One VM to Rule Them All

Christian Wimmer, Chris Seaton

VM Research Group, Oracle Labs
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One Language to Rule Them All?
Let's ask Google…

JavaScript: One language to rule them all | VentureBeat
venturebeat.com/2011/.../javascript-one-language-to-rule-them---
by Peter Yared - in 23 Google+ circles
Jul 29, 2011 - Why code in two different scripting languages, one on the client and one on the server? It's time for one language to rule them all. Peter Yared …

[PDF] Python: One Script (Language) to rule them all - Ian Darwin
www.darwinsys.com/python/python4unix.pdf
Another Language? • Python was invented in 1991 by Guido van. Rossum. • Named after the comedy troupe, not the snake. • Simple. • They all say that!

Q & Stuff: One Language to Rule Them All - Java
qstuff.blogspot.com/2005/10/one-language-to-rule-them-all-java.html
Oct 10, 2005 - One Language to Rule Them All - Java. For a long time I'd been hoping to add a scripting language to LibQ, to use in any of my (or other ...

Dart: one language to rule them all - MixIT 2013 - Slideshare
fr.slideshare.net/sdeleuze/dart-mixit2013en
DartSébastien Deleuze - @sdeleuzeMix-IT 2013One language to rule them all …
One Language to Rule Them All?
Let’s ask Stack Overflow…

Stack Overflow is a question and answer site for professional and enthusiast programmers. It's 100% free, no registration required.

Why can't there be an “ultimate” programming language?

closed as not constructive by Tim, Bo Persson, Devon_C_Miller, Mark, Graviton Jan 17 at 5:58
“Write Your Own Language”

**Current situation**

- Prototype a new language
  - Parser and language work to build syntax tree (AST), AST Interpreter
- Write a “real” VM
  - In C/C++, still using AST interpreter, spend a lot of time implementing runtime system, GC, …
- People start using it
- People complain about performance
  - Define a bytecode format and write bytecode interpreter
- Performance is still bad
  - Write a JIT compiler
  - Improve the garbage collector

**How it should be**

- Prototype a new language in Java
  - Parser and language work to build syntax tree (AST)
  - Execute using AST interpreter
- People start using it
  - And it is already fast
Truffle Requirements

Simplicity

+ Generality

+ Performance

Ruby, JavaScript, Python, R, J, Java, Groovy, Clojure, Scala ...

function f(a, n) {
  var x = 0;
  while (n-- > 0) {
    x = x + a[n];
  }
  return x;
}

L1: decl rax
   jz L2
   movl rcx, rdx[16+4*rax]
   cvtsi2sd xmm1, rcx
   addsd xmm0, xmm1
   jmp L1
L2:

@Specialization(
    rewriteOn=ArithmeticException.class)
int add(int l, int r) {
    return Math.addExact(l, r);
}

@Specialization
double add(double l, double r) {
    return l + r;
}

@Specialization(guards = "isString")
String doString(Object l, Object r) {
    return l.toString() + r.toString();
}
System Structure

- Language agnostic dynamic compiler
- Common API between language implementation and optimization system
- Integrate with Java applications
- Low-footprint VM, also suitable for embedding

Diagram:

- Truffle
- Graal VM
- Substrate VM
- Ruby
- JavaScript
- Python
- R
- ... (other languages)
- Your language here!

- Integrated with Java applications
Truffle Approach

AST Rewriting for Type Feedback

AST Interpreter
Uninitialized Nodes

AST Interpreter
Rewritten Nodes

Compiled Code

Automatic Partial Evaluation

- Eliminate boxing of primitive values
- Eliminate dynamic type checks
- AST Inlining

- Syntax tree nodes are “stable”
- Aggressive constant folding, method inlining, escape analysis
- Deoptimize compiled code on tree rewrite
One VM to Rule Them All

Thomas Würthinger*  Christian Wimmer*  Andreas Wöß†  Lukas Stadler†
Gilles Duboscq†  Christian Humer†  Gregor Richards§  Doug Simon*  Mario Wolczko*

*Oracle Labs  †Institute for System Software, Johannes Kepler University Linz, Austria  §S3 Lab, Purdue University
{thomas.wuerthinger, christian.wimmer, doug.simon, mario.wolczko}@oracle.com
{woess, stadler, duboscq, christian.humer}@ssw.jku.at  gr@purdue.edu

Abstract

Building high-performance virtual machines is a complex and expensive undertaking: many popular languages still have low-performance implementations. We describe a new approach to virtual machine (VM) construction that amortizes much of the effort in initial construction by allowing new languages to be implemented with modest additional effort. The approach relies on abstract syntax tree (AST) interpretation where a node can rewrite itself to a more specialized or more general node, together with an optimizing compiler that exploits the structure of the interpreter. The compiler uses speculative assumptions and deoptimization in order to produce efficient machine code. Our initial experience suggests that high performance is attainable while preserving a modular and layered architecture, and that new high-performance language implementations can be obtained by writing little more than a stylized interpreter.

as Microsoft’s Common Language Runtime, the VM of the .NET framework [43]. These implementations can be characterized in the following way:

- Their performance on typical applications is within a small integer multiple (1-3x) of the best statically compiled code for most equivalent programs written in an unsafe language such as C.
- They are usually written in an unsafe, systems programming language (C or C++).
- Their implementation is highly complex.
- They implement a single language, or provide a bytecode interface that preferentially advantages a narrow set of languages to the detriment of other languages.

In contrast, there are numerous languages that are popular, have been around for about 20 years, and yet still have
Ruby Prototype: High Performance

- Fastest Ruby implementation ...
- ... for the few benchmarks that we looked at

Diagram:
- Ruby
  - Graal
    - Graal VM
  - Truffle
    - Substrate VM
Ruby Prototype: Low Footprint

Startup time ("Hello World") comparable to MRI

Graal → Truffle → Ruby

Graal VM → Substrate VM
Ruby Prototype: Completeness

- RubySpec
  - A library of executable assertions that covers the language, core library and standard library
  - This is the defacto Ruby spec
  - Gives us a quantifiable result for how much of Ruby we implement correctly

Over 45% of RubySpec
Completeness
## Completeness: Informally

<table>
<thead>
<tr>
<th>Language Feature</th>
<th>Implemented</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixnum to Bignum promotion</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Support for floating point</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Closures</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Bindings and eval</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>callcc and Continuation</td>
<td>✓</td>
<td>Very limited support, the same as JRuby</td>
</tr>
<tr>
<td>Fibers</td>
<td>✓</td>
<td>Slightly limited support, the same as JRuby</td>
</tr>
<tr>
<td>Frame local variables</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>C extensions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ruby 1.9 encoding</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Garbage collection</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Concurrency and parallelism</td>
<td>✓</td>
<td>We currently use a GIL</td>
</tr>
<tr>
<td>Tracing and debugging</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>ObjectSpace</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Method invalidation</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Constant invalidation</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Ruby on Rails</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Completeness: More formally via RubySpec

Running language tests

- Topaz
- RubyTruffle
- JRuby
Low Footprint
Substrate VM Execution Model

Static Analysis

Java Application
JDK
Substrate VM

Ahead-of-Time Compilation

Initial Heap
Machine Code
OS

All Java classes from application, JDK, and Substrate VM

Reachable methods, fields, and classes

Application running without compilation or class loading
Startup Performance
Running "Hello World"

Execution time: `time -f "%e"`
Memory footprint: `time -f "%M"`

![Execution Time Graph](chart1)
![Memory Footprint Graph](chart2)
High Performance
Why is Ruby Slow?

\[-b + \frac{(\text{Math.sqrt}(b^{**2} - 4*a*c))}{2*a}\]
Why is Ruby Slow?

\[-b + (\text{Math.sqrt}(b^{**2} - 4a^c)) / 2a\]

execute b
check that b is a Float
check that the negate method in Float has not changed
calculate negation
check the result of that is a Float
execute b
check that b is a Float
check that the power method in Float has not changed
calculate power
check the result of that is a Float
execute a
check that a is a Float
check that the multiply method in Float has not changed
calculate multiplication
check the result of that is a Float
execute c
check that c is a Float
check that the multiply method in Float has not changed
calculate multiplication
check the result of that is a Float
check that Math has not changed
check that the sqrt method in Math has not changed
calculate sqrt
check the result of that is a Float
execute a
check that a is a Float
check that the multiply method in Float has not changed
calculate multiplication
check the result of that is a Float
check that the division method in Float has not changed
calculate division
Improving Performance Using Truffle

-b + (Math.sqrt(b ** 2 - 4 * a * c)) / 2 * a

execute b
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check that b is a Float
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calculate power
check the result of that is a Float
execute a
check that a is a Float
check that the multiply method in Float has not changed
calculate multiplication
check the result of that is a Float
execute c
check that c is a Float
check that the multiply method in Float has not changed
calculate multiplication
check the result of that is a Float
check that Math has not changed
check that the sqrt method in Math has not changed
calculate sqrt
check the result of that is a Float
execute a
check that a is a Float
check that the multiply method in Float has not changed
calculate multiplication
check the result of that is a Float
check that the division method in Float has not changed
calculate division
### Improving Performance Using Truffle

\[ -b + (\text{Math.sqrt}(b^{**2} - 4*a*c)) / 2*a \]

execute \(b\)
check that \(b\) is a Float
check that the negate method in Float has not changed
calculate negation
check the result of that is a Float
execute \(b\)
check that \(b\) is a Float
check that the power method in Float has not changed
calculate power
check the result of that is a Float
execute \(a\)
check that \(a\) is a Float
check that the multiply method in Float has not changed
calculate multiplication
check the result of that is a Float
execute \(c\)
check that \(c\) is a Float
check that the multiply method in Float has not changed
calculate multiplication
check the result of that is a Float
check that Math has not changed
check that the \text{sqrt} method in Math has not changed
calculate \text{sqrt}
check the result of that is a Float
execute \(a\)
check that \(a\) is a Float
check that the multiply method in Float has not changed
calculate multiplication
check the result of that is a Float
check that the division method in Float has not changed
calculate division
Improving Performance Using Truffle

\[-b + \frac{(\text{Math.sqrt}(b^{**2} - 4*a*c))}{2*a}\]

```
execute b
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check the result of that is a Float
execute a
check that a is a Float
check that the multiply method in Float has not changed
calculate multiplication
check the result of that is a Float
execute c
check that c is a Float
check that the multiply method in Float has not changed
calculate multiplication
check the result of that is a Float
check that Math has not changed
check that the sqrt method in Math has not changed
calculate sqrt
check the result of that is a Float
execute a
check that a is a Float
check that the multiply method in Float has not changed
calculate multiplication
check the result of that is a Float
check that the division method in Float has not changed
calculate division
```
Improving Performance Using Truffle

\[-b + (\text{Math.sqrt}(b^{**2} - 4*a*c)) / 2*a\]

execute b
calculate negation
calculate power
calculate multiplication
calculate sqrt

calculate multiplication

calculate multiplication

calculate division

check that b is a Float
check that the negate method in Float has not changed
check the result of that is a Float
execute b
check that b is a Float
check that the power method in Float has not changed
check the result of that is a Float
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check that a is a Float
check that the multiply method in Float has not changed
check the result of that is a Float
execute c
check that c is a Float
check that the multiply method in Float has not changed
check the result of that is a Float
check that Math has not changed
check that the sqrt method in Math has not changed
check sqrt
check the result of that is a Float
execute a
check that a is a Float
check that the multiply method in Float has not changed
check the result of that is a Float
check that the division method in Float has not changed
check division
Improving Performance Using Truffle

\[-b + \left(\text{Math.sqrt}(b^{\ast\ast}2 - 4\ast a\ast c)\right) / 2\ast a\]

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check that a is a Float
check that the multiply method in Float has not changed
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check that the division method in Float has not changed
calculate division
-b + (Math.sqrt(b**2 - 4*a*c)) / 2*a

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Improving Performance Using Truffle

-b + (Math.sqrt(b**2 - 4*a*c)) / 2*a

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check that a is a Float
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calculate sqrt
check that the sqrt method in Math has not changed
calculate division
check the result of that is a Float
execute a
check that a is a Float
check that the multiply method in Float has not changed
calculate multiplication
check that the division method in Float has not changed
calculate division
check the result of that is a Float
execute b
check that the negate method in Float has not changed
calculate negation
calculate power
calculate multiplication
execute b
check that b is a Float
check that the power method in Float has not changed
calculate power
calculate multiplication
execute a
check that a is a Float
check that the multiply method in Float has not changed
calculate multiplication
calculate sqrt
check that the sqrt method in Math has not changed
calculate division
check the result of that is a Float
Improving Performance Using Graal

\[-b + (\text{Math.sqrt}(b^{**2} - 4*a*c)) / 2*a\]

execute b
check that the negate method in Float has not changed
calculate negation
execute b
check that the power method in Float has not changed
calculate power
execute a
check that the multiply method in Float has not changed
calculate multiplication
execute c
check that the multiply method in Float has not changed
calculate multiplication
check that Math has not changed
check that Math has not changed
check that the sqrt method in Math has not changed
calculate sqrt
execute a
check that the multiply method in Float has not changed
calculate multiplication
check that the division method in Float has not changed
calculate division
Improving Performance Using Graal

\[-b + (\text{Math.sqrt}(b^{**2} - 4*a*c)) / 2*a\]

execute b
check that the negate method in Float has not changed
calculate negation
execute b
check that the power method in Float has not changed
calculate power
execute a
calculate multiplication
execute c
calculate multiplication
check that Math has not changed
calculate sqrt
execute a
calculate multiplication
check that the division method in Float has not changed
calculate division

class Float
modified?

module Math
modified?
Improving Performance Using Graal

\[-b + (\text{Math.sqrt}(b^{2} - 4a*c)) / 2*a\]

execute b
check that the negate method in Float has not changed
calculate negation
execute b
check that the power method in Float has not changed
calculate power
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check that the multiply method in Float has not changed
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execute c
check that the multiply method in Float has not changed
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check that the sqrt method in Math has not changed
calculate sqrt
execute a
check that the multiply method in Float has not changed
calculate multiplication
check that the division method in Float has not changed
calculate division
Improving Performance Using Graal

\[-b + (\text{Math.sqrt}(b^{**2} - 4*a*c)) / 2*a\]

java object InstalledCode

execute b
check that the negate method in Float has not changed
calculate negation
execute b
check that the power method in Float has not changed
calculate power
execute a
check that the multiply method in Float has not changed
calculate multiplication
execute c
check that the multiply method in Float has not changed
calculate multiplication
check that Math has not changed
calculate sqrt
execute a
check that the multiply method in Float has not changed
calculate multiplication
check that the division method in Float has not changed
calculate division

.class Float
modified?

.module Math
modified?

 InstalledCode.invalidate()
Improving Performance Using Graal

-b + (Math.sqrt(b**2 - 4*a*c)) / 2*a

java object InstalledCode
execute b
check that the negate method in Float has not changed
calculate negation
execute b
check that the power method in Float has not changed
calculate power
execute a
check that the multiply method in Float has not changed
calculate multiplication
execute c
check that the multiply method in Float has not changed
calculate multiplication
check that Math has not changed
calculate sqrt
eexecute a
check that the multiply method in Float has not changed
calculate multiplication
calculate division

.class Float
_modified?

.module Math
_modified?

invalidate()
Improving Performance Using Graal

unmodified = new Assumption();
unmodified.check();
unmodified.invalidate();
Improving Performance Using Graal

\[-b + (\text{Math.sqrt}(b^{**2} - 4*a*c)) / 2*a\]

execute b
check that the negate method in Float has not changed
calculate negation
execute b
check that the power method in Float has not changed
calculate power
execute a
check that the multiply method in Float has not changed
calculate multiplication
execute c
check that the multiply method in Float has not changed
calculate multiplication
check that Math has not changed
calculate sqrt
execute sqrt
check that the multiply method in Float has not changed
calculate multiplication
check that the division method in Float has not changed
calculate division
Improving Performance

\[-b + (\text{Math.sqrt}(b^{**2} - 4*a*c)) / 2*a\]

execute b
calculate negation
execute b
calculate power
execute a
calculate multiplication
execute c
calculate multiplication
calculate sqrt
execute a
calculate multiplication
calculate division
Peak Performance

Speedup Relative to 1.8.7-p374

- Fannkuch
- N-Body

Speedup

1.8.7-p374  1.9.3-p448  2.0.0-p247  topaz-daily  jruby-1.7.4-server-invokedynamic  truffle-server-nogral  truffle-server
Peak Performance

Speedup Relative to jruby-1.7.4-server-invokedynamic

Fannkuch
N-Body
Simplicity

- One intern working for five months on the Ruby implementation
- New to Truffle, Graal and Ruby

- Written using Eclipse
- Debugged as a normal Java program using the server compiler
- Run using Graal for testing and performance numbers

- No mention in the implementation of bytecode, classloaders, assembly, system calls, OSR
- One very minor use of Unsafe, one very minor use of reflection
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Codrut Stancu
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Hardware and Software

Engineered to Work Together