hop_s.js:8213
hop_request_onready             hop_s.js:7952
onreadystatechange              hop_s.js:7996
Paused on a JavaScript breakpoint.

Local
  l: Array[2]
  this: undefined
Global                          Window

bug1.scm:11
(car l))
```

Figure 2: The Chrome stepper stopped at a breakpoint before a type error is raised. The breakpoints are correctly sets using the actual Hop source file. Unfortunately, as of 2013 summer, the stepper is not able to use the identifier provided in the source map table nor it supports a user settings for pretty printing the execution trace.