



ASSIGNMENT OF MASTER'S THESIS

Title: Improvements of the RIR bytecode toolchain
Student: Bc. Jan Je men
Supervisor: Ing. Petr Máj
Study Programme: Informatics
Study Branch: System Programming
Department: Department of Theoretical Computer Science
Validity: Until the end of winter semester 2018/19

Instructions

Familiarize yourself with the R language, its bytecode compiler, and interpreter architecture. Familiarize yourself with RIR, an alternative bytecode format, compiler, and interpreter for the language. The R bytecode compiler assumes certain invariants (such as built-in meaning of control flow statements and certain operators) about the code to make the compiled code faster. Analyze similar assumptions that are used by RIR and extend RIR to use assumptions made by GNU-R as well. Identify and implement improvements to the RIR (compiler, bytecode format, and interpreter). Discuss your results.

References

Will be provided by the supervisor.

doc. Ing. Jan Janoušek, Ph.D.
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Prague March 1, 2017

CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF INFORMATION TECHNOLOGY

DEPARTMENT OF THEORETICAL COMPUTER
SCIENCE



Master's thesis

Improvements of the RIR bytecode toolchain

Bc. Jan Ječmen

Supervisor: Ing. Petr Máj

April 27, 2017

Acknowledgements

[[acknowledgements]] Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

Declaration

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In Prague on April 27, 2017

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Czech Technical University in Prague

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Citation of this thesis

JEČMEN, Jan. *Improvements of the RIR bytecode toolchain*. Master's thesis. Czech Technical University in Prague, Faculty of Information Technology, 2017. Available also from WWW: [⟨https://github.com/JanJecmen/dip⟩](https://github.com/JanJecmen/dip).

Abstract

[[abstract english]] This is the second paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

Keywords **[[keywords en]]**

Abstrakt

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Klíčová slova **[[keywords cz]]**

Contents

| | |
|---|-----------|
| Introduction | 1 |
| 1 About GNU R | 3 |
| 1.1 Language features of R | 3 |
| 1.2 Why is R hard to optimize | 5 |
| 1.3 Why is R slow | 5 |
| 2 About RIR | 9 |
| 2.1 Why is RIR slow | 10 |
| 3 Improvements | 11 |
| 4 Evaluation | 17 |
| Conclusion | 21 |
| A Acronyms | 23 |
| B Contents of the enclosed CD | 25 |

List of Figures

| | | |
|-----|------------------------|----|
| 4.1 | [[write title]] | 18 |
| 4.2 | [[write title]] | 19 |

List of Listings

| | | |
|-----|---|----|
| 1.1 | Arithmetic operators are function calls in R | 5 |
| 1.2 | AST of a simple expression | 7 |
| 3.1 | [[write listing caption]] microbenchmark (run with jit enable 2) . . | 11 |

List of Tables

| | | |
|-----|---|---|
| 1.1 | Some common types of internal R objects | 6 |
|-----|---|---|

Introduction

[[write intro]]

[[cite: <https://www.tiobe.com/tiobe-index/> <http://pypl.github.io/PYPL.html>]]

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INTRODUCTION

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[[write about structure]] And after the second paragraph follows the third paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

About GNU R

GNU R¹ is a programming language used mainly for statistical computations. It is an open-source dialect of S, an older statistical language created in 1976 by John Chambers at Bell Laboratories. R has been around from 1993 and was designed by Ross Ihaka and Robert Gentleman, both recognised statisticians. It is a part of the GNU software family and is still actively developed by the R Core Team today. It is a popular alternative to the other major implementation of the S language, S-PLUS, which is a commercial version shipped by TIBCO Software Inc. **[[cite]]**

R comes with a software environment built around it, which allows for easily manipulating data, carrying out computations and producing quality graphical outputs such as plots and figures. Although at heart R is used via a command line interface, there are also more user-friendly graphical IDEs available like RStudio. This, together with R's readable syntax and a vast collection of extension packages available through CRAN makes it simple for new users to step in and start working quickly.

1.1 Language features of R

[[cite: <http://r.cs.purdue.edu/pub/ecoop12.pdf>]]

[[cite: <http://adv-r.had.co.nz/>]]

¹Homepage: <https://www.r-project.org/>

R is, as far as programming languages go, very interesting and has some quite unusual semantic features. It is an interpreted language, and is dynamically typed and garbage collected. It supports multiple programming paradigms: users can use procedural imperative style, but at the same time R provides an object system (more than one, in fact!) for object oriented programming, and is heavily influenced by functional programming languages, notably Scheme.

Functions are, in accordance with functional languages, first-class values, so they can be passed around as call arguments, returned as results and created dynamically at runtime. R uses lexical scoping (which it adopted from Scheme) and R functions are closures that capture their enclosing environment at creation time. Arguments are passed by value (although reference counting is implemented, so that deep copies are only created as needed e.g., when an object is modified). All actual arguments to a function are lazy evaluated by default. When applying a closure, parameters are wrapped in promises and these are only evaluated when the value is needed.

These features highlight the functional approach by minimizing side effects. However, R supports assignment which enables programmers to change function's local state by modifying its bindings and thus the imperative programming style. Also, the superassignment operator makes it possible to change non-local bindings and thus brings the side effects back into play.

The basic data type in R is a vector. Vectors are ordered collections of homogeneous values (i.e., a given vector can only hold objects of one particular type). R also provides a list type which is heterogeneous. Higher-dimensional types such as matrices and data frames, as well as objects, are built from vectors. In R there are no scalar types, as scalar values, such as individual numbers and strings, are considered to be vectors of length one.

Atomic vectors can have one of these six types: logical, integer, double, character, complex and raw. Since R targets data analysis, a special “not available” value is provided for these. R encourages vectorized operations and most of R builtin functionality works element-wise with vectors, while recycling the elements as needed (e.g., when adding vectors of different lengths).

[[more listings: assign, vector recycling, promise with side effect...]]

Interestingly, everything that happens in R is in fact a function call. This goes as far as arithmetic operators being just syntactic sugar for function calls, as can be seen in listing 1.1. In this spirit, even assigning into a variable, evaluating a block of code inside curly brackets or grouping expressions with parentheses translate to calling the respective functions.

```
> typeof(`+`)
[1] "builtin"
> `+`
function (e1, e2) .Primitive("+")
> `+`(1, 2)
[1] 3
> 1 + 2
[1] 3
```

Listing 1.1: Arithmetic operators are function calls in R

1.2 Why is R hard to optimize

R is a very dynamic language and gives the programmer a very high degree of freedom.

[[cite: <https://cran.r-project.org/doc/manuals/R-lang.html> section 6 and 2]]

[[dynamic, user can do anything introspection vectorized subsetting, sub-assignment delayed evaluation two different object systems r inferno some examples builtin, special, closures]]

1.3 Why is R slow

[[first: dynamic nature, second: design desicions]] [[vanilla r uses standard repl and ast interpreter single threaded runtime type checking, coercion memory hungry, garbage collection, everything on stack, a lot of metadata and attributes everything is function call written in c, no jit by default, no native jit compiler]]

1.3.1 AST interpreter

In its core R uses a classic architecture for an interpreted language. After initialization, the user enters R's read-eval-print loop (REPL), that lets them type in expressions and have R evaluate them. First, a reader, or parser, waits for the user input and reads it line by line. If, at the end of line, it has read a syntactically complete expression, it passes it to an evaluator (otherwise it waits for more input). After the evaluator returns the evaluated expression, a printer is invoked that displays the result (with some exceptions, such as assignment that sets its result to be invisible). Then the reader is again invoked and the process repeats.

Every object in R is internally represented by a C structure called SEXPREC² (actually, R passes the objects around as pointers to this structure, which are called SEXP). This structure contains a header with metadata about the object, such as its type, reference counter or information for garbage collector, and then a union of other structures that represent different types of R internal objects. Some of these types are listed in table 1.1.

Table 1.1: Some common types of internal R objects

| Type | Usage |
|------------|--|
| NILSXP | the singleton NULL object |
| SYMSXP | symbols (or names) |
| LISTSXP | lists of dotted pairs |
| CLOSXP | closures |
| ENVSXP | environments |
| PROMSXP | promises |
| LANGSXP | language constructs (typically closure application) |
| SPECIALSXP | special forms (typically control flow) |
| BUILTINSXP | builtin non-special forms (e.g., arithmetic operators) |
| INTSXP | integer vectors |
| REALSXP | real vectors |
| STRSXP | string vectors |

²The name refers to S-expressions, or symbolic expressions, as known from Lisp, although the classical linked lists built from dotted pairs are mostly used internally, and vectors are implemented as C arrays for efficiency reasons.

| Type | Usage |
|----------|------------------------------|
| BCODESXP | object compiled to byte code |

The parser, when it scans the stream of input characters, checks that it is syntactically correct and at the same time builds a tree structure that represents the parsed expression. This tree is called the abstract syntax tree (AST) and its nodes are all SEXPs. An example AST is shown in the listing 1.2³. In the listing, parentheses mean function call (i.e., LANGSXP node), the first child being the callee (typically a SYMSXP, i.e., a name that is bound to a function) and the rest its arguments.

```
> pryr::ast(x <- (y + 3) * f(z))
\ - ( )
  \ - `<-
    \ - `x
      \ - ( )
        \ - `*
          \ - ( )
            \ - `(
              \ - ( )
                \ - `+
                  \ - `y
                    \ - 3
              \ - ( )
                \ - `f
                  \ - `z
```

Listing 1.2: AST of a simple expression

The evaluator is a recursive function that gets as its input two SEXP objects, one representing the AST of the expression that is to be evaluated, and the other the environment in which to evaluate the expression. The evaluator walks the given AST and based on the type of nodes it encounters, performs some action. The result is then returned to be processed by the caller of eval.

Some nodes are self-evaluating, meaning that no action needs to be performed and the node itself is the result. These are for example the NULL object, the atomic vectors or the environments.

³[[about pryr]]

If the eval function sees a symbol node, a lookup for its binding is performed in the provided environment. If it is not found there, because of lexical scoping, the parent environment is searched, and so on, until either the binding is found or an empty environment is reached (the empty environment serves as a sentinel parent of all environment chains and does not have a parent itself).

One other prominent type of nodes is LANGSXP. R has internally three types of functions, called special, builtin and closures (or user-defined functions). These have different behavior when they are applied, and the eval function handles that.

Special functions are the core language constructs, such as control flow (conditionals and loops). They take their arguments unevaluated in a list and evaluate them as needed while running. This is necessary for example for the `if[[verb]]` statement, because, since R has side effects, only one of the conditional branches must be evaluated to preserve the correct semantics.

Builtins on the other hand are known to evaluate all their arguments, so it is not necessary to create promises from their arguments. Instead, a list of evaluated arguments is created and passed to the builtin function. Examples of builtin functions are arithmetic operators or the colon operator for generating integer sequences.

Finally, the dispatch to the bytecode interpreter for objects compiled to bytecode is also found in the eval function.

1.3.2 BC interpreter

`[[from when only now as default out of the box behaviour for base compiler written in R 120sth bc instructions interoperates with the normal eval, but for bytecode evaluation uses loop with switch (or threading) bytecode encoded in vector of ints, plus per object constant pool]] [[disassembled bytecode listing]]`

About RIR

[[Introduce RIR]] RIR⁴ is an alternative compiler for the R language. It comes with its own internal representation, an interpreter for its bytecode and an abstract interpretation framework which provides a way to easily implement static analyses on top of the RIR bytecode.

[[history: research project, northeastern? grants? first appearance?]]

RIR acts as a drop-in replacement for the GNU R bytecode compiler. It requires a patched version of GNU R that makes some slight adjustments that allow the standard GNU R expression evaluator function to interface with the RIR bytecode compiler and interpreter. RIR is written in C and C++ and is compiled as a shared library that can be dynamically loaded by R.

[[write about rir bytecode]]

[[how is rir bc different]]

[[optimizations, ai framework...]]

[[architecture]]

⁴Homepage: <https://github.com/reactorlabs/rir>

2.1 Why is RIR slow

[[TODO]]After this fourth paragraph, we start a new paragraph sequence. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

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[[subsection about gnur compiler assumptions]]

Improvements

[[to compiler, to ir, to interpreter, use code snippets, describe microbenchmarks, theory (threaded code...)]] [[everywhere: motivation - how it helped in microbenchmarks, then how in real]] This is the second paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

```
f <- function() {  
  i <- 10000000L  
  while (i > 0) {  
    i <- i - 1  
  }  
}  
system.time(f())[[3]] # jit everything  
t <- c()  
for (x in 1:15) t <- c(t, system.time(f())[[3]])  
mean(t[5:15]) # only include measurments after warmup
```

Listing 3.1: **[[write listing caption]]** microbenchmark (run with jit enable 2)

[[relational operators, fast paths for logical args, unary plus minus not, loop contexts, bc cleanup, colon, superassing, inlining of instructions

3. IMPROVEMENTS

in main loop, threaded code, inline stack funcs, loops refactor, disable guardfuncs]]

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3. IMPROVEMENTS

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3. IMPROVEMENTS

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Evaluation

[[discussion of results, add figures]] [[discuss interesting point in measurements - naive nbody and threading etc.]] This is the second paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

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Figure 4.1: [[write title]]

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This is the second paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font,



Figure 4.2: `[[write title]]`

how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

And after the second paragraph follows the third paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

After this fourth paragraph, we start a new paragraph sequence. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and

4. EVALUATION

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Conclusion

[[conclusion, future work, related work, fails - stoke etc.]] This is the second paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

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CONCLUSION

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Acronyms

| | |
|-------------|-------------------------------------|
| API | Application programming interface |
| AST | Abstract syntax tree |
| CLI | Command Line Interface |
| CRAN | The Comprehensive R Archive Network |
| GNU | GNU's Not Unix! |
| REPL | Read-eval-print loop |

Contents of the enclosed CD

[[contents of cd]] Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.