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One VM to Rule Them All

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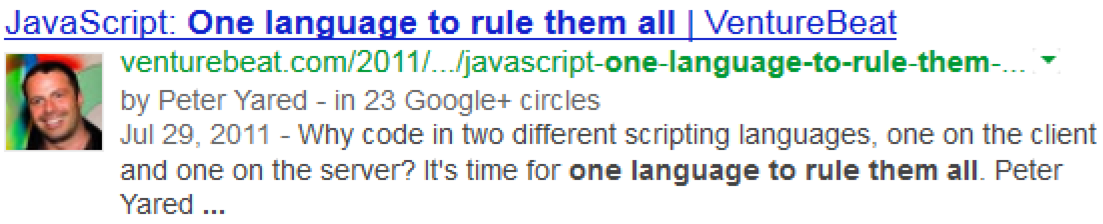
Agenda

- Motivation and project overview
- Implementation of a Simple Language (SL)
  - Truffle nodes
  - Specializations using Truffle DSL
  - Function calls
  - Compilation
  - Object layout
- Additional benefits of Truffle
  - Substrate VM: low-footprint standalone executables
  - Tools: language-agnostic debugging infrastructure

One Language to Rule Them All?

Let’s ask a search engine…

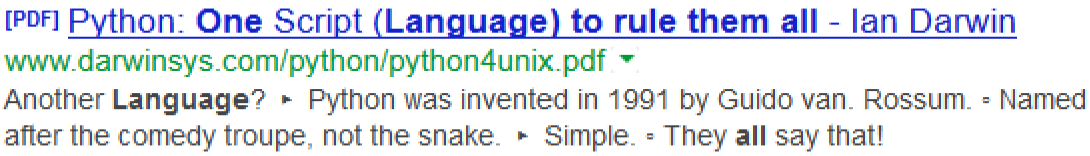


[JavaScript: **One language to rule them all** | VentureBeat]

venturebeat.com/2011/.../javascript-**one-language-to-rule-them**-...

by Peter Yared - in 23 Google+ circles

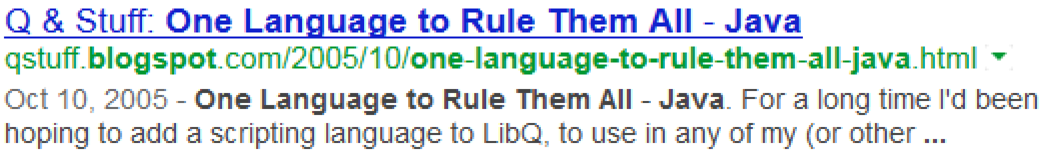
Jul 29, 2011 - Why code in two different scripting languages, one on the client and one on the server? It's time for **one language to rule them all**. Peter Yared **...**



[PDF] [Python: **One** Script (**Language**) **to rule them all** - Ian Darwin]

www.darwinsys.com/python/python4unix.pdf

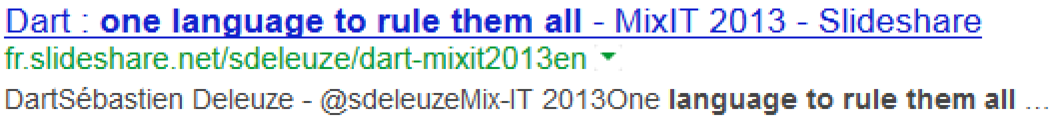
Another **Language**? ▸ Python was invented in 1991 by Guido van. Rossum. ▪ Named after the comedy troupe, not the snake. ▸ Simple. ▪ They **all** say that!



[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 **...**



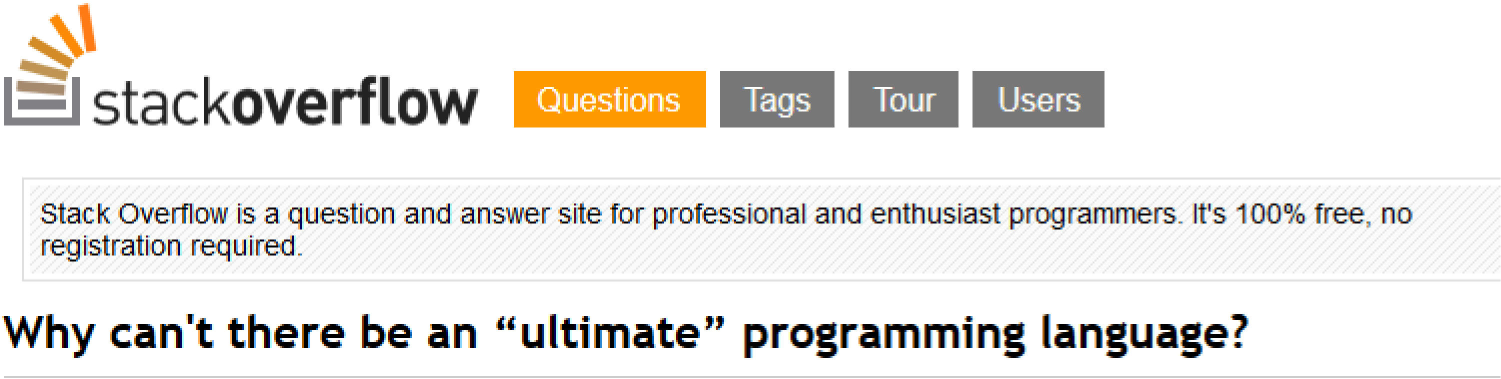
[Dart : **one language to rule them all** - MixIT 2013 - Slideshare]

fr.slideshare.net/sdeleuze/dart-mixit2013en

DartSébastien Deleuze - @sdeleuzeMix-IT 2013One **language to rule them all** ...

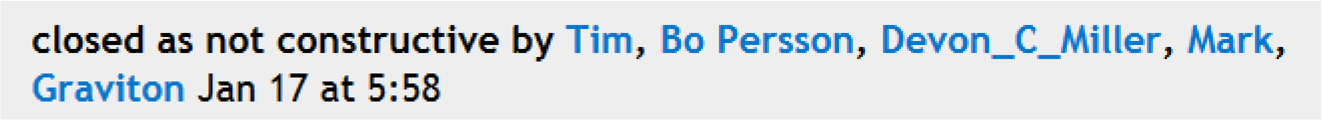
One Language to Rule Them All?

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.

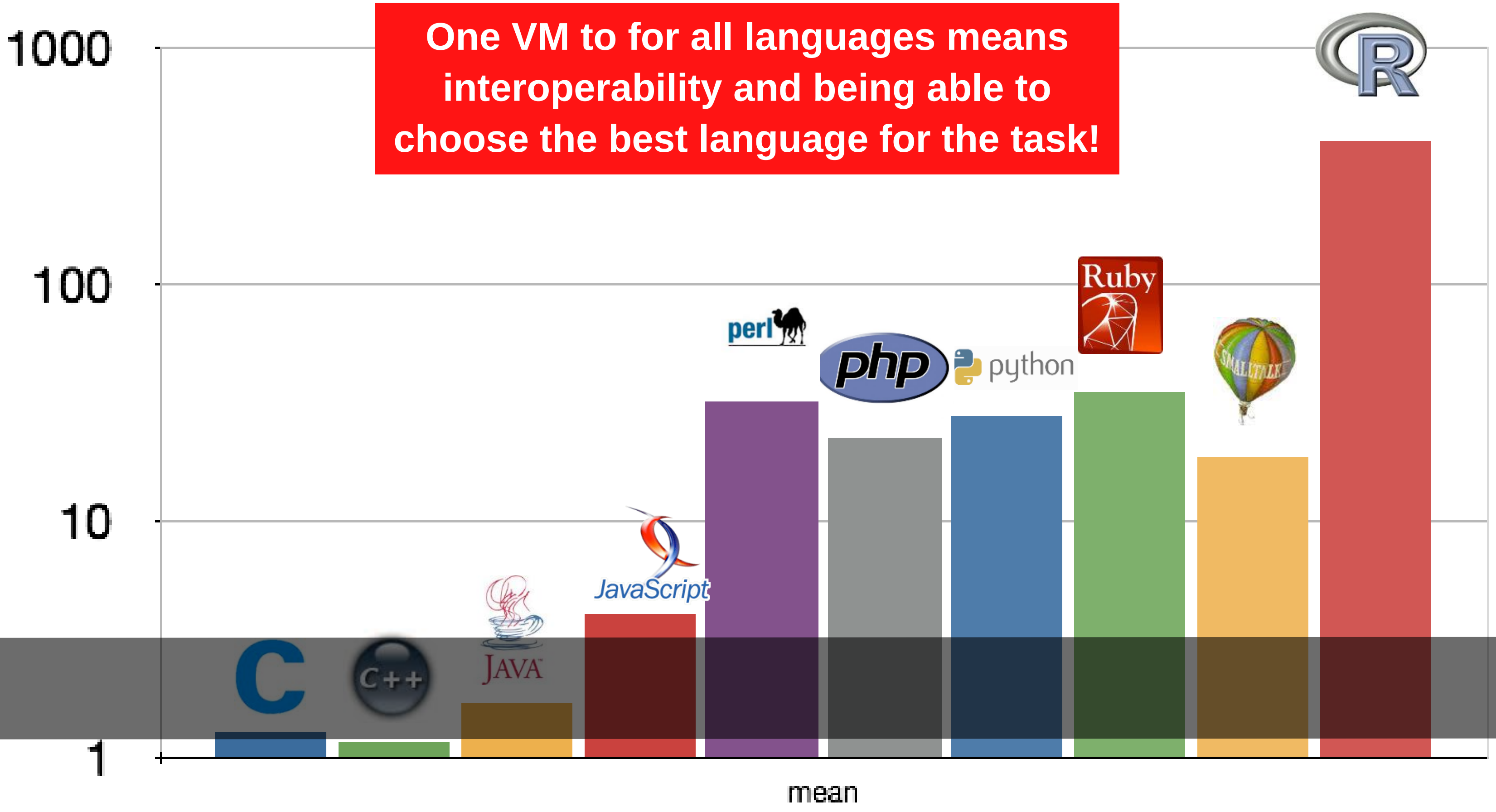
Why can't there be an “ultimate” programming language?



closed as not constructive by Tim, Bo Persson, Devon_C_Miller, Mark, Graviton Jan 17 at 5:58

Relative Speed of Programming Languages

From the Computer Language Benchmarks Game, ~1y ago



One VM to for all languages means interoperability and being able to choose the best language for the task!

Goal:

“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

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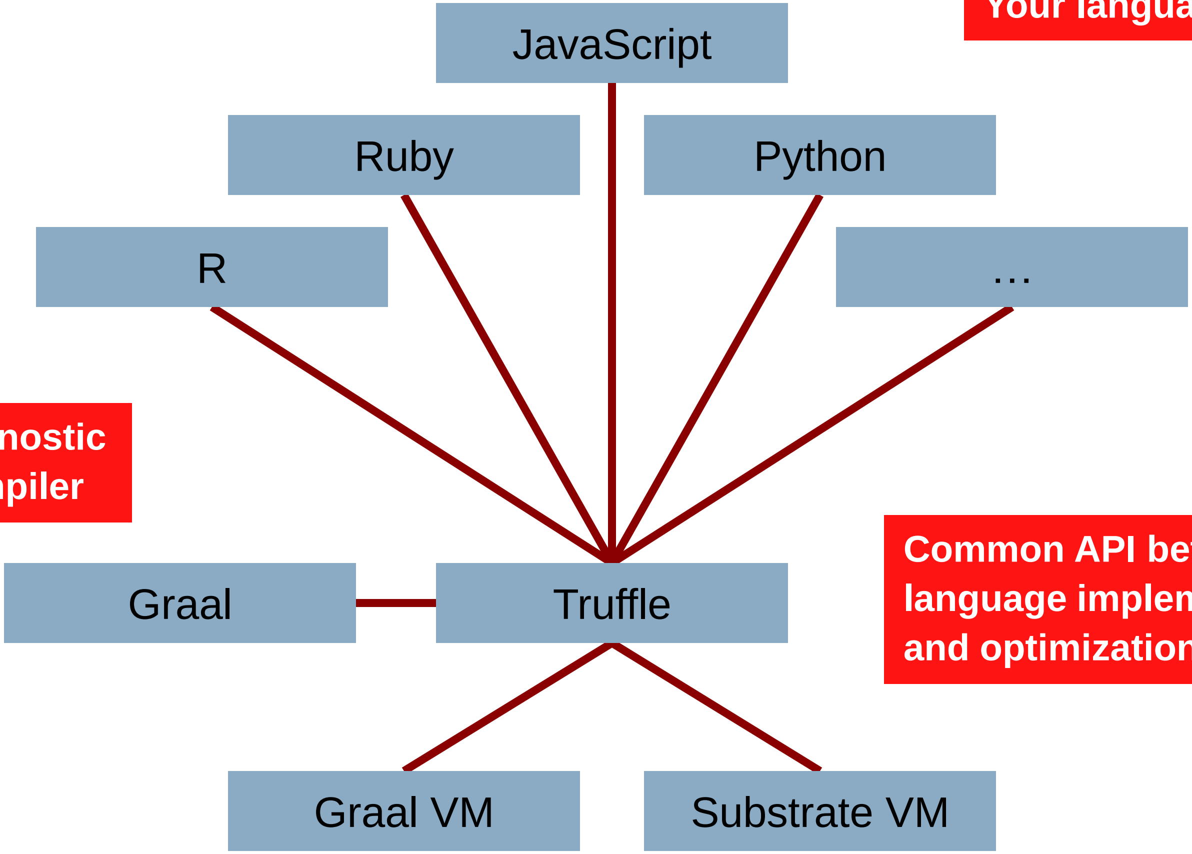
System Structure



JavaScript

Ruby

Python

R

…

Graal

Truffle

Graal VM

Substrate VM

Your language here!

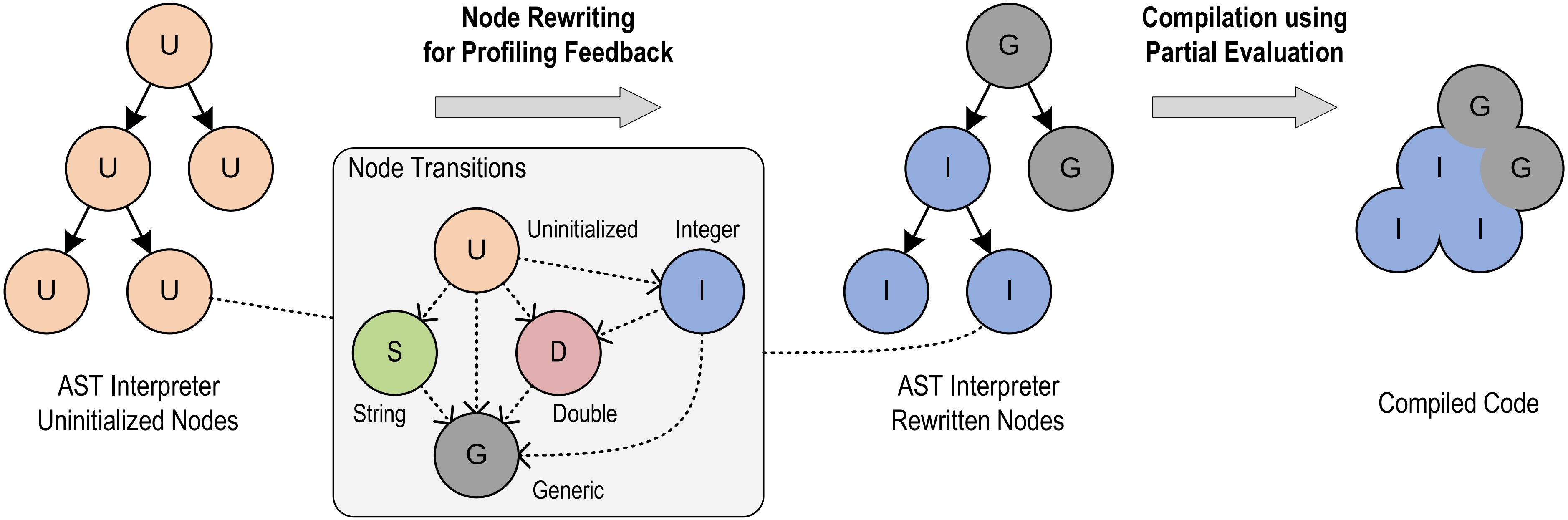
Language agnostic dynamic compiler

Common API between language implementation and optimization system

Integrate with Java applications

Low-footprint VM, also suitable for embedding

Speculate and Optimize …



Node Rewriting for Profiling Feedback

Compilation using Partial Evaluation

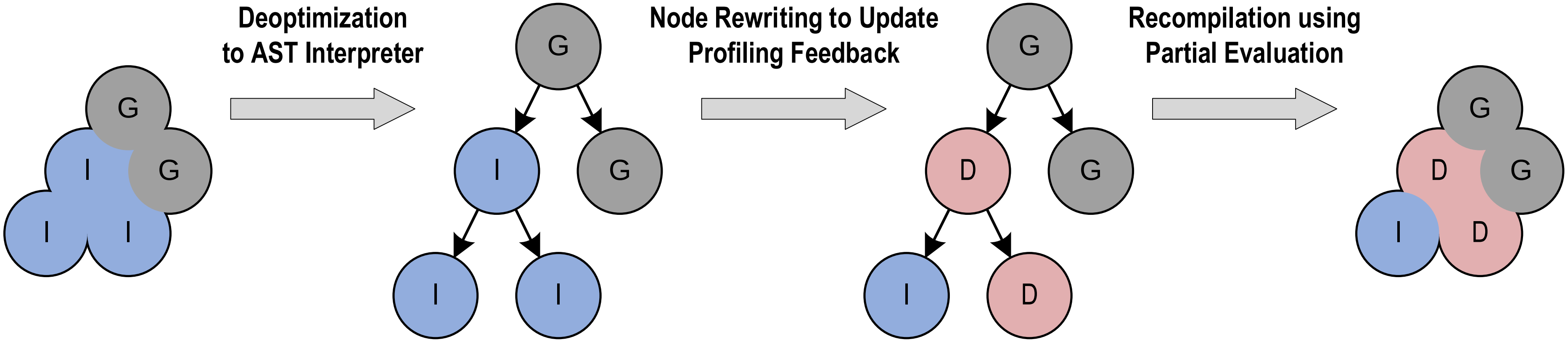
Node Transitions

AST Interpreter
Uninitialized Nodes

AST Interpreter
Rewritten Nodes

Compiled Code

… and Deoptimize and Reoptimize!



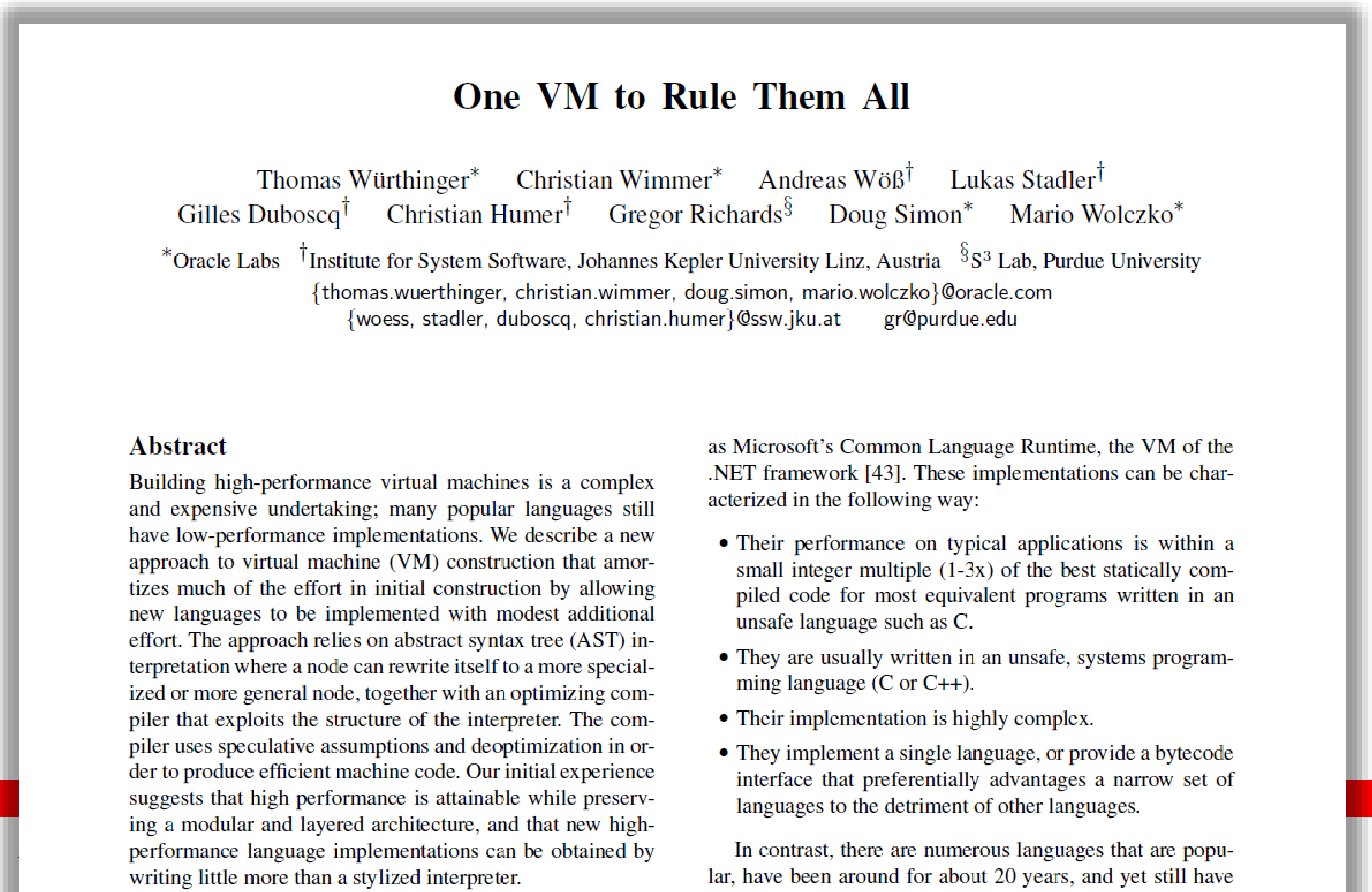
Deoptimization
to AST Interpreter

Node Rewriting to Update
Profiling Feedback

Recompilation using
Partial Evaluation

More Details on Truffle Approach

https://wiki.openjdk.java.net/display/Graal/Publications+and+Presentations



One VM to Rule Them All

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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

Truffle Language Projects

Languages that we are aware of

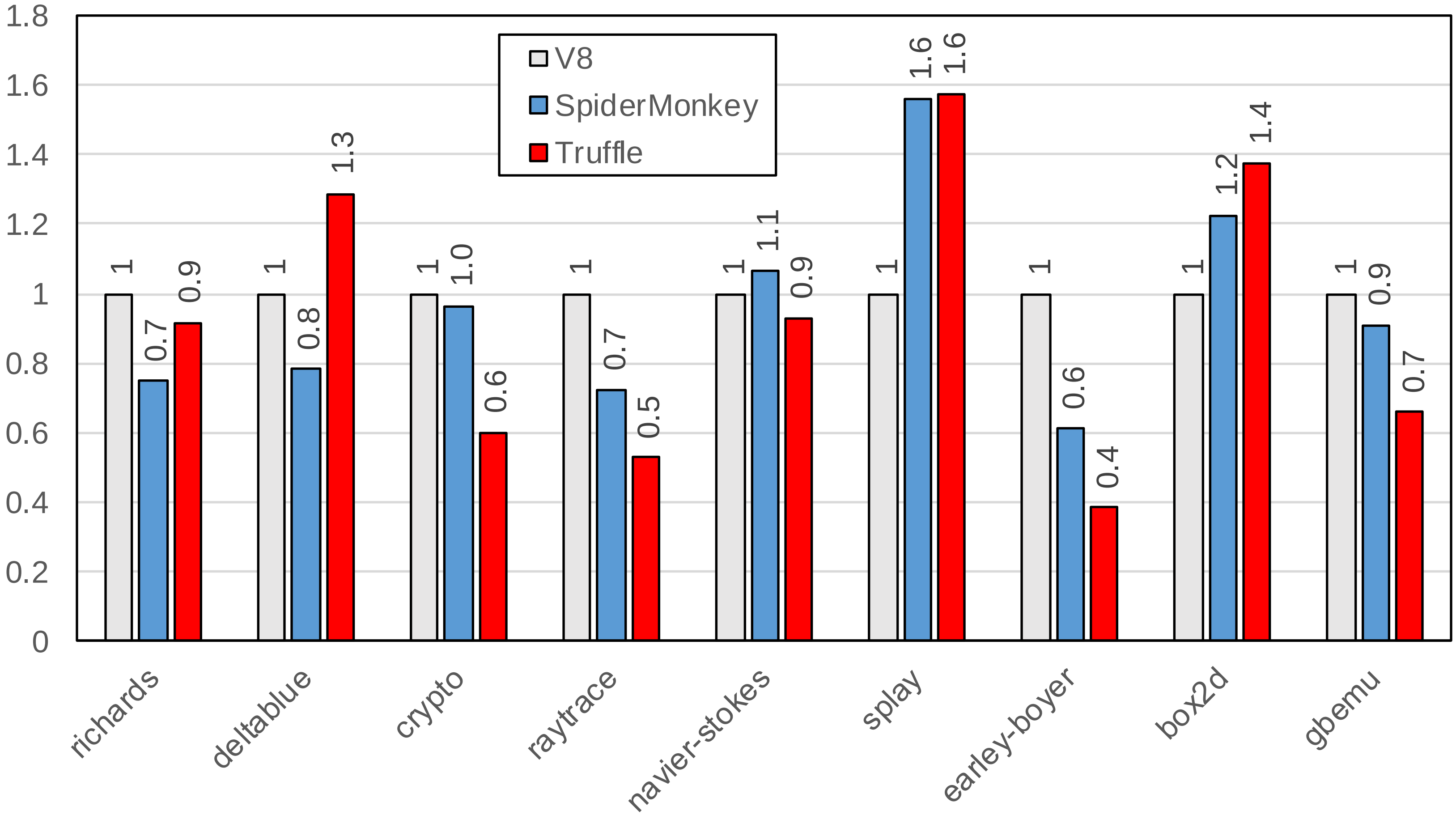
- Ruby
  - Oracle Labs, experimental part of JRuby
  - Open source: https://github.com/jruby/jruby
- R
  - JKU Linz, Purdue University, Oracle Labs
  - Open source: https://bitbucket.org/allr/fastr
- Python
  - ZipPy: UC Irvine
  - Open source: https://bitbucket.org/ssllab/zippy/
- JavaScript
  - JKU Linz, Oracle Labs
- SOM (Smalltalk)
  - Stefan Marr
  - Open source: https://github.com/smarr/TruffleSOM

Performance Disclaimers

- All Truffle numbers reflect the current development snapshot
  - Subject to change at any time (hopefully improve)
  - You have to know a benchmark to understand why it is slow or fast
- We are not claiming to have complete language implementations
  - JavaScript: passes 100% of ECMAscript standard tests
  - Ruby: passing >45% of RubySpec language tests
    - About as complete as Topaz
  - R: early prototype
  - Python: early prototype
- Benchmarks that are not shown
  - may not run at all, or
  - may not run fast

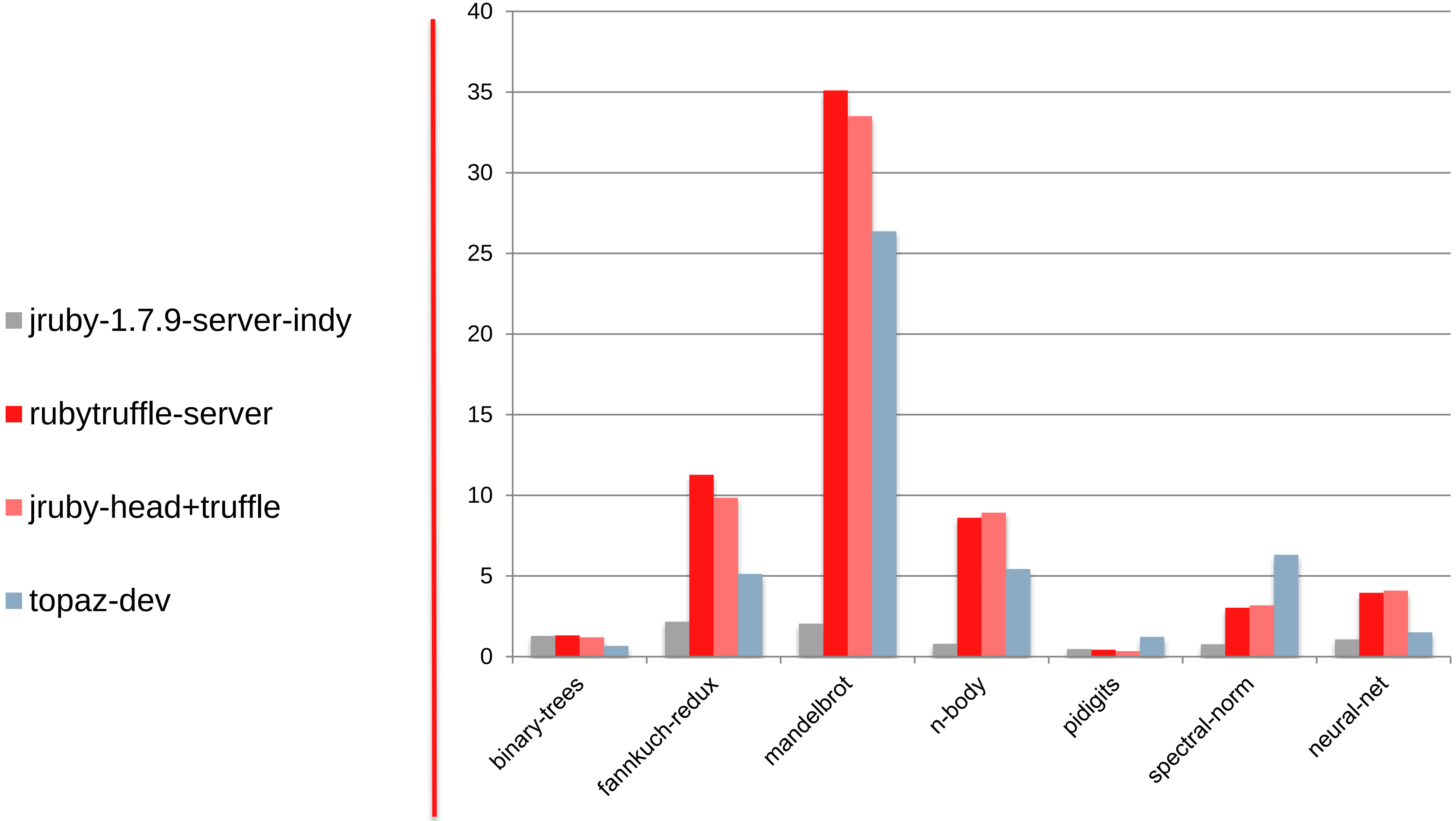
Performance: JavaScript

Speedup relative to V8



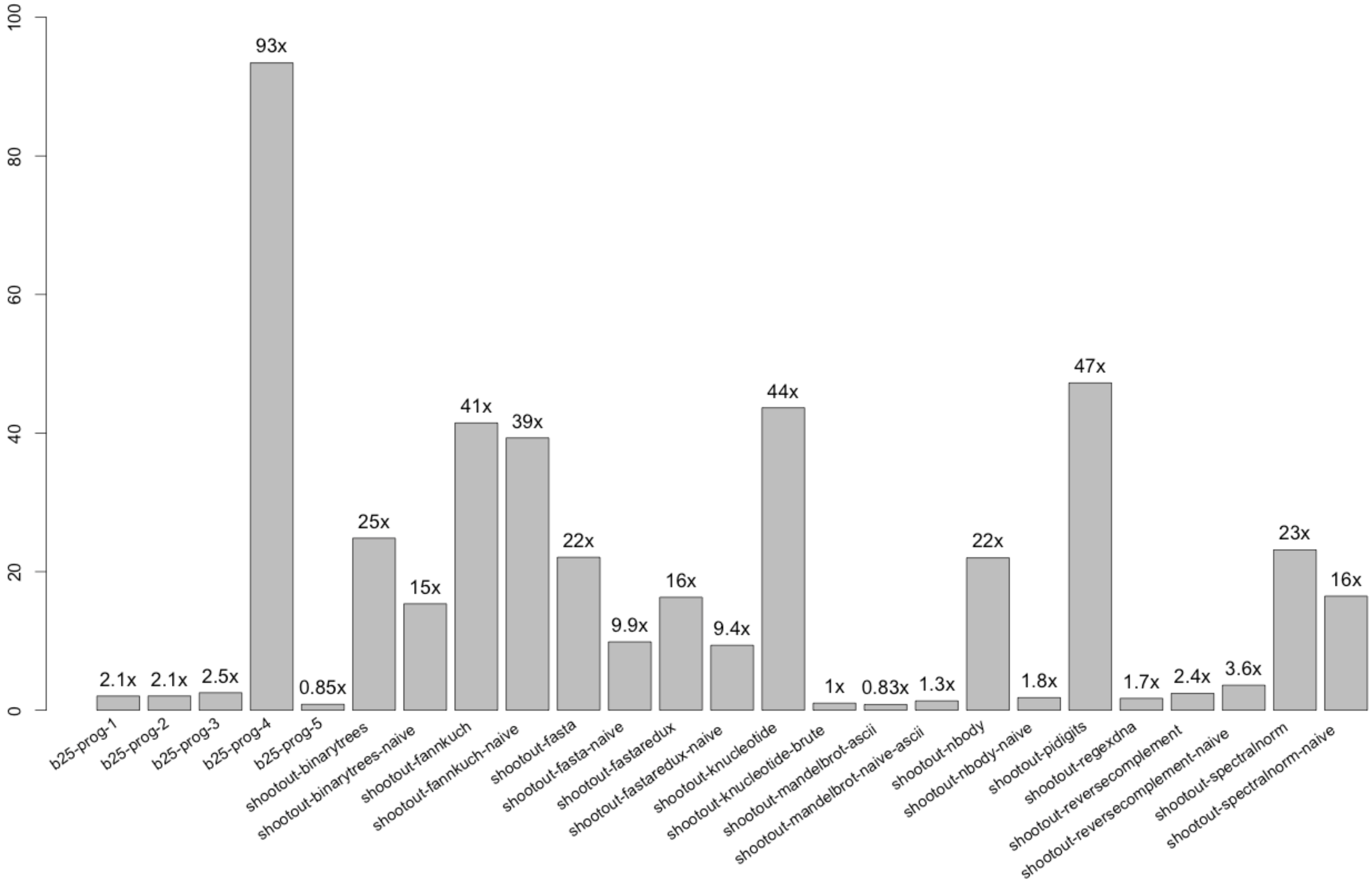
Performance: Ruby

Speedup relative to Ruby 2.1.0-p0



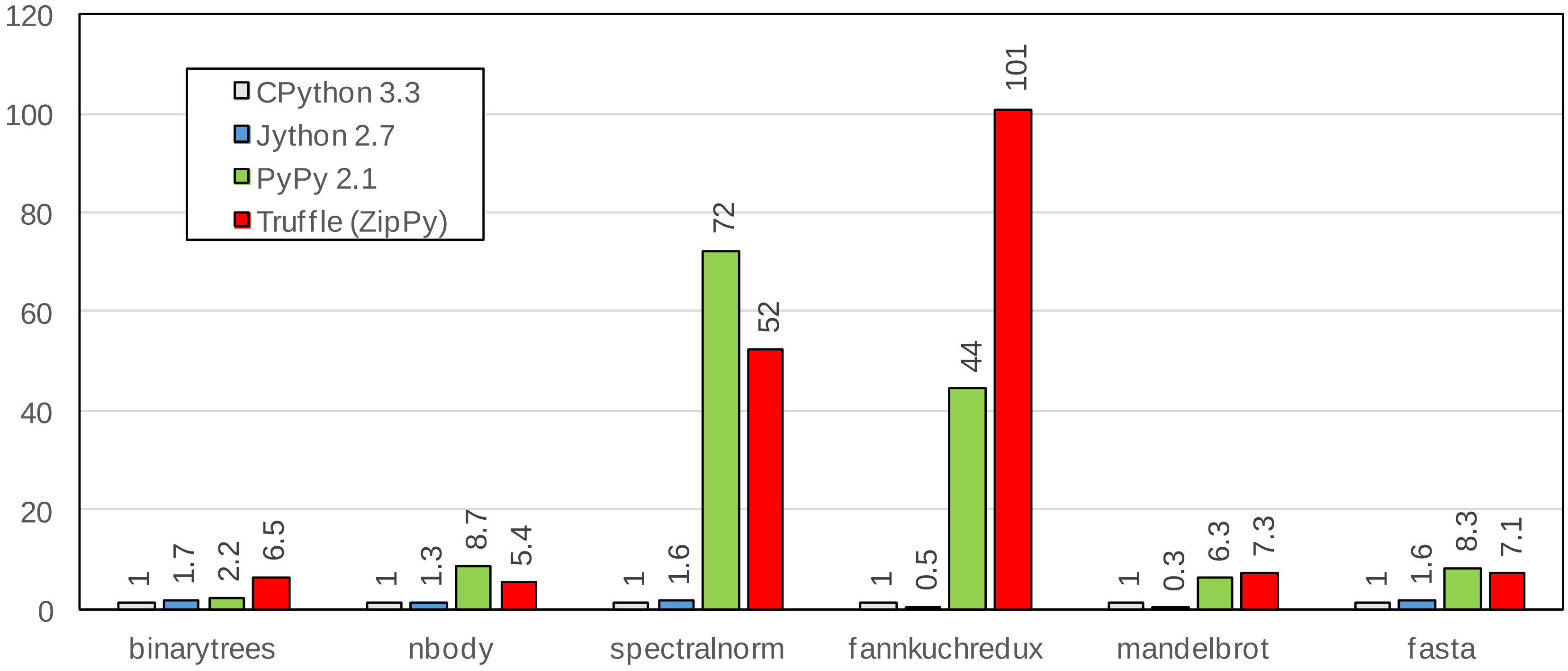
Performance: R

Speedup compared to GNU R 3.0 Bytecode Interpreter



Performance: Python

Speedup relative to CPython 3.3



Acknowledgements

Oracle Labs
Danilo Ansaloni
Daniele Bonetta
Laurent Daynès
Erik Eckstein
Michael Haupt
Mick Jordan
Peter Kessler
Christos Kotselidis
David Leibs
Tom Rodriguez
Roland Schatz
Doug Simon
Lukas Stadler
Michael Van De Vanter
Christian Wimmer
Christian Wirth
Mario Wolczko
Thomas Würthinger
Laura Hill (Manager)

Interns
Shams Imam
Stephen Kell
Gregor Richards
Rifat Shariyar

JKU Linz
Prof. Hanspeter Mössenböck
Gilles Duboscq
Matthias Grimmer
Christian Häubl
Josef Haider
Christian Humer
Christian Huber
Manuel Rigger
Bernhard Urban
Andreas Wöß

University of Manchester
Chris Seaton

University of Edinburgh
Christophe Dubach
Juan José Fumero Alfonso
Ranjeet Singh
Toomas Remmelg

LaBRI
Floréal Morandat

University of California, Irvine
Prof. Michael Franz
Codrut Stancu
Gulfem Savrun Yeniceri
Wei Zhang

Purdue University
Prof. Jan Vitek
Tomas Kalibera
Petr Maj
Lei Zhao

T. U. Dortmund
Prof. Peter Marwedel
Helena Kotthaus
Ingo Korb

University of California, Davis
Prof. Duncan Temple Lang
Nicholas Ulle

Simple Language

SL: A Simple Language

- Language to demonstrate and showcase features of Truffle
  - Simple and clean implementation
  - Not the language for your next implementation project
- Language highlights
  - Dynamically typed
  - Strongly typed
    - No automatic type conversions
  - Arbitrary precision integer numbers
  - First class functions
  - Dynamic function redefinition
- Omitted language features
  - No floating point numbers
  - No object model: no run-time memory allocation

Types

SL Type	Values	Java Type in Implementation
Number	Arbitrary precision integer numbers	`long` for values that fit within 64 bits `java.lang.BigInteger` on overflow
Boolean	true, false	`boolean`
String	Unicode characters	`java.lang.String`
Function	Reference to a function	`SLFunction`
Null	null	`SLNull.SINGLETON`

Null is its own type because SL has no object type; could also be called "Undefined"

Best Practice: Use Java primitive types as much as possible to increase performance

Best Practice: Do not use the Java `null` value for the guest language null value

Syntax

- C-like syntax
- Control flow statements
  - `if`, `while`, `break`, `continue`, `return`
- Operators
  - +, -, *, /, ==, !=, <, <=, >, >=, &&, ||, ( )
  - + is defined on String, performs String concatenation
  - && and || have short-circuit semantics
- Literals
  - Number, String, Function
- Builtin functions
  - println, readln: Standard I/O
  - nanoTime: to allow time measurements
  - defineFunction: dynamic function redefinition

Parsing

- Scanner and parser generated from grammar
  - Using Coco/R
  - Available from http://ssw.jku.at/coco/
- Refer to Coco/R documentation for details
  - This is not a tutorial about parsing
- Building a Truffle AST from a parse tree is usually simple

Best Practice: Use your favorite parser generator, or an existing parser for your language

SL Examples

Hello World:

```
function main() {
  println("Hello World!");
}
```

Strings:

```
function f(a, b) {
  return a + " < " + b + ": " + (a < b);
}

function main() {
  println(f(2, 4));
  println(f(2, "4"));
}
```

First class functions:

```
function add(a, b) { return a + b; }
function sub(a, b) { return a - b; }

function foo(f) {
  println(f(40, 2));
}

function main() {
  foo(add);
  foo(sub);
}
```

Simple loop:

```
function main() {
  i = 0;
  sum = 0;
  while (i <= 10000) {
    sum = sum + i;
    i = i + 1;
  }
  return sum;
}
```

Function definition and redefinition:

```
function foo() { println(f(40, 2)); }

function main() {
  defineFunction("function f(a, b) { return a + b; }");
  foo();

  defineFunction("function f(a, b) { return a - b; }");
  foo();
}
```

SL Examples with Output

Hello World:

```
function main() {
  println("Hello World!");
}
```

```
Hello World!
```

Strings:

```
function f(a, b) {
  return a + " < " + b + ": " + (a < b);
}

function main() {
  println(f(2, 4));
  println(f(2, "4"));
}
```

```
2 < 4: true
Type error
```

First class functions:

```
function add(a, b) { return a + b; }
function sub(a, b) { return a - b; }

function foo(f) {
  println(f(40, 2));
}

function main() {
  foo(add);
  foo(sub);
}
```

```
42
38
```

Simple loop:

```
function main() {
  i = 0;
  sum = 0;
  while (i <= 10000) {
    sum = sum + i;
    i = i + 1;
  }
  return sum;
}
```

```
50005000
```

Function definition and redefinition:

```
function foo() { println(f(40, 2)); }

function main() {
  defineFunction("function f(a, b) { return a + b; }");
  foo();

  defineFunction("function f(a, b) { return a - b; }");
  foo();
}
```

```
42
38
```

Getting Started

Get and build the source code:

```
$ hg clone http://hg.openjdk.java.net/graal/graal
$ cd graal
$ ./mx.sh build
```

Use the "server" configuration when `mx` asks you

Run SL example program:

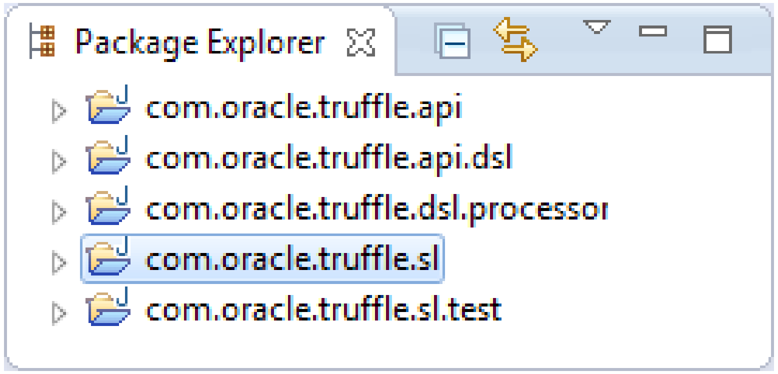
```
$ ./mx.sh sl graal/com.oracle.truffle.sl.test/tests/HelloWorld.sl
```

Generate Eclipse and NetBeans projects:

```
$ ./mx.sh ideinit
```

`mx` is our script to simplify building and execution

Import (at least) the following projects to work with SL:



- com.oracle.truffle.api
- com.oracle.truffle.api.dsl
- com.oracle.truffle.dsl.processor
- com.oracle.truffle.sl
- com.oracle.truffle.sl.test

Simple Tree Nodes

Truffle Nodes and Trees

- Class `Node`: base class of all Truffle tree nodes
  - Management of parent and children
  - Replacement of this node with a (new) node
  - Copy a node
  - No `execute()` methods: define your own in subclasses
- Class `NodeUtil` provides useful utility methods

```
public abstract class Node implements Cloneable {
  protected Node(SourceSection sourceSection) { ... }

  public final Node getParent() { ... }
  public final Iterable<Node> getChildren() { ... }

  protected final <T extends Node> T adoptChild(T newChild) { ... }
  protected final <T extends Node> T[] adoptChildren(T[] newChildren) { ... }

  public final <T extends Node> T replace(T newNode) { ... }
  public Node copy() { ... }
}
```

If Statement

```java
public final class SLIfNode extends SLStatementNode {
  @Child private SLExpressionNode conditionNode;
  @Child private SLStatementNode thenPartNode;
  @Child private SLStatementNode elsePartNode;

  public SLIfNode(SLExpressionNode conditionNode,
                  SLStatementNode thenPartNode, SLStatementNode elsePartNode) {
    this.conditionNode = adoptChild(conditionNode);
    this.thenPartNode = adoptChild(thenPartNode);
    this.elsePartNode = adoptChild(elsePartNode);
  }

  public void executeVoid(VirtualFrame frame) {
    if (conditionNode.executeBoolean(frame)) {
      thenPartNode.executeVoid(frame);
    } else {
      elsePartNode.executeVoid(frame);
    }
  }
}
```

Rule: A field for a child node must be annotated with `@Child` and must not be `final`

Rule: `adoptChild()` must be called when assigning a child node field

Blocks

```
public final class SLBlockNode extends SLStatementNode {
  @Children private final SLStatementNode[] bodyNodes;

  public SLBlockNode(SLStatementNode[] bodyNodes) {
    this.bodyNodes = adoptChildren(bodyNodes);
  }

  @ExplodeLoop
  public void executeVoid(VirtualFrame frame) {
    for (SLStatementNode statement : bodyNodes) {
      statement.executeVoid(frame);
    }
  }
}
```

Rule: A field for multiple child nodes must be annotated with `@Children` and a `final` array

Rule: `adoptChildren()` must be called when assigning a children node field

Rule: The iteration of the children must be annotated with `@ExplodeLoop`

Return Statement: Inter-Node Control Flow

```
public final class SLReturnNode extends SLStatementNode {
  @Child private SLExpressionNode valueNode;
  ...
  public void executeVoid(VirtualFrame frame) {
    throw new SLReturnException(valueNode.executeGeneric(frame));
  }
}
```

```
public final class SLFunctionBodyNode extends SLExpressionNode {
  @Child private SLStatementNode bodyNode;
  ...
  public Object executeGeneric(VirtualFrame frame) {
    try {
      bodyNode.executeVoid(frame);
    } catch (SLReturnException ex) {
      return ex.getResult();
    }
    return SLNull.SINGLETON;
  }
}
```

```
public final class SLReturnException
      extends ControlFlowException {

  private final Object result;
  ...
}
```

Best practice: Use Java exceptions for inter-node control flow

Rule: Exceptions used to model control flow extend `ControlFlowException`

Example for Inter-Node Control Flow

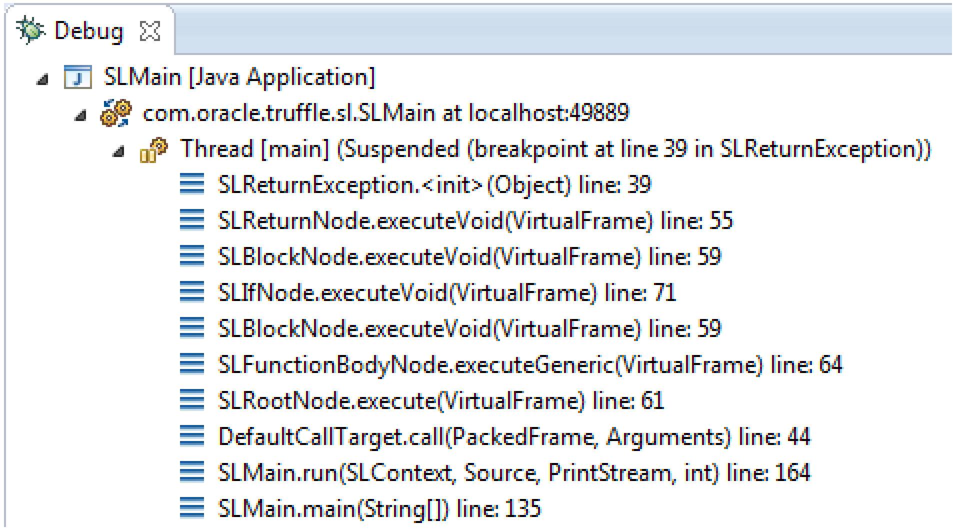
SL source code:

```
function main() {
  foo();
  if (1 < 2) {
    bar();
    return 1;
  }
}
```

AST:

```
SLFunctionBodyNode
  bodyNode = SLBlockNode
    bodyNodes[0] = SLInvokeNode
    bodyNodes[1] = SLIfNode
      conditionNode = ...
      thenPartNode = SLBlockNode
        bodyNodes[0] = SLInvokeNode
        bodyNodes[1] = SLReturnNode
          valueNode = SLLongLiteralNode
      elsePartNode = ...
```

Screenshot of stack frames in debugger:



```
SLMain [Java Application]
  com.oracle.truffle.sl.SLMain at localhost:49889
    Thread [main] (Suspended (breakpoint at line 39 in SLReturnException))
      SLReturnException.<init>(Object) line: 39
      SLReturnNode.executeVoid(VirtualFrame) line: 55
      SLBlockNode.executeVoid(VirtualFrame) line: 59
      SLIfNode.executeVoid(VirtualFrame) line: 71
      SLBlockNode.executeVoid(VirtualFrame) line: 59
      SLFunctionBodyNode.executeGeneric(VirtualFrame) line: 64
      SLRootNode.execute(VirtualFrame) line: 61
      DefaultCallTarget.call(PackedFrame, Arguments) line: 44
      SLMain.run(SLContext, Source, PrintStream, int) line: 164
      SLMain.main(String[]) line: 135
```

Specialization and Node Rewriting

Addition: A First Try (1)

```
public final class SLAddNode extends SLExpressionNode {
  @Child private SLExpressionNode leftNode;
  @Child private SLExpressionNode rightNode;

  @Override
  public Object executeGeneric(VirtualFrame frame) {
    Object left = leftNode.executeGeneric(frame);
    Object right = rightNode.executeGeneric(frame);

    if (left instanceof Long && right instanceof Long) {
      try {
        return ExactMath.addExact((Long) left, (Long) right);
      } catch (ArithmeticException ex) { }
    }

    if (left instanceof Long) {
      left = BigInteger.valueOf((Long) left);
    }
    if (right instanceof Long) {
      right = BigInteger.valueOf((Long) right);
    }
    if (left instanceof BigInteger && right instanceof BigInteger) {
      return ((BigInteger) left).add((BigInteger) right);
    }

    if (left instanceof String || right instanceof String) {
      return left.toString() + right.toString();
    }

    throw new UnsupportedSpecializationException(this, ...);
  }
}
```

Warning: If you ever write such code for a Truffle node, you did something wrong!

Addition: A First Try (2)

Problems of the code on the previous slide

- Type checks and type casts
  - Many `instanceof` checks to select correct operation
- Boxing
  - Primitive `long` value is boxed into `Long`
  - Boxing consumes time and memory
- Complex control flow, including exception handling
  - Error prone code
- Slow
  - A lot of code to execute just to perform an addition

- Solution: node rewriting
  - Factor out every type into a separate node class
  - Truffle DSL generates the boilerplate code for you

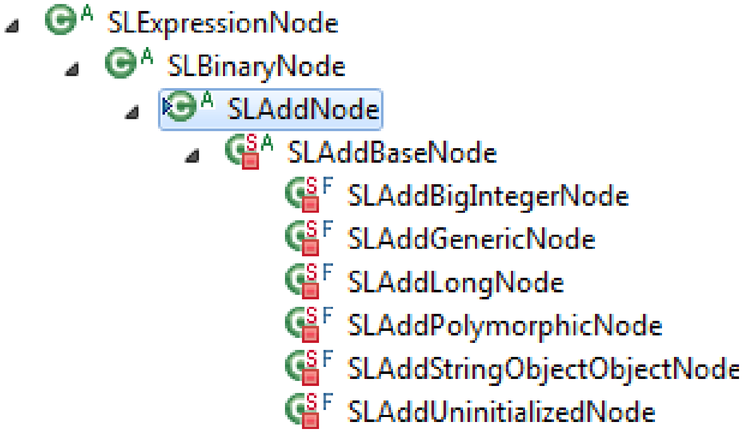
Addition with Truffle DSL

```
@NodeChildren({@NodeChild("leftNode"), @NodeChild("rightNode")})
public abstract class SLBinaryNode extends SLExpressionNode {
}

public abstract class SLAddNode extends SLBinaryNode {

  @Specialization(rewriteOn = ArithmeticException.class)
  protected final long add(long left, long right) {
    return ExactMath.addExact(left, right);
  }

  @Specialization
  protected final BigInteger add(BigInteger left, BigInteger right) {
    return left.add(right);
  }

  @Specialization(guards = "isString")
  protected final String add(Object left, Object right) {
    return left.toString() + right.toString();
  }

  protected final boolean isString(Object a, Object b) {
    return a instanceof String || b instanceof String;
  }
}
```

For all other specializations, guards are implicit based on method signature

Code Generated by Truffle DSL (1)

Generated class hierarchy:



- SLExpressionNode
  - SLBinaryNode
    - SLAddNode
      - SLAddBaseNode
        - SLAddBigIntegerNode
        - SLAddGenericNode
        - SLAddLongNode
        - SLAddPolymorphicNode
        - SLAddStringObjectObjectNode
        - SLAddUninitializedNode

The parser creates a `SLAddUninitializedNode`, using the `SLAddNodeFactory`

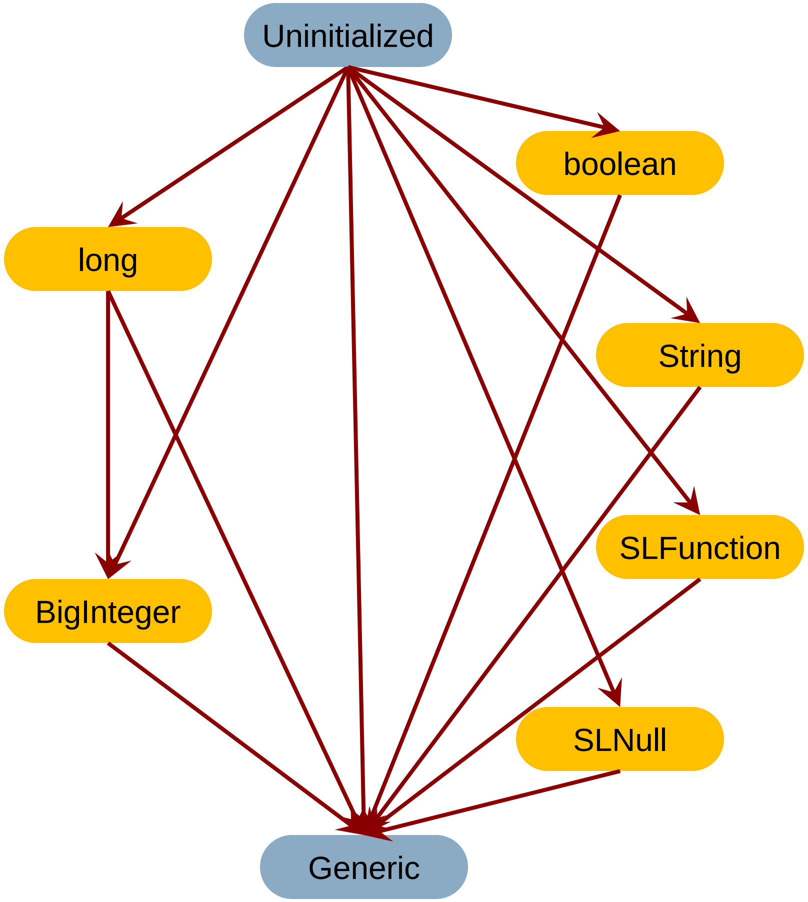
`SLAddPolymorphicNode` is a performance optimization

Generated factory class:

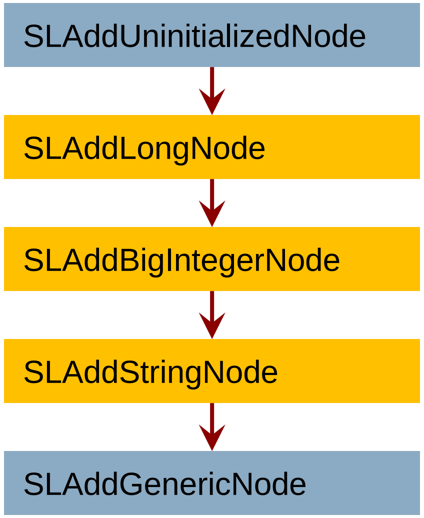
```
@GeneratedBy(SLAddNode.class)
public final class SLAddNodeFactory implements NodeFactory<SLAddNode> {

  public SLAddNode createNode(Object... arguments) { ... }

  public static SLAddNode create(SLExpressionNode leftNode,
                                 SLExpressionNode rightNode) { ... }
  ...
}
```

Type Transitions vs. Node Rewriting

Possible type transitions:



Node rewriting for addition:


SLAddUninitializedNode

SLAddLongNode

SLAddBigIntegerNode

SLAddStringNode

SLAddGenericNode

The linearization of the type lattice simplifies the node rewriting logic

Code Generated by Truffle DSL (2)

```
@GeneratedBy(SLAddNode.class)
@NodeInfo(kind = Kind.SPECIALIZED, shortName = "+")
private final class SLAddLongNode extends SLAddBaseNode {
  public long executeLong(VirtualFrame frameValue) throws UnexpectedResultException {
    long leftNodeValue;
    try {
      leftNodeValue = leftNode.executeLong(frameValue);
    } catch (UnexpectedResultException ex) {
      Object rightNodeValue = rightNode.executeGeneric(frameValue);
      return SLTYPES.expectLong(executeAndSpecialize0(1, frameValue, ex.getResult(), rightNodeValue));
    }
    long rightNodeValue;
    try {
      rightNodeValue = this.rightNode.executeLong(frameValue);
    } catch (UnexpectedResultException ex) {
      return SLTYPES.expectLong(executeAndSpecialize0(1, frameValue, leftNodeValue, ex.getResult()));
    }
    try {
      return super.add(leftNodeValue, rightNodeValue);
    } catch (ArithmeticException ex) {
      return SLTYPES.expectLong(executeAndSpecialize0(1, frameValue, leftNodeValue, rightNodeValue));
    }
  }

  public Object executeGeneric(VirtualFrame frameValue) {
    try {
      return executeLong(frameValue);
    } catch (UnexpectedResultException ex) {
      return ex.getResult();
    }
  }
}
```

Type System Definition in Truffle DSL

```
@TypeSystem({long.class, BigInteger.class,
             boolean.class, String.class,
             SLFunction.class, SLNull.class})
public abstract class SLTypes {
  @ImplicitCast
  public BigInteger castBigInteger(long value) {
    return BigInteger.valueOf(value);
  }
}
```

Order of types is important: defines the order in which specializations are matched

Not shown in slide: Use `@TypeCheck` and `@TypeCast` to customize type conversions

```
@TypeSystemReference(SLTypes.class)
public abstract class SLExpressionNode extends SLStatementNode {
  public abstract Object executeGeneric(VirtualFrame frame);

  public long executeLong(VirtualFrame frame) throws UnexpectedResultException {
    return SLTypesGen.SLTYPES.expectLong(executeGeneric(frame));
  }
  public BigInteger executeBigInteger(VirtualFrame frame) ...
  public boolean executeBoolean(VirtualFrame frame) ...
  public String executeString(VirtualFrame frame ...
  public SLFunction executeFunction(VirtualFrame frame) ...
  public SLNull executeNull(VirtualFrame frame) ...
}
```

`SLTypesGen` is a generated subclass of `SLTypes`

Rule: One `execute()` method per type, in addition to the abstract `executeGeneric()` method

`UnexpectedResultException`

- Type-specialized `execute()` methods have specialized return type
  - Allows primitive return types, to avoid boxing
  - Allows to use the result without type casts
  - Speculation types are stable and the specialization fits
- But what to do when speculation was too optimistic?
  - Need to return a value with a type more general than the return type
  - Solution: return the value "boxed" in an `UnexpectedResultException`
- Exception handler performs node rewriting
  - Exception is thrown only once, so no performance bottleneck

Source Position Information

- Every node can specify a pointer to a source location
  - For error messages, tool support, and sometime language features
  - Created by the parser

- `Source`
  - A file, or any other source of code
- `SourceManager`
  - Keeps all sources in one place
  - Allows, e.g., lookup by file name
- `SourceSection`
  - A range of characters in a `Source`

- The `Source` of a node is preserved during node rewriting

ORACLE

Frames and Local Variables

Frame Layout

- In the interpreter, a frame is an object on the heap
  - Allocated in the function prologue
  - Passed around as parameter to `execute()` methods
- The compiler eliminates the allocation
  - No object allocation and object access
  - Guest language local variables have the same performance as Java local variables

- `FrameDescriptor`: describes the layout of a frame
  - A mapping from identifiers (usually variable names) to typed slots
  - Every slot has a unique index into the frame object
  - Created and filled during parsing
- `Frame`
  - Created for every invoked guest language function
- `Arguments`
  - Data that is passed around between functions
  - Allocated in caller, accessed in callee function
  - Language implementations have their own subclasses

Frame Management

- Truffle API only exposes frame interfaces
  - Implementation class depends on the optimizing system

- `VirtualFrame`
  - What you usually use: automatically optimized by the compiler
  - Must never be assigned to a field, or escape out of an interpreted function
- `MaterializedFrame`
  - A frame that can be stored without restrictions
  - Example: frame of a closure that needs to be passed to other function
- `PackedFrame`
  - A handle to a `VirtualFrame`

- Allocation of frames
  - Factory methods in the class `TruffleRuntime`

Frame Management

```
public interface Frame {
  FrameDescriptor getFrameDescriptor();
  <T extends Arguments> T getArguments(Class<T> clazz);

  Object getValue(FrameSlot slot);

  boolean isType(FrameSlot slot);
  Type getType(FrameSlot slot) throws FrameSlotTypeException;
  void setType(FrameSlot slot, Type value);

  PackedFrame pack();
  MaterializedFrame materialize();
}
```

Frames support all Java primitive types, and `Object`

SL types String, SLFunction, and SLNull are stored as `Object` in the frame

Rule: Never allocate frames yourself, and never make your own frame implementations

Local Variables

```
@NodeField(name = "slot", type = FrameSlot.class)
public abstract class SLReadLocalVariableNode extends SLExpressionNode {

  protected abstract FrameSlot getSlot();

  @Specialization(rewriteOn = FrameSlotTypeException.class)
  protected final long readLong(VirtualFrame frame) throws FrameSlotTypeException {
    return frame.getLong(getSlot());
  }

  ...

  @Specialization(order = 1, rewriteOn = FrameSlotTypeException.class)
  protected final Object readObject(VirtualFrame frame) throws FrameSlotTypeException {
    return frame.getObject(getSlot());
  }

  @Specialization(order = 2)
  protected final Object read(VirtualFrame frame) {
    return frame.getValue(getSlot());
  }
}
```

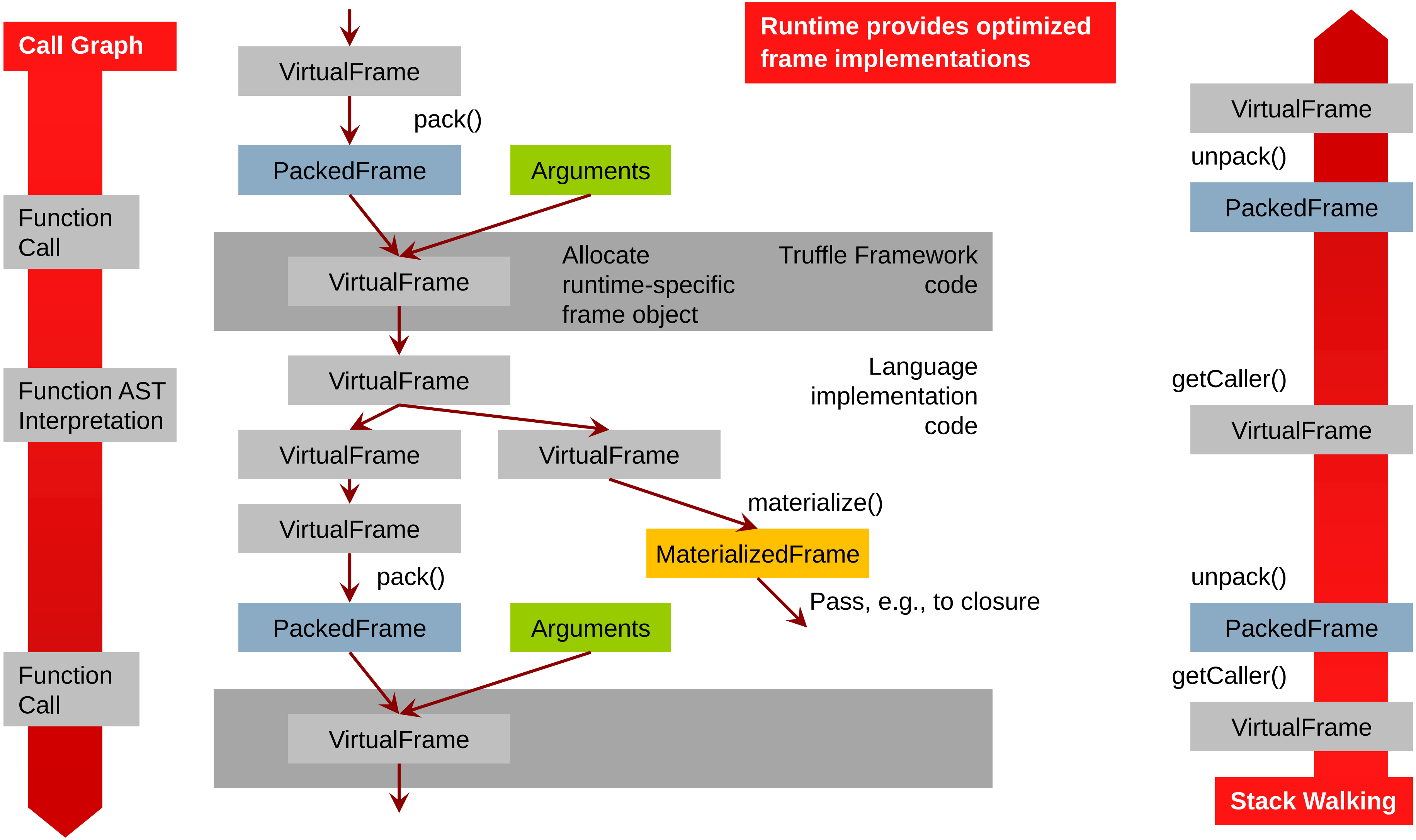
Order of specialization is specified manually because it cannot be inferred from the method signature

`Frame.getValue()` never fails, also returns boxed primitive values

Local Variables

```
@NodeChild("valueNode")
@NodeField(name = "slot", type = FrameSlot.class)
public abstract class SLWriteLocalVariableNode extends SLExpressionNode {
  protected abstract FrameSlot getSlot();

  @Specialization(guards = "isLongKind")
  protected final long write(VirtualFrame frame, long value) {
    frame.setLong(getSlot(), value);
    return value;
  }
  ...
  @Specialization
  protected final Object write(VirtualFrame frame, Object value) {
    if (getSlot().getKind() != FrameSlotKind.Object) {
      getSlot().setKind(FrameSlotKind.Object);
    }
    frame.setObject(getSlot(), value);
    return value;
  }

  protected final boolean isLongKind() {
    return isKind(FrameSlotKind.Long);
  }
  private boolean isKind(FrameSlotKind kind) {
    if (getSlot().getKind() == kind) {
      return true;
    } else if (getSlot().getKind() == FrameSlotKind.Illegal) {
      getSlot().setKind(kind);
      return true;
    } else {
      return false;
    }
  }
}
```

Frame Management



Call Graph

Function Call

Function AST Interpretation

Function Call

VirtualFrame

pack()

PackedFrame

Arguments

VirtualFrame

Allocate runtime-specific frame object

Truffle Framework code

VirtualFrame

Language implementation code

VirtualFrame

VirtualFrame

VirtualFrame

materialize()

MaterializedFrame

pack()

Pass, e.g., to closure

PackedFrame

Arguments

VirtualFrame

Runtime provides optimized frame implementations

VirtualFrame

unpack()

PackedFrame

getCaller()

VirtualFrame

unpack()

PackedFrame

getCaller()

VirtualFrame

Stack Walking

Compilation

Compilation

- Automatic partial evaluation of AST
  - Automatically triggered by function execution count
- Compilation assumes that the AST is stable
  - All `@Child` and `@Children` fields treated like `final` fields
- Later node rewriting invalidates the machine code
  - Transfer back to the interpreter: "Deoptimization"
  - Complex logic for node rewriting not part of compiled code
  - Essential for excellent peak performance
- Compiler optimizations eliminate the interpreter overhead
  - No more dispatch between nodes
  - No more allocation of `VirtualFrame` objects
  - No more exceptions for inter-node control flow

Compilation

SL source code:

```
function loop(n) {
  i = 0;
  while (i < n) {
    i = i + 1;
  }
  return i;
}
```

Machine code for loop:

```
     ...
     movq      rcx, 0x0
     jmp       L2:
L1:  safepoint
     mov       rsi, rcx
     addq      rsi, 0x1
     jo        L3:
     mov       rcx, rsi
L2:  cmp       rax, rcx
     jnle      L1:
     ...
L3:  call      deoptimize
```

Run this example:

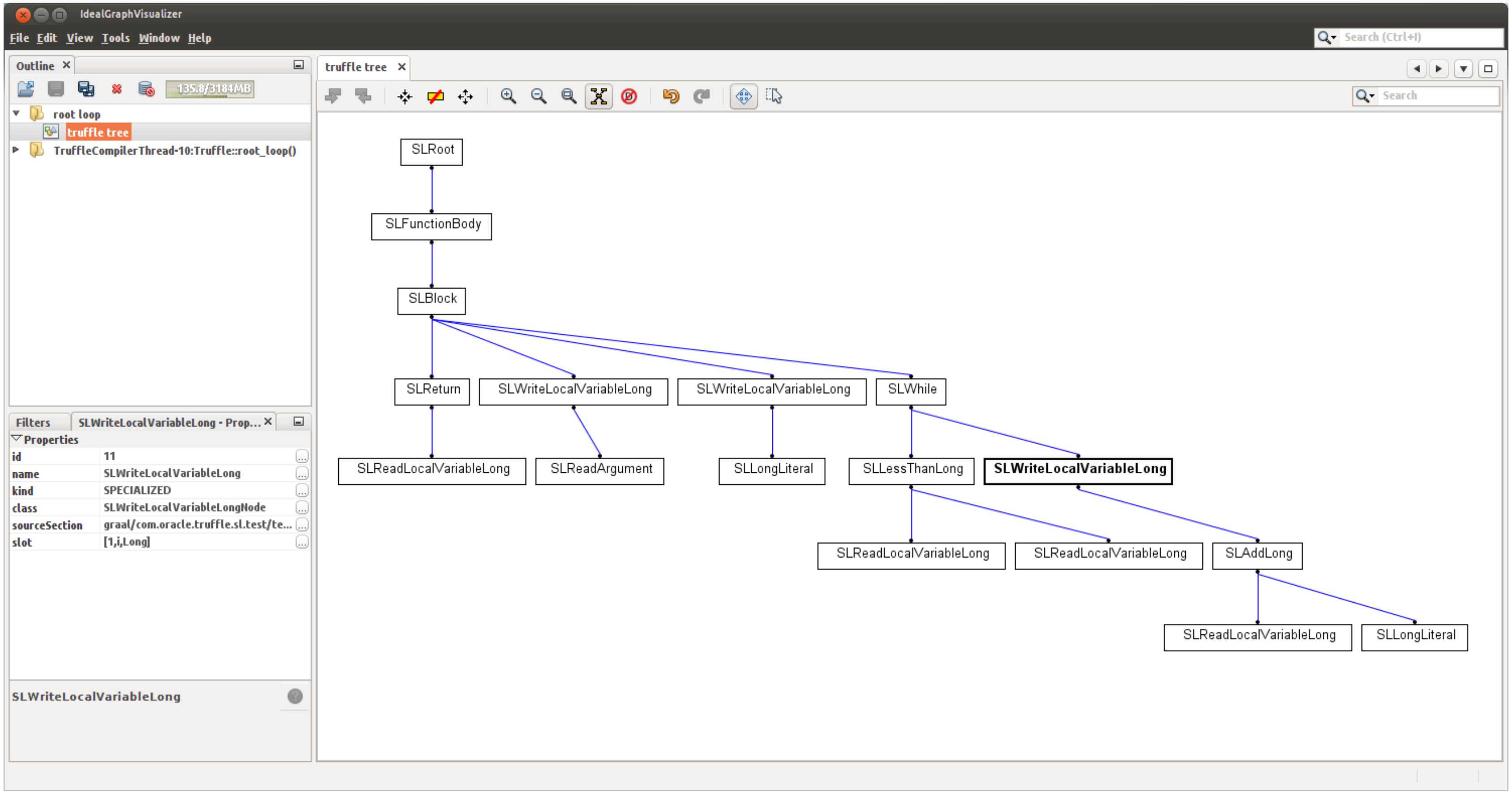
```
./mx.sh sl -G:-TruffleBackgroundCompilation
graal/com.oracle.truffle.sl.test/tests/LoopPrint.sl
```

-G:-TruffleBackgroundCompilation forces compilation in the main execution thread

```
./mx.sh igv &

./mx.sh sl -G:Dump=
-G:-TruffleBackgroundCompilation
graal/com.oracle.truffle.sl.test/tests/LoopPrint.sl
```

Add the flag -G:Dump= to dump compiled functions to IGV

Visualization Tools: IGV

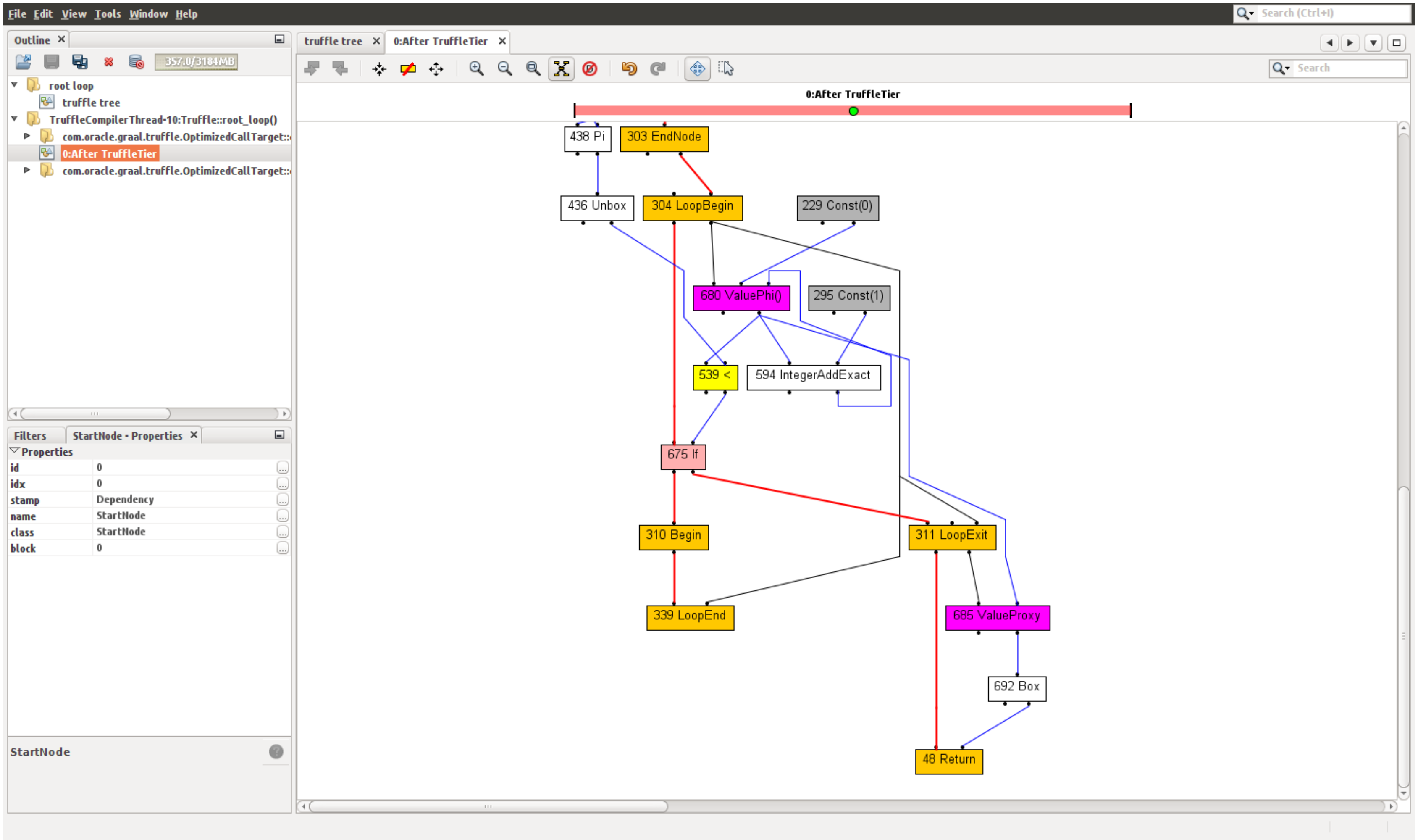


Properties

id	11
name	SLWriteLocalVariableLong
kind	SPECIALIZED
class	SLWriteLocalVariableLongNode
sourceSection	graal/com.oracle.truffle.sl.test/te...
slot	[1,i,Long]

SLWriteLocalVariableLong

Visualization Tools: IGV



id	0
idx	0
stamp	Dependency
name	StartNode
class	StartNode
block	0

Function Calls

Polymorphic Inline Caches

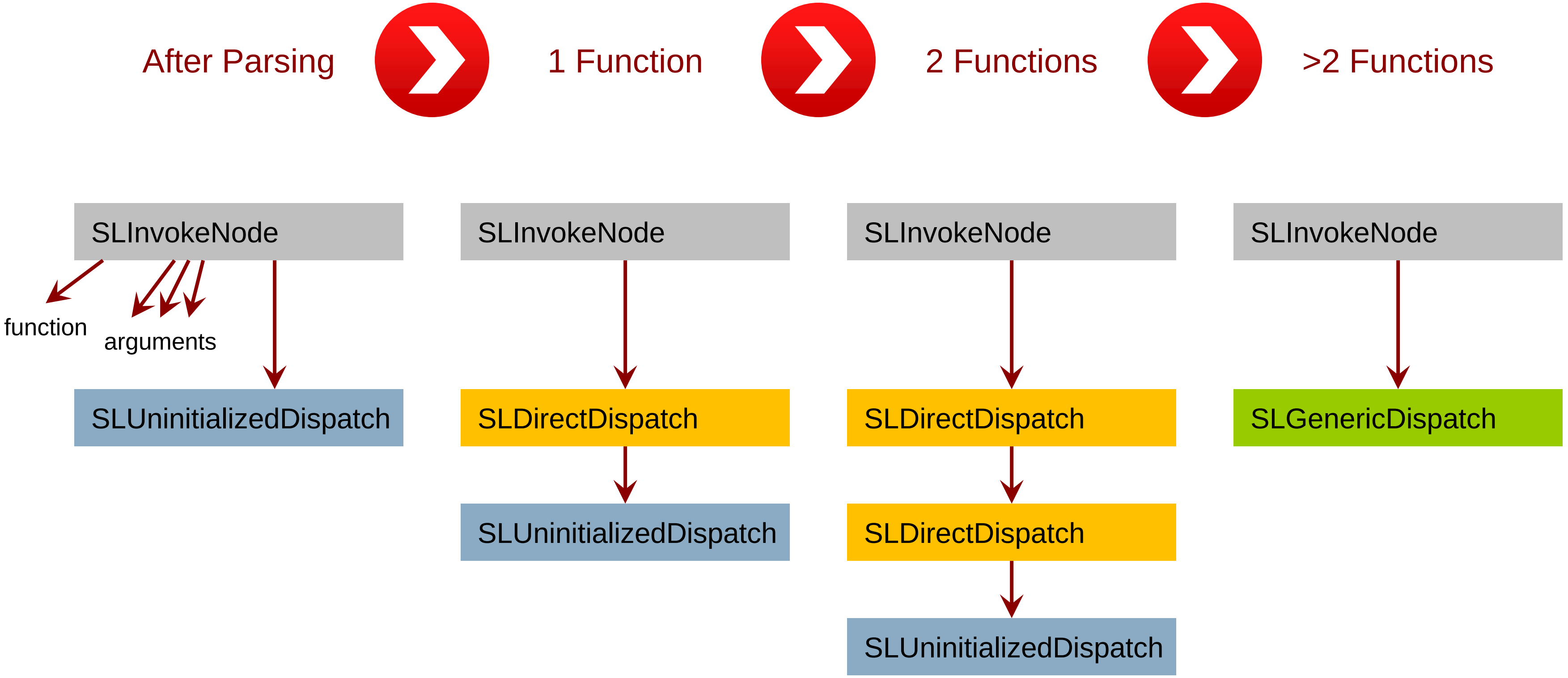
- Function lookups are expensive
  - At least in a real language, in SL lookups are only a few field loads
- Checking whether a function is the correct one is cheap
  - Always a single comparison

- Inline Cache
  - Cache the result of the previous lookup and check if it still correct
- Polymorphic Inline Cache
  - Cache multiple previous lookups, up to a certain limit
- Inline cache miss needs to perform the slow lookup

- Implementation using tree rewriting
  - One node per cached value
  - Build chain of multiple cache nodes

Polymorphic Inline Cache

Example of cache with length 2



After Parsing

1 Function

2 Functions

>2 Functions

SLInvokeNode

function

arguments

SLUninitializedDispatch

SLInvokeNode

SLDirectDispatch

SLUninitializedDispatch

SLInvokeNode

SLDirectDispatch

SLDirectDispatch

SLUninitializedDispatch

SLInvokeNode

SLGenericDispatch

Invoke Node

```
public final class SLInvokeNode extends SLExpressionNode {

  @Child protected SLExpressionNode functionNode;
  @Children protected final SLExpressionNode[] argumentNodes;
  @Child protected SLAbstractDispatchNode dispatchNode;

  @ExplodeLoop
  public Object executeGeneric(VirtualFrame frame) {
    SLFunction function = functionNode.executeFunction(frame);

    Object[] argumentValues = new Object[argumentNodes.length];
    for (int i = 0; i < argumentNodes.length; i++) {
      argumentValues[i] = argumentNodes[i].executeGeneric(frame);
    }
    SLArguments arguments = new SLArguments(argumentValues);

    return dispatchNode.executeDispatch(frame, function, arguments);
  }
}
```

Separation of concerns: this node evaluates the function and arguments only

Uninitialized Dispatch Node

```
final class SLUninitializedDispatchNode extends SLAbstractDispatchNode {

  protected Object executeDispatch(VirtualFrame frame,
        SLFunction function, SLArguments arguments) {

    int depth = ...
    SLInvokeNode invokeNode = ...

    SLAbstractDispatchNode replacement;
    if (depth < INLINE_CACHE_SIZE) {
      SLAbstractDispatchNode next = new SLUninitializedDispatchNode();
      replacement = new SLDirectDispatchNode(next, function);
      replace(replacement);

    } else {
      replacement = new SLGenericDispatchNode();
      invokeNode.dispatchNode.replace(replacement);
    }

    return replacement.executeDispatch(frame, function, arguments);
  }
}
```

Separation of concerns: this node builds the inline cache chain

Inline Cache Node

```
final class SLDirectDispatchNode extends SLAbstractDispatchNode {

  private final SLFunction cachedFunction;
  @Child private CallNode callCachedTargetNode;
  @Child private SLAbstractDispatchNode nextNode;

  protected SLDirectDispatchNode(SLAbstractDispatchNode next,
        SLFunction cachedFunction) {
    this.cachedFunction = cachedFunction;
    this.callCachedTargetNode = adoptChild(...);
    this.nextNode = adoptChild(next);
  }

  protected Object executeDispatch(VirtualFrame frame,
        SLFunction function, SLArguments arguments) {

    if (this.cachedFunction == function) {
      return callCachedTargetNode.call(frame.pack(), arguments);
    } else {
      return nextNode.executeDispatch(frame, function, arguments);
    }
  }
}
```

Rule: the `cachedFunction` must be a `final` field

Separation of concerns: this node performs the inline cache check and optimized dispatch

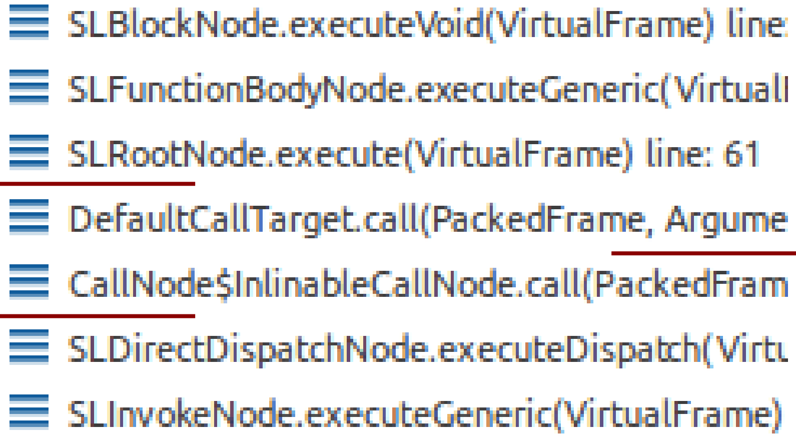
Generic Dispatch Node

```
final class SLGenericDispatchNode extends SLAbstractDispatchNode {

  protected Object executeDispatch(VirtualFrame frame,
        SLFunction function, SLArguments arguments) {

    return function.getCallTarget().call(frame.pack(), arguments);
  }
}
```

Separation of concerns: this is the always succeeding, but slow, fallback node

Example: Function Calls (1)

Stack trace of a function call



Simple Language

```
SLBlockNode.executeVoid(VirtualFrame) line
SLFunctionBodyNode.executeGeneric(Virtual
SLRootNode.execute(VirtualFrame) line: 61
```

Truffle Framework

```
DefaultCallTarget.call(PackedFrame, Argume
CallNode$InlinableCallNode.call(PackedFram
```

Callee

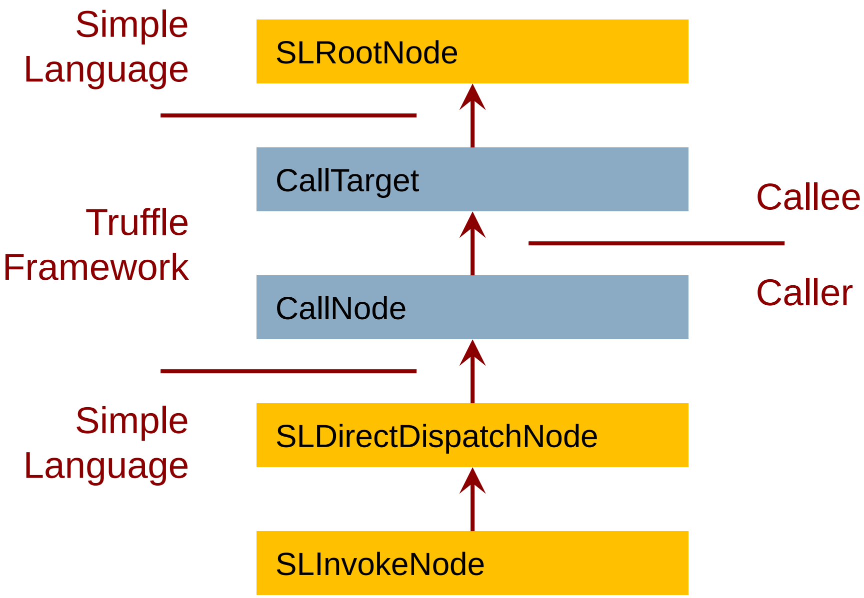
Caller

Simple Language

```
SLDirectDispatchNode.executeDispatch(Virt
SLInvokeNode.executeGeneric(VirtualFrame)
```

Truffle framework code triggers compilation, function inlining, …

Example: Function Calls (2)



Truffle framework code triggers compilation, function inlining, …

Function Arguments

- Function arguments are not type-specialized
  - Passed in `Object[]` array
- Function prologue writes them to local variables
  - `SLReadArgumentNode` in the function prologue
  - Local variable accesses are type-specialized, so only one unboxing

Example SL code:

```
function add(a, b) {
  return a + b;
}

function main() {
  add(2, 3);
}
```

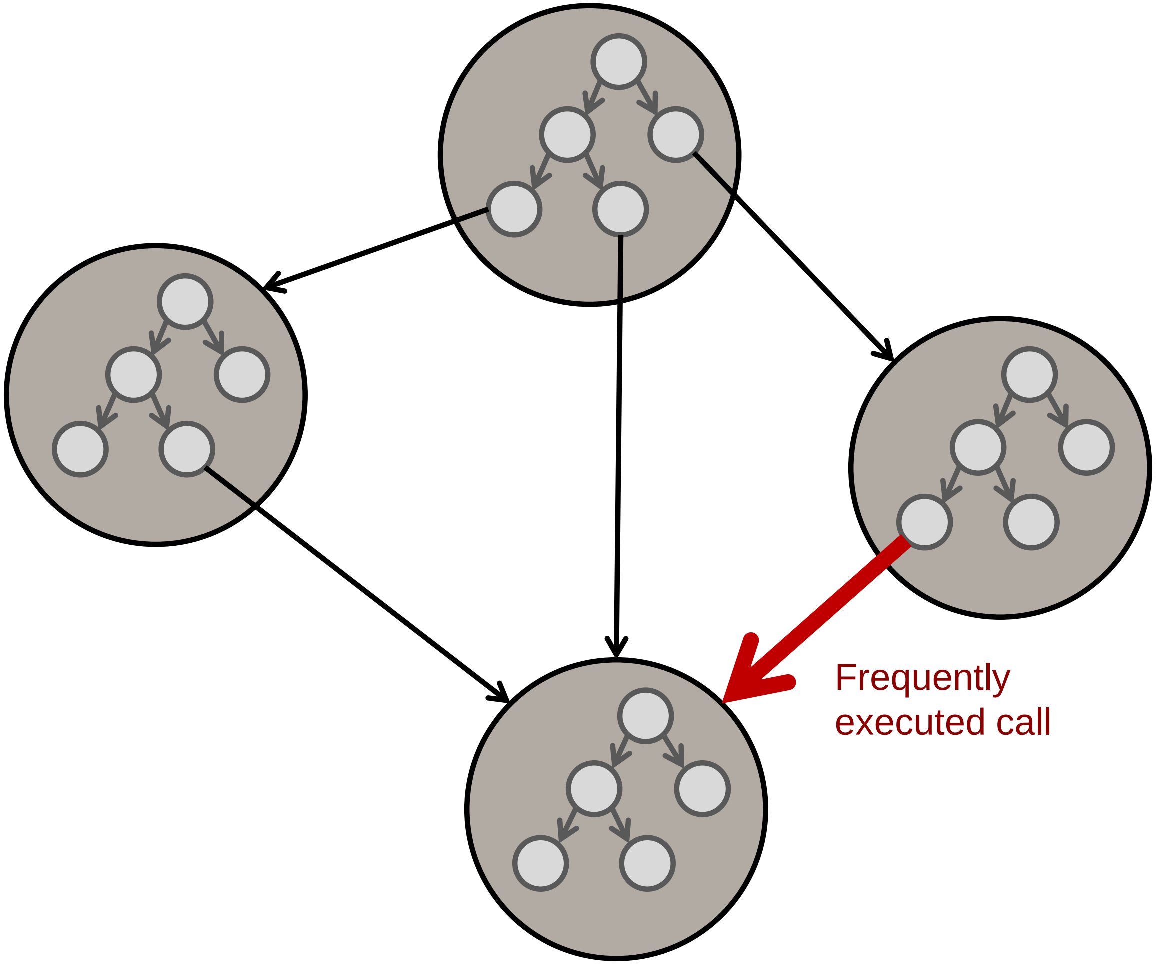
Specialized AST for function `add()`:

```
SLRootNode
  bodyNode = SLFunctionBodyNode
    bodyNode = SLBlockNode
      bodyNodes[0] = SLWriteLocalVariableLongNode(name = "a")
        valueNode = SLReadArgumentNode(index = 0)
      bodyNodes[1] = SLWriteLocalVariableLongNode(name = "b")
        valueNode = SLReadArgumentNode(index = 1)
      bodyNodes[2] = SLReturnNode
        valueNode = SLAddLongNode
          leftNode = SLReadLocalVariableLongNode(name = "a")
          rightNode = SLReadLocalVariableLongNode(name = "b")
```

Function Inlining

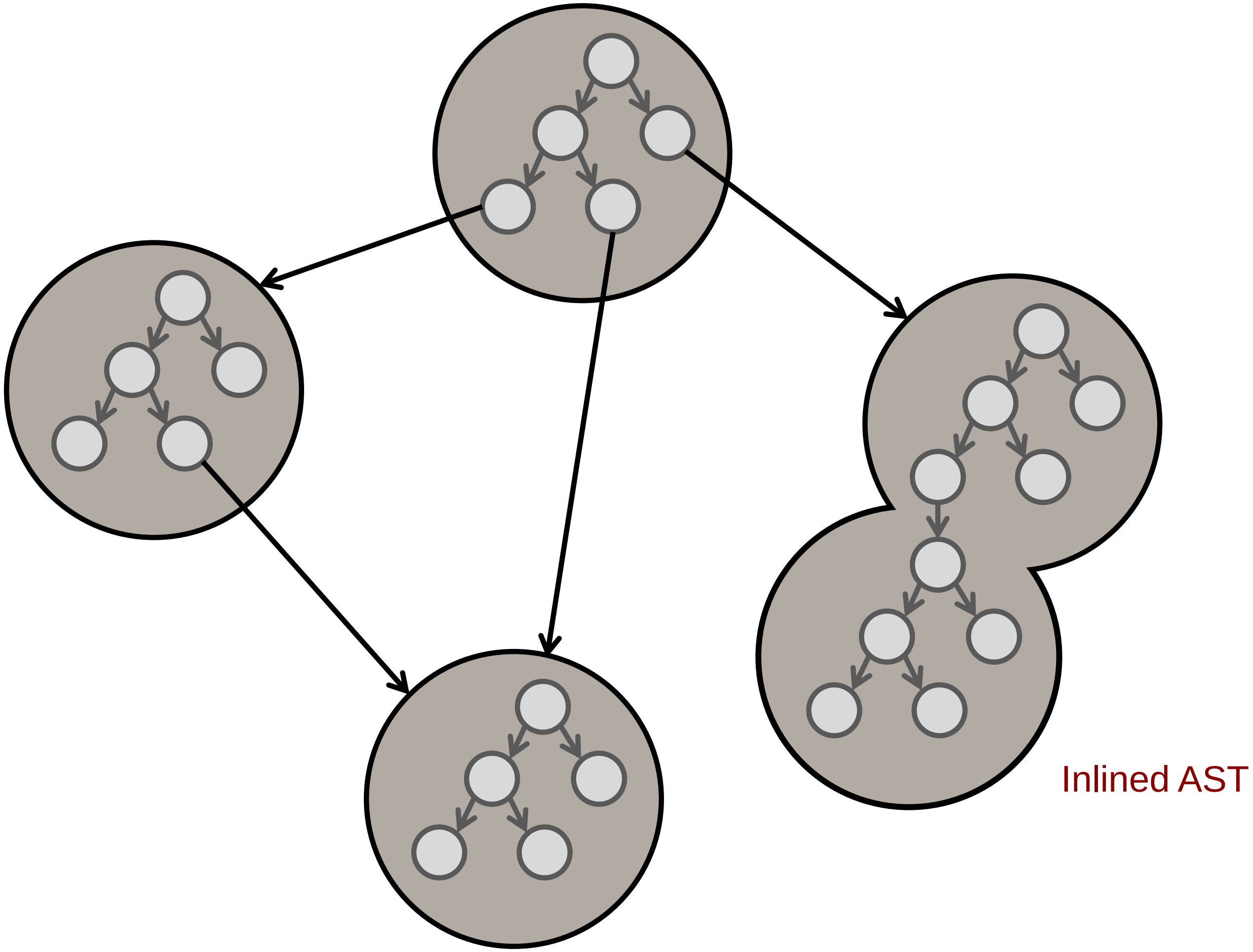
- Function inlining is one of the most important optimizations
  - Replace a call with a copy of the callee
- Function inlining in Truffle operates on the AST level
  - The whole node tree of a function is duplicated
  - Call node is replaced with the root of the duplicated tree
- Benefits
  - Inlined tree is specialized separately
    - Result: context sensitive profiling information
  - All later optimizations see the big combined tree, without further work
    - Partial evaluation operates on the inlined tree
- Language-independent inlining logic in class `CallNode`
  - `SLRootNode` overrides methods that provide the AST copy that is inlined
  - `SLRootNode` keeps copy of the uninitialized (= non-specialized) AST

Function Inlining (1)



Frequently executed call

Function Inlining (2)



Function Inlining Nodes

```
final class SLDirectDispatchNode extends SLAbstractDispatchNode {
  protected SLDirectDispatchNode(... SLFunction cachedFunction) {
    this.callCachedTargetNode = adoptChild(
        CallNode.create(cachedFunction.getCallTarget()));
    ...
  }
}
```

```
public final class SLRootNode extends RootNode {
  @Child private SLExpressionNode bodyNode;
  private final SLExpressionNode uninitializedBodyNode;

  public SLRootNode(... SLExpressionNode bodyNode) {
    this.uninitializedBodyNode = NodeUtil.cloneNode(bodyNode);
    this.bodyNode = adoptChild(bodyNode);
  }

  public RootNode inline() {
    return new SLRootNode(... NodeUtil.cloneNode(uninitializedBodyNode));
  }
  public int getInlineNodeCount() {
    return NodeUtil.countNodes(uninitializedBodyNode);
  }
  public boolean isInlinable() {
    return true;
  }
}
```

Function Inlining Example

SL source code:

```
function add(a, b) {
  return a + b;
}
function foo() {
  add(1, 2);
  add("x", "y") {
}
```

AST before function inlining:

function add() called by both calls

```
SLReturnNode
  value = SLAddGenericNode
    left = SLReadLocalVariableObjectNode
    right = SLReadLocalVariableObjectNode
```

AST after function inlining:

function add() inlined for first call

```
SLReturnNode
  value = SLAddLongNode
    left = SLReadLocalVariableLongNode
    right = SLReadLocalVariableLongNode
```

function add() inlined for second call

```
SLReturnNode
  value = SLAddStringNode
    left = SLReadLocalVariableObjectNode
    right = SLReadLocalVariableObjectNode
```

Compilation with Inlined Function

SL source code without call:

```
function loop(n) {
  i = 0;
  while (i < n) {
    i = i + 1;
  }
  return i;
}
```

SL source code with call:

```
function add(a, b) {
  return a + b;
}
function loop(n) {
  i = 0;
  while (i < n) {
    i = add(i, 1);
  }
  return i;
}
```

Machine code for loop without call:

```
     ...
     movq      rcx, 0x0
     jmp       L2:
L1:  safepoint
     mov       rsi, rcx
     addq      rsi, 0x1
     jo        L3:
     mov       rcx, rsi
L2:  cmp       rax, rcx
     jnle      L1:
     ...
L3:  call      deoptimize
```

Machine code for loop with inlined call:

```
     ...
     movq      rcx, 0x0
     jmp       L2:
L1:  safepoint
     mov       rsi, rcx
     addq      rsi, 0x1
     jo        L3:
     mov       rcx, rsi
L2:  cmp       rax, rcx
     jnle      L1:
     ...
L3:  call      deoptimize
```

Compilation API

Truffle Compilation API

- Default behavior of compilation: Inline all reachable Java methods
- Truffle API provides class `CompilerDirectives` to influence compilation
  - `@CompilationFinal`
    - Treat a field as `final` during compilation
  - `transferToInterpreter()`
    - Never compile part of a Java method
  - `transferToInterpreterAndInvalidate()`
    - Invalidate machine code when reached
    - Implicitly done by `Node.replace()`
  - `@SlowPath`
    - Hint that this method is not important for performance, i.e., hint to not inline it
  - `inInterpreter()`
    - For profiling code that runs only in the interpreter
  - `Assumption`
    - Invalidate machine code from outside
    - Avoid checking a condition over and over in compiled code

Guards

```
public final class BranchProfile {

  @CompilationFinal private boolean visited;

  public void enter() {
    if (!visited) {
      CompilerDirectives.transferToInterpreterAndInvalidate();
      visited = true;
    }
  }
}
```

`transferToInterpreter*()` does nothing when running in interpreter

```
public final class SLIfNode extends SLStatementNode {
  private final BranchProfile thenTaken = new BranchProfile();
  private final BranchProfile elseTaken = new BranchProfile();

  public void executeVoid(VirtualFrame frame) {
    if (conditionNode.executeBoolean(frame)) {
      thenTaken.enter();
      thenPartNode.executeVoid(frame);
    } else {
      elseTaken.enter();
      elsePartNode.executeVoid(frame);
    }
  }
}
```

Best practice: Profiling in the interpreter allows the compiler to generate better code

Slow Path Annotation

```
public abstract class SLPrintlnBuiltin extends SLBuiltinNode {

  @Specialization
  public final Object println(Object value) {
    doPrint(getContext().getOutput(), value);
    return value;
  }

  @SlowPath
  private static void doPrint(PrintStream out, Object value) {
    out.println(value);
  }
}
```

When compiling, the output stream is a constant

Why `@SlowPath`? Inlining something as big as `println()` would lead to code explosion

Function Redefinition (1)

- Problem
  - In SL, functions can be redefined at any time
  - This invalidates optimized call dispatch, and function inlining
  - Checking for redefinition before each call would be a huge overhead
- Solution
  - Every `SLFunction` has an `Assumption`
  - `Assumption` is invalidated when the function is redefined
    - This invalidates optimized machine code
- Result
  - No overhead when calling a function

Assumptions

Create an assumption:

```
Assumption assumption = Truffle.getRuntime().createAssumption();
```

Check an assumption:

```
void foo() {
  assumption.check();
  // Some code that is only valid if assumption is true.
}
```

Respond to an invalidated assumption:

```
void bar() {
  try {
    foo();
  } catch (InvalidAssumptionException ex) {
    // Perform node rewriting, or other slow-path code to respond to change.
  }
}
```

Invalidate an assumption:

```
assumption.invalidate();
```

Function Redefinition (2)

```
public abstract class SLDefineFunctionBuiltin extends SLBuiltinNode {

  @Specialization
  public final String defineFunction(String code) {
    doDefineFunction(getContext(), code);
    return code;
  }

  @SlowPath
  private static void doDefineFunction(SLContext context, String code) {
    Source source = context.getSourceManager().get("[defineFunction]", code);
    Parser.parseSL(context, source);
  }
}
```

Why `@SlowPath`? Inlining something as big as the parser would lead to code explosion

SL semantics: Functions can be defined and redefined at any time

Function Redefinition (3)

```
public final class SLFunction {

  private RootCallTarget callTarget;
  private Assumption callTargetStable;

  protected void setCallTarget(RootCallTarget callTarget) {
    this.callTarget = callTarget;

    if (callTargetStable != null) {
      callTargetStable.invalidate();
    }
    callTargetStable = Truffle.getRuntime().createAssumption(name);
  }

  public RootCallTarget getCallTarget() {
    return callTarget;
  }

  public Assumption getCallTargetStable() {
    return callTargetStable;
  }
}
```

The utility class `CyclicAssumption` simplifies this code

Function Redefinition (4)

```
final class SLDirectDispatchNode extends SLAbstractDispatchNode {

  private final SLFunction cachedFunction;
  @Child private CallNode callCachedTargetNode;
  private final Assumption cachedTargetStable;

  protected SLDirectDispatchNode(... SLFunction cachedFunction) {
    this.cachedFunction = cachedFunction;
    this.callCachedTargetNode = adoptChild(...);
    this.cachedTargetStable = cachedFunction.getCallTargetStable();
  }

  protected Object executeDispatch(VirtualFrame frame,
        SLFunction function, SLArguments arguments) {
    if (this.cachedFunction == function) {
      try {
        cachedTargetStable.check();
        return callCachedTargetNode.call(frame.pack(), arguments);

      } catch (InvalidAssumptionException ex) {
        replace(nextNode);
      }
    }
    return nextNode.executeDispatch(frame, function, arguments);
  }
}
```

No compiled code for check()

Exception handler is not compiled

Loop Count Profiling

```java
public final class SLWhileNode extends SLStatementNode {
  @Child private SLExpressionNode conditionNode;
  @Child private SLStatementNode bodyNode;
  private final BranchProfile continueTaken = new BranchProfile();
  private final BranchProfile breakTaken = new BranchProfile();

  public void executeVoid(VirtualFrame frame) {
    int count = 0;
    try {
      while (conditionNode.executeBoolean(frame)) {
        try {
          bodyNode.executeVoid(frame);
          if (CompilerDirectives.inInterpreter()) {
            count++;
          }
        } catch (SLContinueException ex) {
          continueTaken.enter();
        }
      }
    } catch (SLBreakException ex) {
      breakTaken.enter();
    } finally {
      if (CompilerDirectives.inInterpreter()) {
        getRootNode().reportLoopCount(count);
      }
    }
  }
}
```

Best practice: Profiling in the interpreter allows the compiler to generate better code

Compilation and function inlining heuristics of Truffle use the loop count

Compiler Assertions

- You work hard to help the compiler
- How do you check that you succeeded?

- `CompilerAsserts.compilationConstant()`
  - Checks that the passed in value is a compile-time constant
  - Compiler fails with a compilation error if the value is not a constant
  - When the assertion holds, no code is generated to produce the value

- `CompilerAsserts.neverPartOfCompilation()`
  - Checks that this code is never reached in a compiled method
  - Compiler fails with a compilation error if code is reachable
  - Useful at the beginning of helper methods that are big or rewrite nodes
  - All code dominated by the assertion is never compiled

- Assertions are checked after aggressive compiler optimizations
  - Method inlining, constant folding, dead code elimination, escape analysis, …

Trace the Compilation (1)

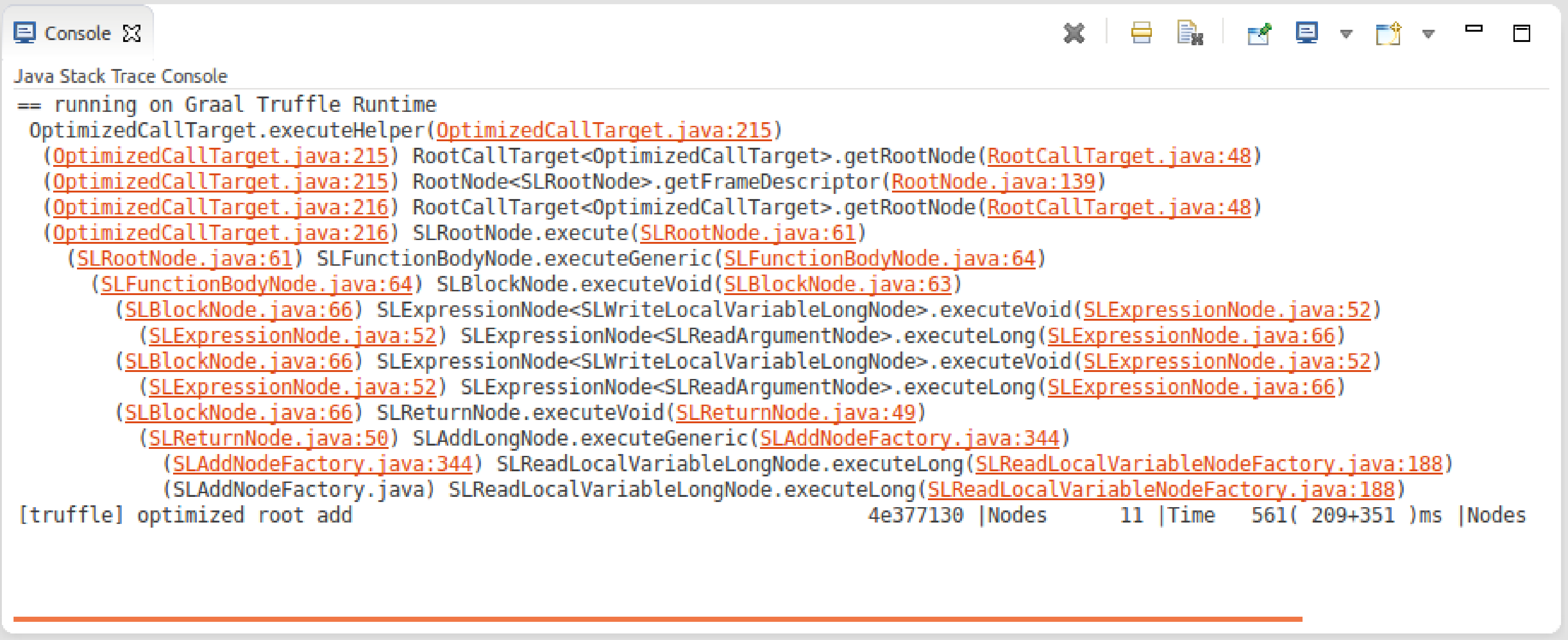
```
./mx.sh sl -G:-TruffleBackgroundCompilation -G:+TraceTruffleExpansion
graal/com.oracle.truffle.sl.test/tests/LoopCall.sl
```

```
== running on Graal Truffle Runtime
 OptimizedCallTarget.executeHelper
   RootCallTarget<OptimizedCallTarget>.getRootNode
   RootNode<SLRootNode>.getFrameDescriptor
   RootCallTarget<OptimizedCallTarget>.getRootNode
   SLRootNode.execute
     SLFunctionBodyNode.executeGeneric
       SLBlockNode.executeVoid
         SLExpressionNode<SLWriteLocalVariableLongNode>.executeVoid
           SLExpressionNode<SLReadArgumentNode>.executeLong
         SLExpressionNode<SLWriteLocalVariableLongNode>.executeVoid
           SLExpressionNode<SLReadArgumentNode>.executeLong
         SLReturnNode.executeVoid
           SLAddLongNode.executeGeneric
             SLReadLocalVariableLongNode.executeLong
             SLReadLocalVariableLongNode.executeLong
[truffle] optimized root add
77533eef |Nodes      11 |Time   529( 289+240 )ms |Nodes    34/  130 |CodeSize 456
```

Useful to start finding performance problems, if you do not really have a clue what is wrong. You can then look at the tree, method by method, see what code is expanded, and optimize it with that information.

Trace the Compilation (2)

```
./mx.sh sl -G:-TruffleBackgroundCompilation -G:+TraceTruffleExpansion
-G:+TraceTruffleExpansionSource graal/com.oracle.truffle.sl.test/tests/LoopCall.sl
```



Java Stack Trace Console

```
== running on Graal Truffle Runtime
 OptimizedCallTarget.executeHelper(OptimizedCallTarget.java:215)
  (OptimizedCallTarget.java:215) RootCallTarget<OptimizedCallTarget>.getRootNode(RootCallTarget.java:48)
  (OptimizedCallTarget.java:215) RootNode<SLRootNode>.getFrameDescriptor(RootNode.java:139)
  (OptimizedCallTarget.java:216) RootCallTarget<OptimizedCallTarget>.getRootNode(RootCallTarget.java:48)
  (OptimizedCallTarget.java:216) SLRootNode.execute(SLRootNode.java:61)
    (SLRootNode.java:61) SLFunctionBodyNode.executeGeneric(SLFunctionBodyNode.java:64)
      (SLFunctionBodyNode.java:64) SLBlockNode.executeVoid(SLBlockNode.java:63)
        (SLBlockNode.java:66) SLExpressionNode<SLWriteLocalVariableLongNode>.executeVoid(SLExpressionNode.java:52)
          (SLExpressionNode.java:52) SLExpressionNode<SLReadArgumentNode>.executeLong(SLExpressionNode.java:66)
        (SLBlockNode.java:66) SLExpressionNode<SLWriteLocalVariableLongNode>.executeVoid(SLExpressionNode.java:52)
          (SLExpressionNode.java:52) SLExpressionNode<SLReadArgumentNode>.executeLong(SLExpressionNode.java:66)
        (SLBlockNode.java:66) SLReturnNode.executeVoid(SLReturnNode.java:49)
          (SLReturnNode.java:50) SLAddLongNode.executeGeneric(SLAddNodeFactory.java:344)
            (SLAddNodeFactory.java:344) SLReadLocalVariableLongNode.executeLong(SLReadLocalVariableNodeFactory.java:188)
            (SLAddNodeFactory.java) SLReadLocalVariableLongNode.executeLong(SLReadLocalVariableNodeFactory.java:188)
[truffle] optimized root add                                           4e377130 |Nodes      11 |Time   561( 209+351 )ms |Nodes
```

Makes the output "clickable" in the Eclipse Console view

Print the Function Inlining Tree

```
./mx.sh sl -G:-TruffleBackgroundCompilation -G:+TraceTruffleInliningTree
graal/com.oracle.truffle.sl.test/tests/Inlining.sl
```

```
== running on Graal Truffle Runtime
Inlining tree for: root g
root d
   root c
      root b
         root a
root e
   root c
      root b
         root a
root f
   root c
      root b
         root a
[truffle] optimized root g
60412166 |Nodes      92 |Time   105( 102+3   )ms |Nodes     8/    3 |CodeSize 64
```

Print CallTarget Profile

```
./mx.sh sl -G:-TruffleBackgroundCompilation -G:+TruffleCallTargetProfiling
graal/com.oracle.truffle.sl.test/tests/Inlining.sl
```

```
Call Target     | Call Count | Calls Sites Inlined / Not Inlined | Node Count | Inv
root g          |       2200 |               12 |                0 |         92 |   0
root f          |       1300 |                3 |                0 |         25 |   0
root e          |       1300 |                3 |                0 |         25 |   0
root c          |       1200 |                2 |                0 |         18 |   0
root b          |       1100 |                1 |                0 |         11 |   0
root a          |       1000 |                0 |                0 |          4 |   0
root d          |        999 |                0 |                1 |          8 |   0 int
root main       |          1 |                0 |                1 |         26 |   0 int
Total           |       9100 |               21 |                2 |        209 |   0
```

Print Histogram of Nodes

```
./mx.sh sl -G:-TruffleBackgroundCompilation -G:+TraceTruffleCompilationDetails
graal/com.oracle.truffle.sl.test/tests/Inlining.sl
```

```
Expanded Truffle Nodes has 11 unique elements and 99 total elements:
--------------------------------------------------------------------------------------------------------------------------------------------------
| SLRootNode                 | 13         | ==================================================================================================== |
| SLFunctionBodyNode         | 13         | ==================================================================================================== |
| SLReturnNode               | 13         | ==================================================================================================== |
| SLInvokeNode               | 12         | ============================================================================================         |
| InlinedCallNode            | 12         | ============================================================================================         |
| SLFunctionLiteralNode      | 12         | ============================================================================================         |
| SLDirectDispatchNode       | 12         | ============================================================================================         |
| OptimizedAssumption        | 6          | ==============================================                                                       |
| SLLongLiteralNode          | 3          | =======================                                                                              |
| SLAddLongNode              | 2          | ===============                                                                                      |
| OptimizedCallTarget        | 1          | =======                                                                                              |
--------------------------------------------------------------------------------------------------------------------------------------------------
[truffle] optimized root g                                             69e85433 |Nodes      92 |Time   129( 125+4   )ms |Nodes     8/    3 |CodeSize 64
```

Truffle Mindset

- Do not optimize interpreter performance
  - Only optimize compiled code performance
- Collect profiling information in interpreter
  - Yes, it makes the interpreter slower
  - But it makes your compiled code faster
- Do not specialize nodes in the parser, e.g., via static analysis
  - Trust the specialization at run time
- Keep node implementations small and simple
  - Split complex control flow into multiple nodes, use node rewriting
- Use `final` fields
  - Compiler can aggressively optimize them
  - Example: An `if` on a `final` field is optimized away by the compiler
  - Try using `@CompilationFinal` if the Java `final` is too restrictive
- Use microbenchmarks to assess and track performance of specializations
  - Ensure and assert that you end up in the expected specialization

Truffle Mindset: Frames

- Use `VirtualFrame`, and ensure it does not escape
  - Sometimes, you get strangely looking error messages about escaping frames
  - Graal must be able to inline all methods that get the `VirtualFrame` parameter
    - Call must be statically bound during compilation
    - Calls to `static` or `private` methods are always statically bound
    - Virtual calls and interface calls work if either
      - The receiver has a known exact type, e.g., comes from a `final` field
      - The method is not overridden in a subclass
- Important rules on passing around a `VirtualFrame`
  - Never assign it to a field
  - Never pass it to a recursive method
    - Graal cannot inline a call to a recursive method
- Use a `MaterializedFrame` if a `VirtualFrame` is too restrictive
  - But keep in mind that access is probably slower

Object Layout

Object Layout

- SL has no dynamically allocated objects
- But most other languages do…

- Problem when implementing a dynamic programming language
  - Java does not allow objects to grow
  - How to support adding properties to an object dynamically?

- Non-solution
  - Use `java.util.HashMap`
  - High memory overhead, slow access, no specialization possible

- Solution
  - Define a Java class with a few primitive and object fields
  - Extension array if the few inline fields are not sufficient

  - Use shapes (also called hidden classes) to map property names to indices
  - Use polymorphic inline caches to optimize access

Dynamic Object

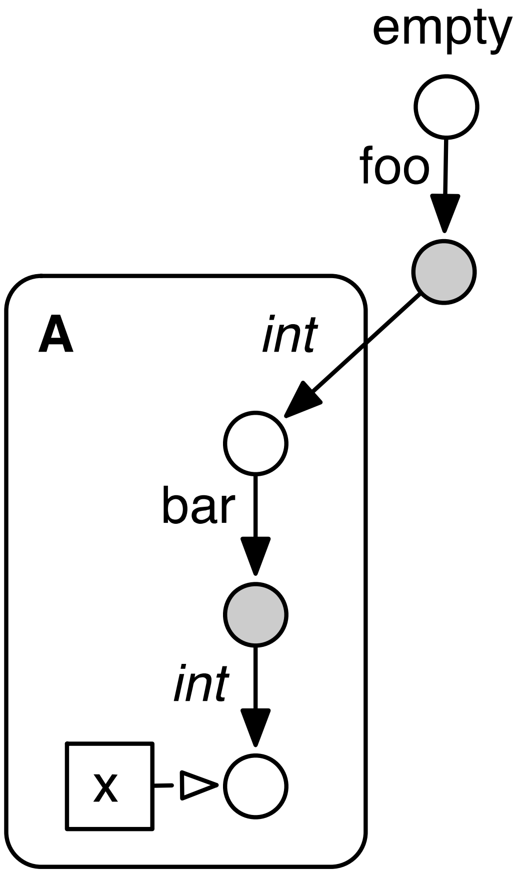
```
public class YourLanguageOject {

  ObjectLayout objectLayout;

  long primitiveStorageLocation1;
  ...
  long primitiveStorageLocationN;

  Object objectStorageLocation1;
  ...
  Object objectStorageLocationN;

  long[] primitiveStorageExtension; // Allocated only when necessary.
  Object[] objectStorageExtension;  // Allocated only when necessary.
}
```

Most guest language objects require only one Java object

```
public class ObjectLayout {

  ObjectLayout parent;

  String propertyName;
  Type propertyType;
  int propertyIndex;
}
```

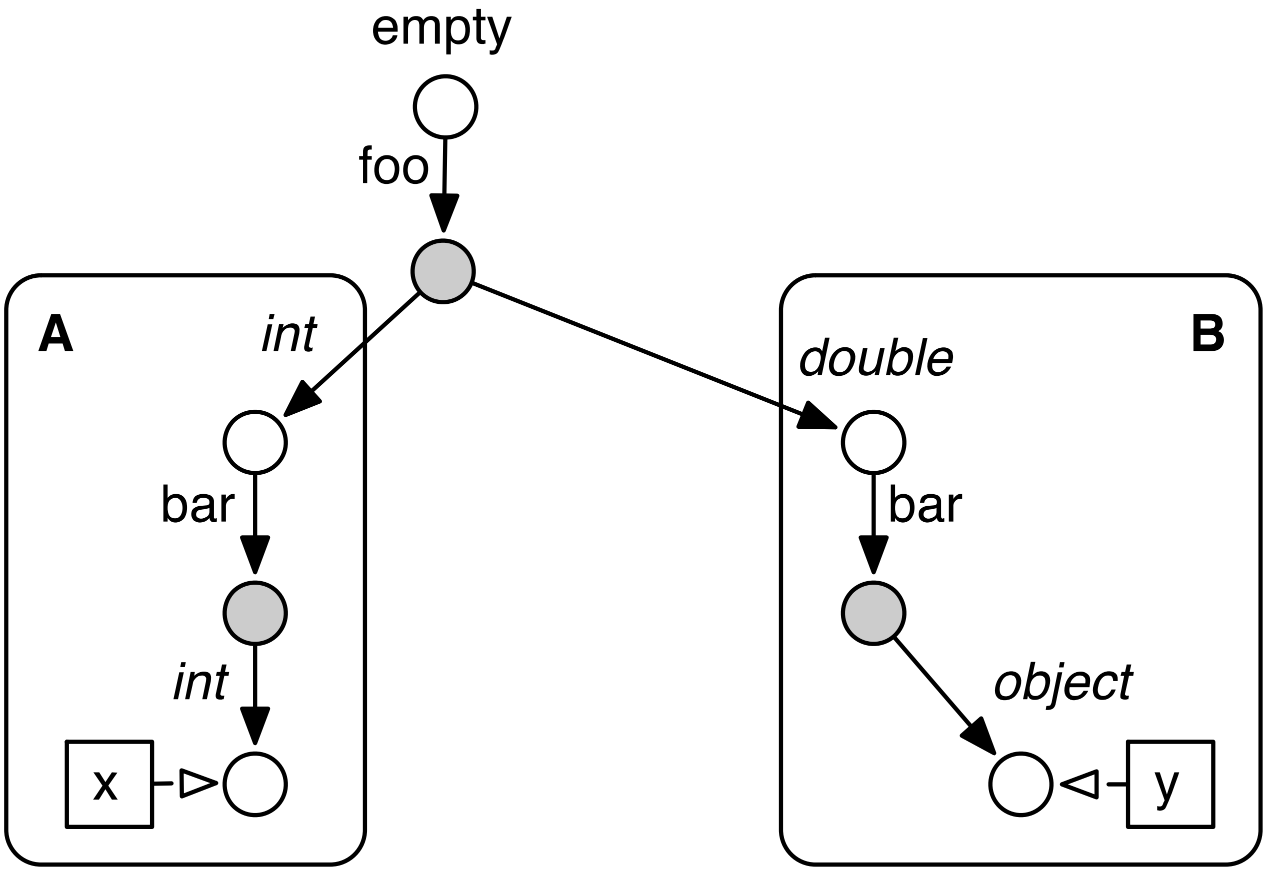
Object Layout Transitions (1)

```
var x = {};
x.foo = 0;
x.bar = 0;
// + subtree A
```



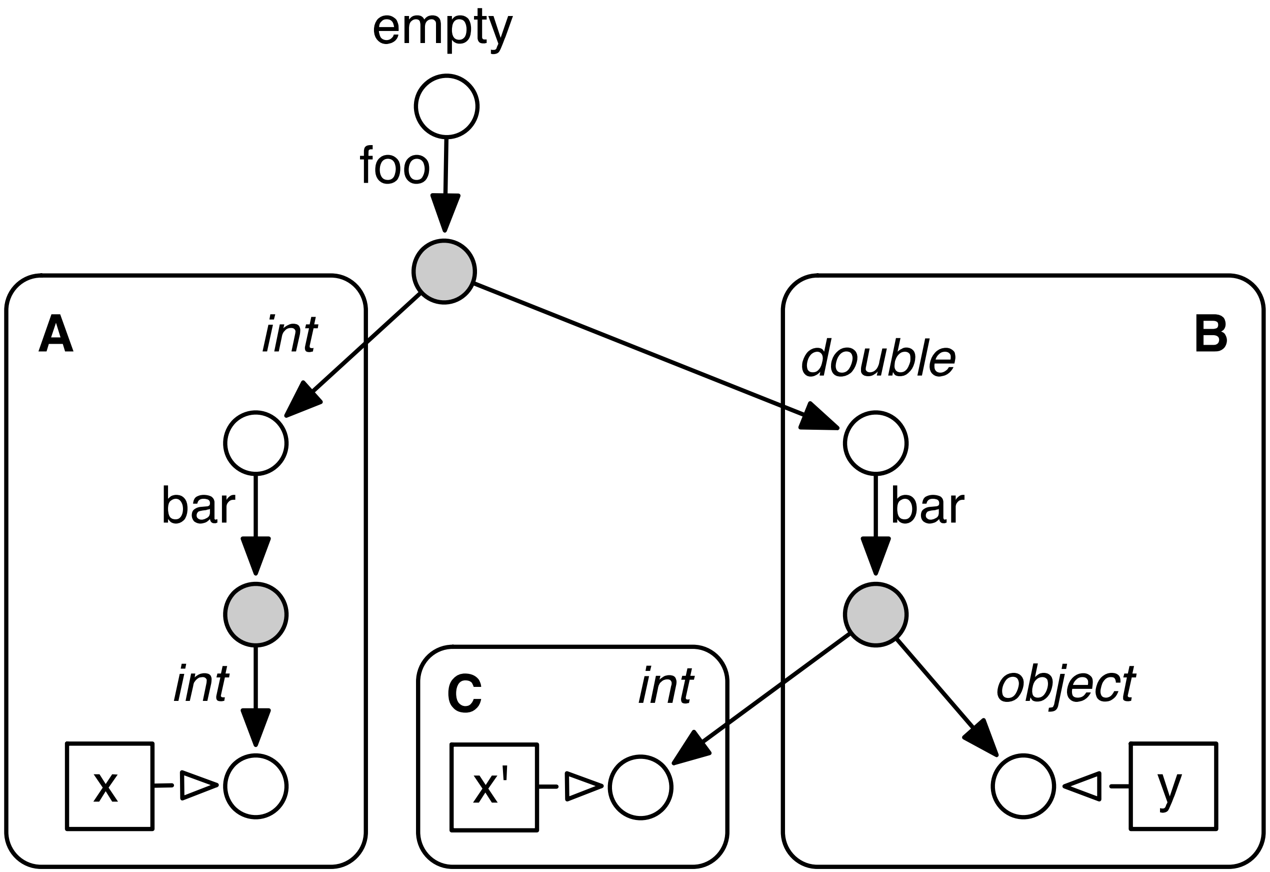
Object Layout Transitions (2)

```
var x = {};
x.foo = 0;
x.bar = 0;
// + subtree A

var y = {};
y.foo = 0.5;
y.bar = "foo";
// + subtree B
```



Object Layout Transitions (3)

```
var x = {};
x.foo = 0;
x.bar = 0;
// + subtree A

var y = {};
y.foo = 0.5;
y.bar = "foo";
// + subtree B

x.foo += 0.2
// + subtree C
```



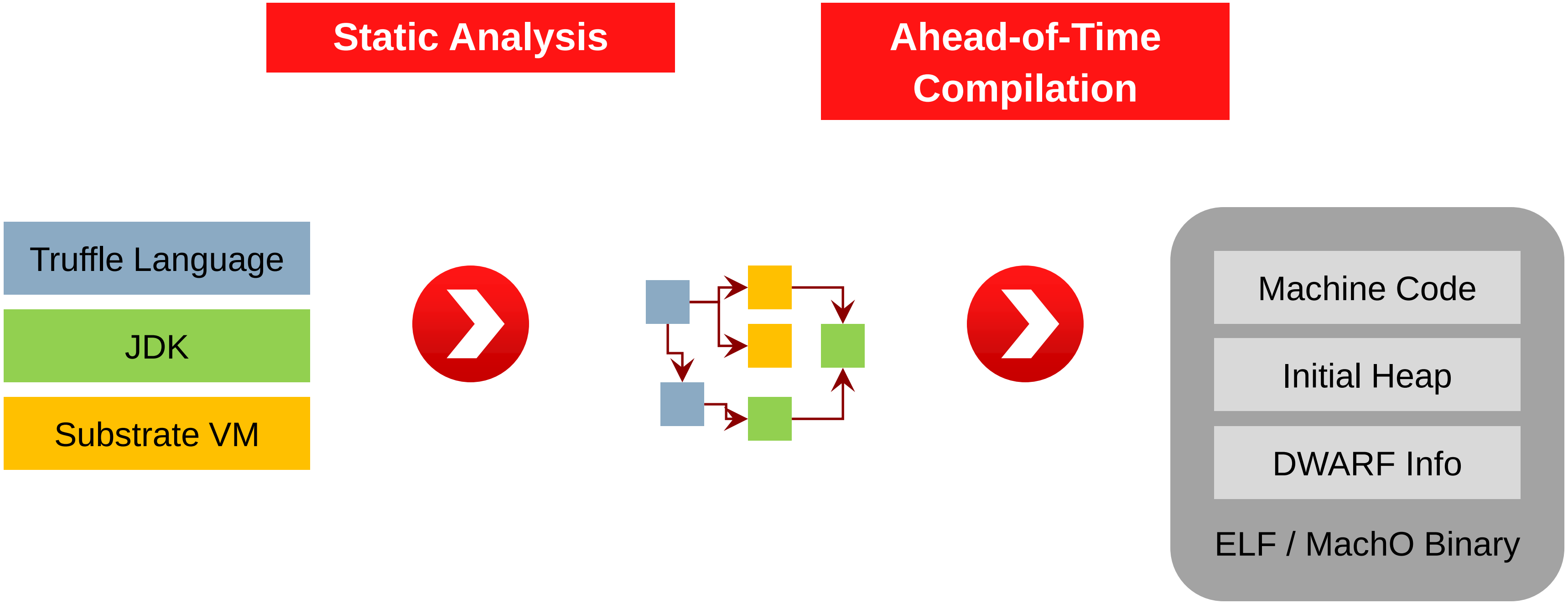
Substrate VM

Substrate VM

- Goal
  - Run Truffle languages without the overhead of a Java VM

- Approach
  - Ahead-of-time compile the Java bytecodes to machine code
  - Build standard Linux / MacOS executable

Substrate VM Execution Model



Static Analysis

Ahead-of-Time Compilation

Truffle Language

JDK

Substrate VM

Machine Code

Initial Heap

DWARF Info

ELF / MachO Binary

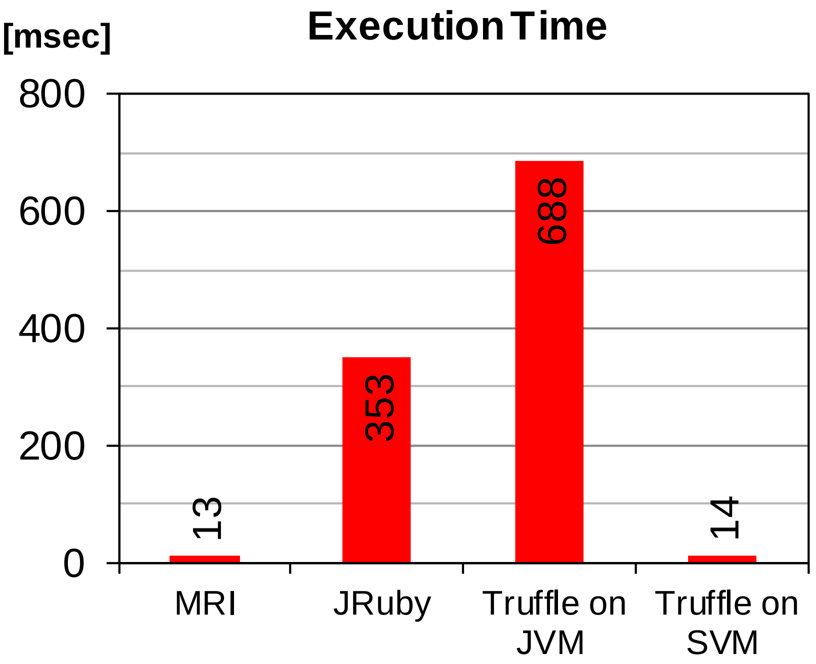
All Java classes from Truffle language (or any application), JDK, and Substrate VM

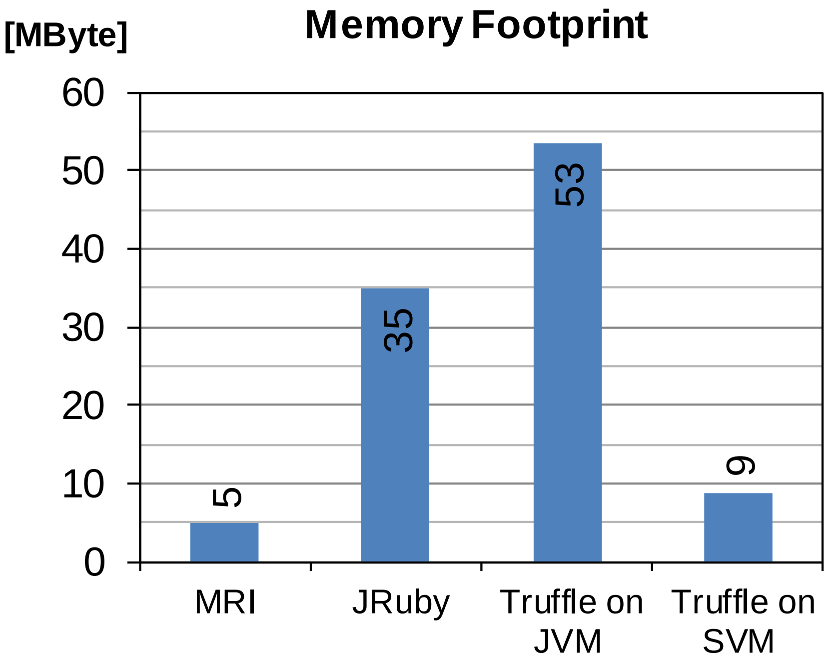
Reachable methods, fields, and classes

Application running without compilation or Java class loading

Startup Performance

Running Ruby "Hello World"





Execution time: `time -f "%e"`

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

Debugging Tools

“Write Your Own Language and Debugger”

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

People want supporting tools

Write a debugger (really?)
Use *printf* (most likely)

How it should be

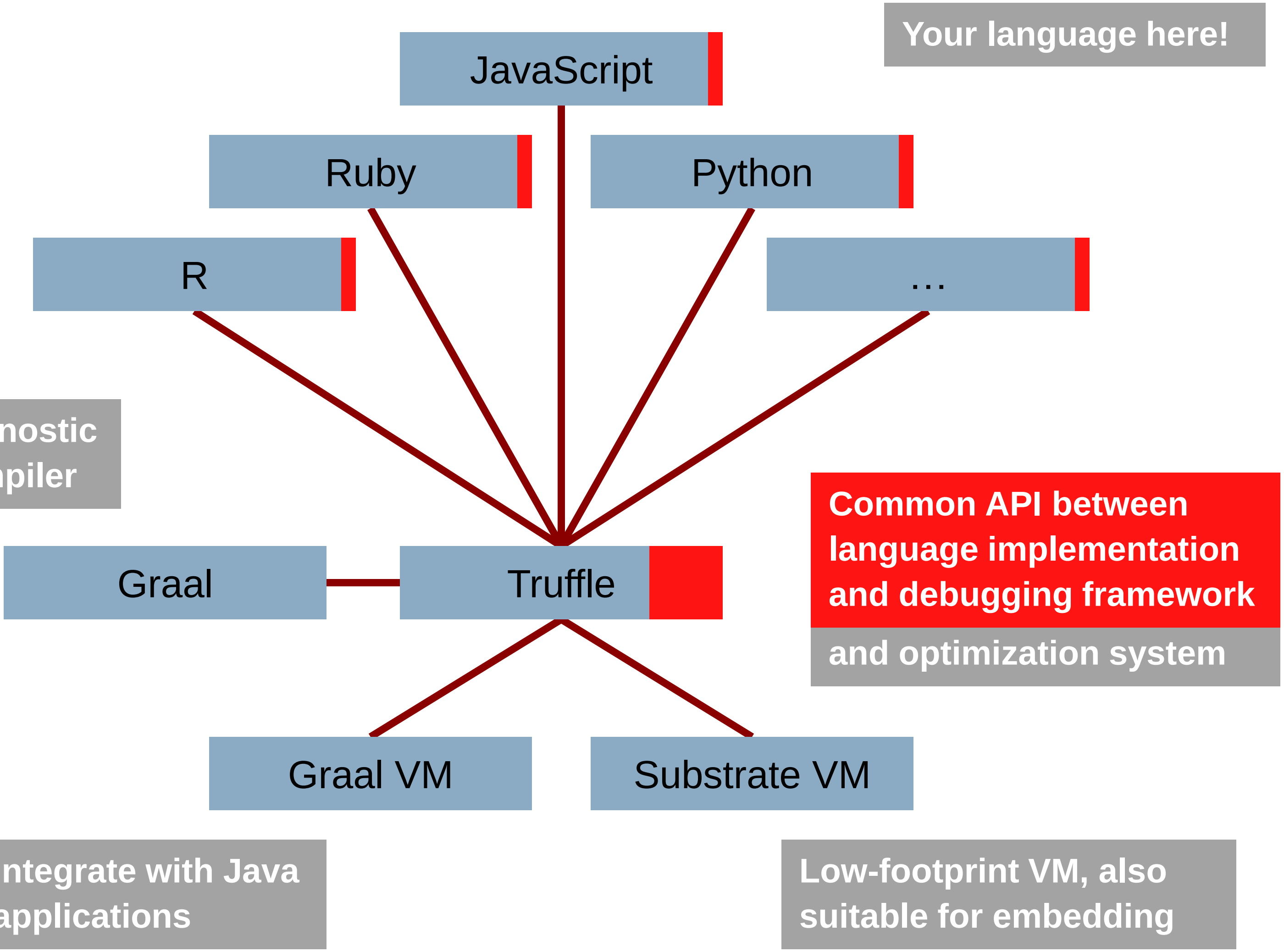
Prototype a new language in Java

Parser and language work to build syntax tree (AST)
Execute using AST interpreter

People start using it

And it is already fast
And it has a debugger

System Structure **Extended for Debugging**



Your language here!

JavaScript

Ruby

Python

R

…

Language agnostic dynamic compiler

Graal

Truffle

Common API between language implementation and debugging framework

and optimization system

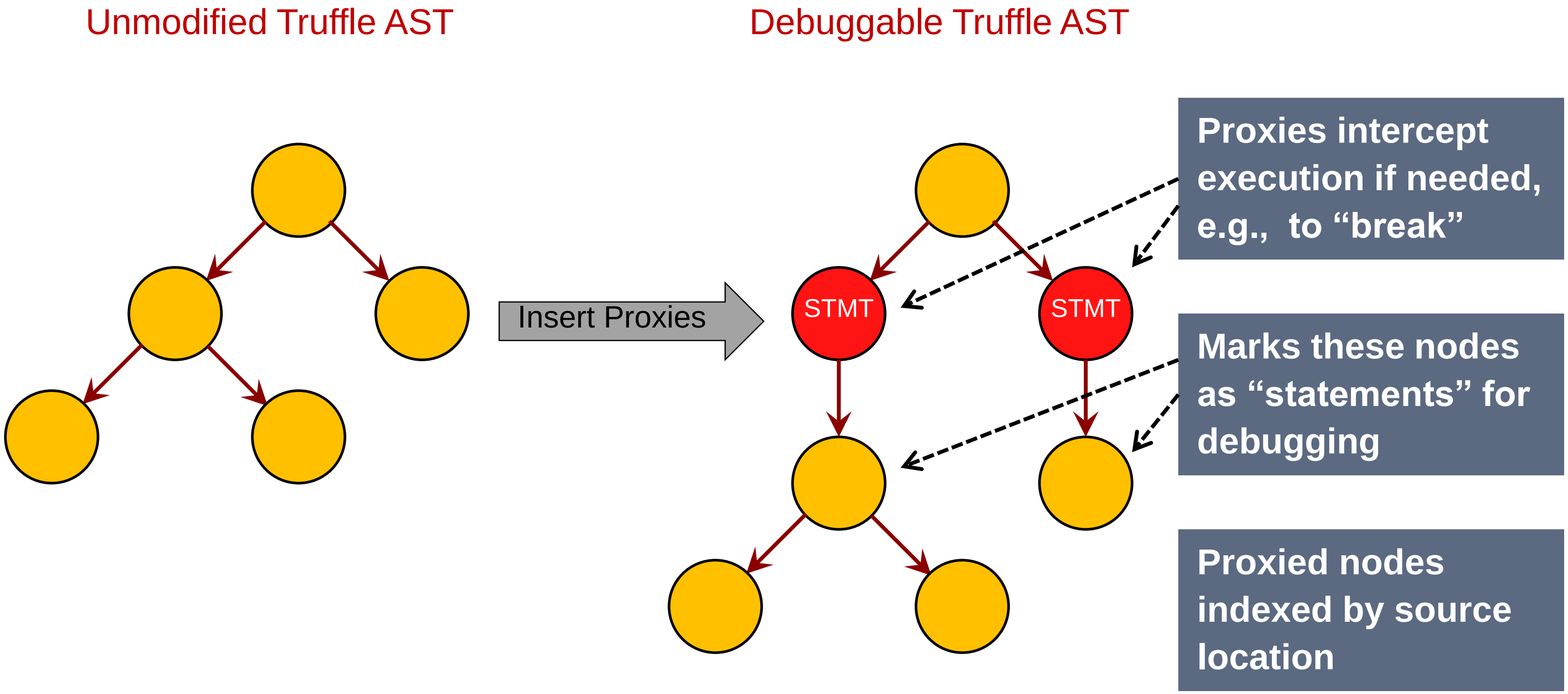
Graal VM

Substrate VM

Integrate with Java applications

Low-footprint VM, also suitable for embedding

Proxy Nodes as Evaluation “Hooks”



Proxies intercept execution if needed, e.g., to “break”

Marks these nodes as “statements” for debugging

Proxied nodes indexed by source location

The language implementer:

- Decides which nodes to proxy
- Tags nodes with desired debugging behavior
- Adds other language-specific behavior as needed

Proxy Nodes

- Debugging Proxies are
  - Legitimate Truffle AST nodes
  - Transparent to execution semantics of program
    - Default behavior is to pass through all invocations
  - Independent of other platform services (mostly)
  - Compiled to no-ops when not active
  - Compiled into fast-path when active
    - Useful for breakpoint conditions in long-running code
  - Reconstructed through deoptimization, simplifying user interaction
  - A generalization of the approach used for the Self Debugger[†]
    - Set a breakpoint by modifying program, then reoptimize

[†] Urs Hölzle, Craig Chambers, and David Ungar. 1992. Debugging optimized code with dynamic deoptimization. In *Proceedings of the ACM SIGPLAN 1992 conference on Programming language design and implementation (PLDI '92)*

Summary

Your Language?

http://openjdk.java.net/projects/graal/

graal-dev@openjdk.java.net

```
$ hg clone http://hg.openjdk.java.net/graal/graal
$ cd graal
$ ./mx --vm server build
$ ./mx ideinit
$ ./mx --vm server sl
```

- Truffle API Resources

  https://wiki.openjdk.java.net/display/Graal/Truffle+FAQ+and+Guidelines

- Truffle API License: GPLv2 with Classpath Exception

Hardware and Software

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