Truffle/Graal:
From Interpreters to Optimizing Compilers via Partial Evaluation

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17-396/17-696/17-960: Language Design and Prototyping

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Many slides from Oracle's PLDI 2016 and 2017 tutorials on Truffle/Graal—marked where they occur.

Interpreters for Prototyping

- Writing optimizing compilers is hard
  - Many complex optimization algorithms
  - Relies on knowledge of architecture and performance characteristics
  - See 15-411/15-611, 15-745
- So when we prototype with interpreters
  - Easy to write
  - Easy to change when the language changes
- Unfortunately, interpreters are slow
  - Especially if you make them simple!
  - Could be 2 orders of magnitude slower than an optimizing compiler
  - Is there any way to make an interpreter faster?

From Interpreter to Compiler

- Given
  - An interpreter for guest language G written in host language H
    - "if you see an add expression, add the two arguments"
  - A program in language G
    - "add(add(x, y), z)"
- What if we "run" the interpreter on the program?
  - Whenever we get to actual input data, we'll stop evaluating there (but keep going elsewhere)
  - "add(add(x, y), z)" → x+y+z
  - We have essentially "compiled" the language
- This is called Partial Evaluation
  - When applied in the context of interpreters and programs, it's called the First Futamura Projection (after Futamura, who proposed it in 1971)

Example: Partial Evaluation

```
class ExampleNode {
  @CompilationFinal boolean flag;

  int foo() {
    if (this.flag) {
      return 42;
    } else {
      return -1;
    }
  }
}
```

normal compilation
of method `foo()`

```
     // parameter this in rsi
     cmpb [rsi + 16], 0
     jz   L1
     mov  eax, 42
     ret
L1:  mov  eax, -1
     ret
```

Object value of `this`

```
ExampleNode
flag: true
```

partial evaluation
of method `foo()`
with known parameter `this`

```
     mov  rax, 42
     ret
```

Memory access is eliminated and condition is constant folded during partial evaluation

`@CompilationFinal` field is treated like a `final` field during partial evaluation

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Introduction to Partial Evaluation

```
abstract class Node {
    abstract int execute(int[] args);
}

class AddNode extends Node {
    final Node left, right;

    AddNode(Node left, Node right) {
        this.left = right; this.right = right;
    }

    int execute(int args[]) {
        return left.execute(args) + right.execute(args);
    }
}
```

```
class Arg extends Node {
    final int index;
    Arg(int i) {this.index = i;}

    int execute(int[] args) {
        return args[index];
    }
}
```

```
int interpret(Node node, int[] args) {
    return node.execute(args);
}
```

```
// Sample program (arg[0] + arg[1]) + arg[2]
sample = new Add(new Add(new Arg(0), new Arg(1)), new Arg(2));
```

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Introduction to Partial Evaluation

```
// Sample program (arg[0] + arg[1]) + arg[2]
sample = new Add(new Add(new Arg(0), new Arg(1)), new Arg(2));
```

```
int interpret(Node node, int[] args) {
    return node.execute(args);
}
```

```
partiallyEvaluate(interpret, sample)
```

```
int interpretSample(int[] args) {
    return sample.execute(args);
}
```

Introduction to Partial Evaluation

```
// Sample program (arg[0] + arg[1]) + arg[2]
sample = new Add(new Add(new Arg(0), new Arg(1)), new Arg(2));
```

```
int interpretSample(int[] args) {
    return sample.execute(args);
}
```

```
int interpretSample(int[] args) {
    return sample.left.execute(args)
         + sample.right.execute(args);
}
```

```
int interpretSample(int[] args) {
    return sample.left.left.execute(args)
         + sample.left.right.execute(args)
         + args[sample.right.index];
}
```

```
int interpretSample(int[] args) {
    return args[sample.left.left.index]
         + args[sample.left.right.index]
         + args[sample.right.index];
}
```

```
int interpretSample(int[] args) {
    return args[0]
         + args[1]
         + args[2];
}
```

Challenge: how to get high-performance code? (1)

- With naïve Futamura projection / partial evaluation, code size explodes
- Real implementation of "+" in a dynamic language is something like:

```
if (arg1 instanceof Int && arg2 instanceof Int)
        return arg1+arg2;
else if (arg1 instanceof String || arg2 instanceof String)
        return strcat(toString(arg1), toString(arg2)
else
        throw addError
```

- This is a lot of code to generate every time we see a + operator

Challenge: how to get high-performance code? (2)

- Alternative: don't partially evaluate inside complex operations

add(add(x, y), z)

is transformed to

let t = doAdd(x, y) in
doAdd(z)

- But now we lose many of the benefits of partial evaluation
  - We want add to turn into ~2 instructions, not an expensive function call.
  - Plus we can't do further optimization easily – e.g. constant-fold when x and y are constants.

Challenge: how to get high-performance code? (3)

- Assume y is the constant 1, z is an Int, and x is probably an Int
- What we want is to translate "add(add(x, y), z)" into:

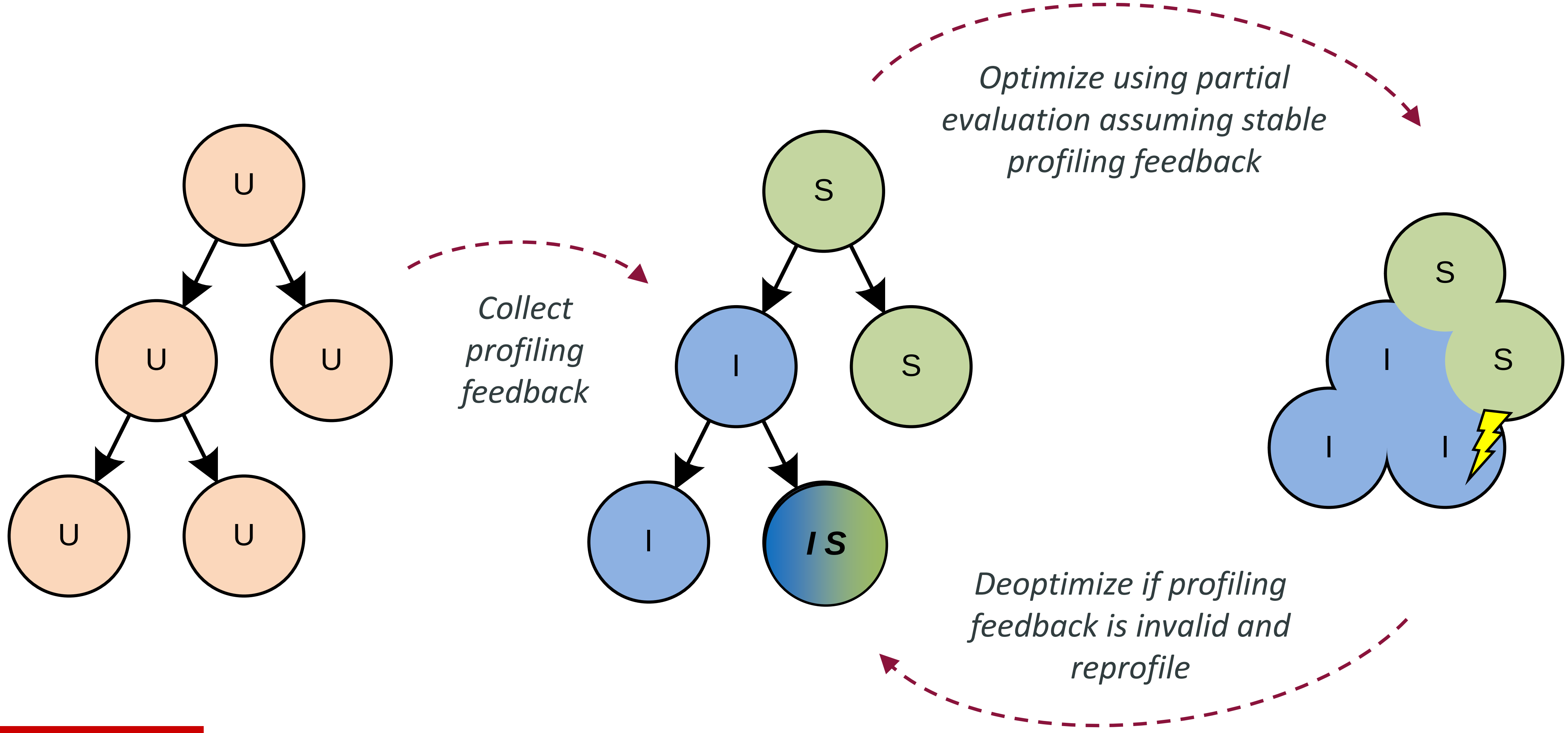
```
// guess that x is an Int, but check to make sure
if (!(x instanceof Int)) goto do_it_slowly
x+1+z
```

- We can figure out the y is the constant 1 with partial evaluation
- How do we know that z is definitely an Int?
- How can we guess that x is probably an Int?

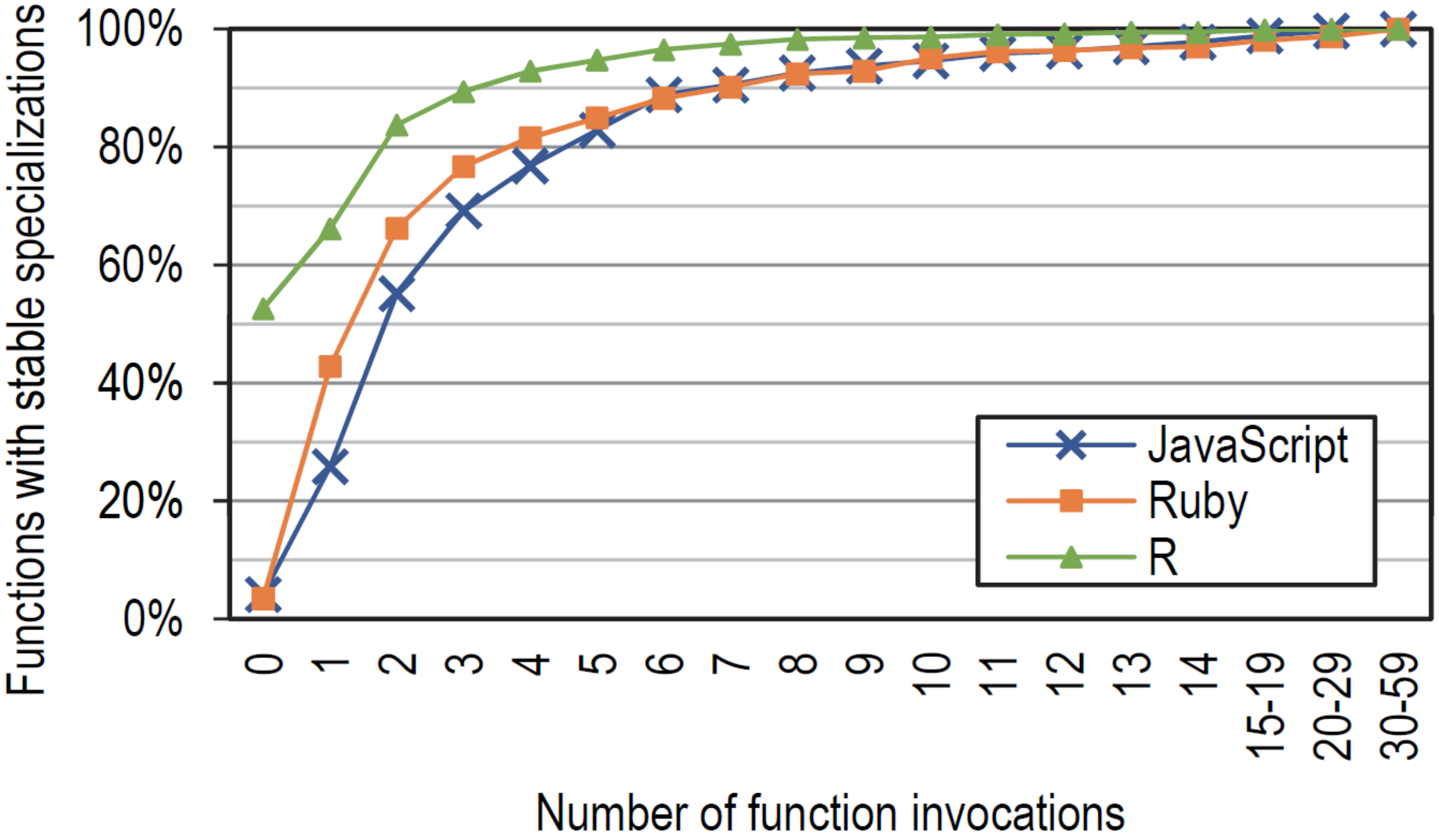
Profile-Based Optimizing Interpreters

- Run each function in the Guest language a few times
- Gather profile information for each node in the AST
  - Call nodes: what functions are called?
  - Operation nodes: what are the datatypes?
- Specialize the interpreter
  - Replace unspecialized nodes with specialized ones
    - E.g. replace unspecializeAdd() with intAdd()
  - Each specialized node has a guard
    - intAdd(): check that my arguments are ints
    - If the guard fails, intAdd() knows how to replace itself with genericAdd()
- Partially evaluate the specialization
  - Generates optimized code
  - This is speculative – must include a check, and a hook to jump back to the interpreter to de-specialize

The Truffle Idea



Stability



Functions with stable specializations
100%
80%
60%
40%
20%
0%
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15-19
20-29
30-59
Number of function invocations
JavaScript
Ruby
R

Example: Transfer to Interpreter

```
class ExampleNode {
  int foo(boolean flag) {
    if (flag) {
      return 42;
    } else {
      throw new IllegalArgumentException(
                     "flag: " + flag);
    }
}
```

compilation of method foo()

```
     // parameter flag in edi
     cmp  edi, 0
     jz   L1
     mov  eax, 42
     ret
L1:  ...
     // lots of code here
```

```
class ExampleNode {
  int foo(boolean flag) {
    if (flag) {
      return 42;
    } else {
      transferToInterpreter();
      throw new IllegalArgumentException(
                     "flag: " + flag);
    }
}
```

compilation of method foo()

```
     // parameter flag in edi
     cmp  edi, 0
     jz   L1
     mov  eax, 42
     ret
L1:  mov  [rsp + 24], edi
     call transferToInterpreter
     // no more code, this point is unreachable
```

`transferToInterpreter()` is a call into the VM runtime that does not return to its caller, because execution continues in the interpreter

Example: Partial Evaluation and Transfer to Interpreter

```
class ExampleNode {

  @CompilationFinal boolean minValueSeen;

  int negate(int value) {
    if (value == Integer.MIN_VALUE) {
      if (!minValueSeen) {
        transferToInterpreterAndInvalidate();
        minValueSeen = true;
      }
      throw new ArithmeticException()
    }

    return -value;
  }
}
```

partial evaluation
of method `negate()`
with known parameter `this`

ExampleNode
minValueSeen: false

Expected behavior: method `negate()` only called with allowed values

```
      // parameter value in eax
      cmp   eax, 0x80000000
      jz    L1
      neg   eax
      ret
L1:   mov   [rsp + 24], eax
      call  transferToInterpreterAndInvalidate
      // no more code, this point is unreachable
```

if compiled code is invoked with minimum `int` value:

1) transfer back to the interpreter
2) invalidate the compiled code

ExampleNode
minValueSeen: true

second
partial evaluation

```
      // parameter value in eax
      cmp   eax, 0x80000000
      jz    L1
      neg   eax
      ret
L1:   ...
      // lots of code here to throw exception
```

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Assumptions

Create an assumption:

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

Assumptions allow non-local speculation (across multiple compiled methods)

Check an assumption:

```
void foo() {
  if (assumption.isValid()) {
    // Fast-path code that is only valid if assumption is true.
  } else {
    // Perform node specialization, or other slow-path code to respond to change.
  }
}
```

Checking an assumption does not need machine code, it really is a "free lunch"

Invalidate an assumption:

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

When an assumption is invalidate, all compiled methods that checked it are invalidated

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Example: Assumptions

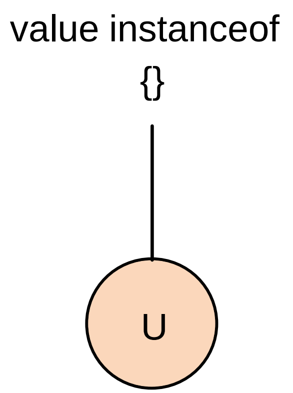
```
class ExampleNode {

  public static final Assumption addNotRedefined = Truffle.getRuntime().createAssumption();

  int add(int left, int right) {
    if (addNotRedefined.isValid()) {
      return left + right;
    } else {
      ...
      // Complicated code to call user-defined add function
    }
  }
}
```

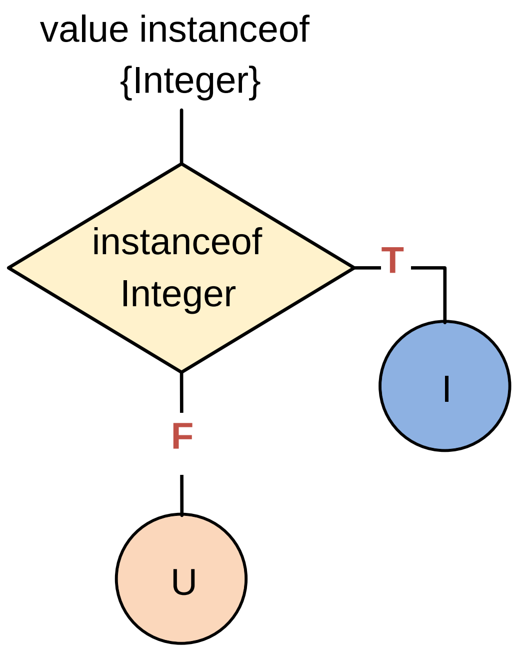
Expected behavior: user does not redefine "+" for integer values

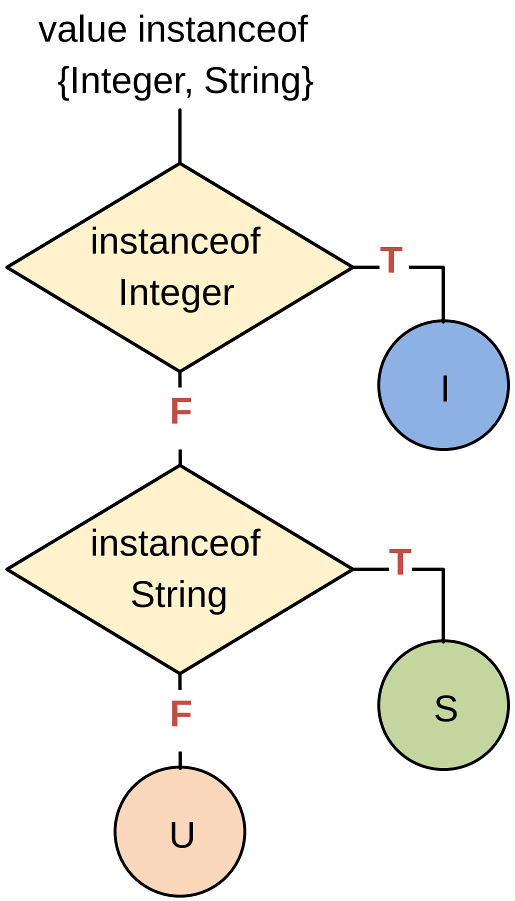
```
void redefineFunction(String name, ...) {
  if (name.equals("+")) {
    addNotRedefined.invalidate()) {
    ...
  }
}
```

This is not a synthetic example: Ruby allows redefinition of all operators on all types, including the standard numeric types

Specialization







Truffle provides a DSL for this use case, see later slides that introduce `@Specialization`

Profile, Assumption, or Specialization?

- Use profiles where local, monomorphic speculation is sufficient
  - Transfer to interpreter is triggered by the compiled method itself
  - Recompilation does not speculate again
- Use assumptions for non-local speculation
  - Transfer to interpreter is triggered from outside of a compiled method
  - Recompilation often speculates on a new assumption (or does not speculate again)
- Use specializations for local speculations where polymorphism is required
  - Transfer to interpreter is triggered by the compiled method method
  - Interpreter adds a new specialization
  - Recompilation speculates again, but with more allowed cases

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A 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
  - Objects are key-value stores
    - Key and value can have any type, but typically the key is a String

About 2.5k lines of code

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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`
Object	key-value store	`DynamicObject`
Null	null	`SLNull.SINGLETON`

Null is its own 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

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Syntax

- C-like syntax for control flow
  - `if`, `while`, `break`, `continue`, `return`
- Operators
  - +, -, *, /, ==, !=, <, <=, >, >=, &&, ||, ( )
  - + is defined on String, performs String concatenation
  - && and || have short-circuit semantics
  - . or [] for property access
- Literals
  - Number, String, Function
- Builtin functions
  - println, readln: Standard I/O
  - nanoTime: to allow time measurements
  - defineFunction: dynamic function redefinition
  - stacktrace, helloEqualsWorld: stack walking and stack frame manipulation
  - new: Allocate a new object without properties

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

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SL Examples

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
```

Objects:

```
function main() {
  obj = new();
  obj.prop = "Hello World!";
  println(obj["pr" + "op"]);
}
```

```
Hello World!
```

Simple loop:

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

```
50005000
```

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
```

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

- Clone repository
  - `git clone https://github.com/graalvm/simplelanguage`

Version used in this tutorial: tag PLDI_2016

- Download Graal VM Development Kit
  - http://www.oracle.com/technetwork/oracle-labs/program-languages/downloads
  - Unpack the downloaded `graalvm_*.tar.gz` into `simplelanguage/graalvm`
  - Verify that launcher exists and is executable: `simplelanguage/graalvm/bin/java`

Version used in this tutorial: Graal VM 0.12

- Build
  - `mvn package`
- Run example program
  - `./sl tests/HelloWorld.sl`
- IDE Support
  - Import the Maven project into your favorite IDE
  - Instructions for Eclipse, NetBeans, IntelliJ are in README.md

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Simple Tree Nodes

AST Interpreters

- AST = Abstract Syntax Tree
  - The tree produced by a parser of a high-level language compiler
- Every node can be executed
  - For our purposes, we implement nodes as a class hierarchy
  - Abstract `execute` method defined in Node base class
  - Execute overwritten in every subclass
- Children of an AST node produce input operand values
  - Example: AddNode to perform addition has two children: `left` and `right`
    - AddNode.execute first calls left.execute and right.execute to compute the operand values
    - Then peforms the addition and returns the result
  - Example: `IfNode` has three children: `condition`, `thenBranch`, `elseBranch`
    - `IfNode.execute` first calls `condition.execute` to compute the condition value
    - Based on the condition value, it either calls `thenBranch.execute` or `elseBranch.execute` (but never both of them)
- Textbook summary
  - Execution in an AST interpreter is slow (virtual call for every executed node)
  - But, easy to write and reason about; portable

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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 {

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

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

  public SourceSection getSourceSection();
}
```

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If Statement

```
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 = conditionNode;
    this.thenPartNode = thenPartNode;
    this.elsePartNode = 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`

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If Statement with Profiling

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

  private final ConditionProfile condition = ConditionProfile.createCountingProfile();

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

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

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

Blocks

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

  public SLBlockNode(SLStatementNode[] bodyNodes) {
    this.bodyNodes = 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: 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`

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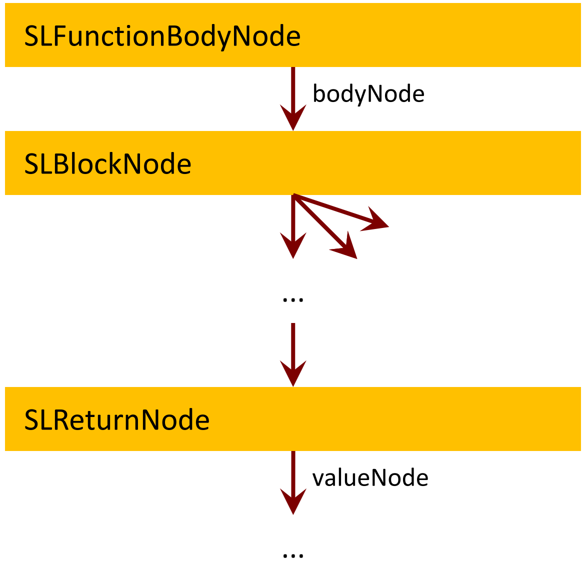
Exceptions for Inter-Node Control Flow




```
try {
  bodyNode.executeVoid(frame);
} catch (SLReturnException ex) {
  return ex.getResult();
}
```

SLReturnException
value: ...

Inter-Node Control Flow

```
Object value = valueNode.executeGeneric(frame);
throw new SLReturnException(value);
```

Exception unwinds all the interpreter stack frames of the method (loops, conditions, blocks, ...)

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Truffle DSL for Specializations

Addition

```
@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(left, right)")
  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;
  }
}
```

The order of the @Specialization methods is important: the first matching specialization is selected

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

Code Generated by Truffle DSL (1)

Generated code with factory method:

```
@GeneratedBy(SLAddNode.class)
public final class SLAddNodeGen extends SLAddNode {

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

  ...
}
```

The parser uses the factory to create a node that is initially in the uninitialized state

The generated code performs all the transitions between specialization states

Code Generated by Truffle DSL (2)

```
@GeneratedBy(methodName = "add(long, long)", value = SLAddNode.class)
private static final class Add0Node_ extends BaseNode_ {
  @Override
  public long executeLong(VirtualFrame frameValue) throws UnexpectedResultException {
    long leftNodeValue_;
    try {
      leftNodeValue_ = root.leftNode_.executeLong(frameValue);
    } catch (UnexpectedResultException ex) {
      Object rightNodeValue = executeRightNode_(frameValue);
      return SLTypesGen.expectLong(getNext().execute_(frameValue, ex.getResult(), rightNodeValue));
    }
    long rightNodeValue_;
    try {
      rightNodeValue_ = root.rightNode_.executeLong(frameValue);
    } catch (UnexpectedResultException ex) {
      return SLTypesGen.expectLong(getNext().execute_(frameValue, leftNodeValue_, ex.getResult()));
    }
    try {
      return root.add(leftNodeValue_, rightNodeValue_);
    } catch (ArithmeticException ex) {
      root.excludeAdd0_ = true;
      return SLTypesGen.expectLong(remove("threw rewrite exception", frameValue, leftNodeValue_, rightNodeValue_));
    }
  }

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

The generated code can and will change at any time

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);
  }
}
```

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 boolean executeBoolean(VirtualFrame frame) ...
}
```

`SLTypesGen` is a generated subclass of `SLTypes`

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

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`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

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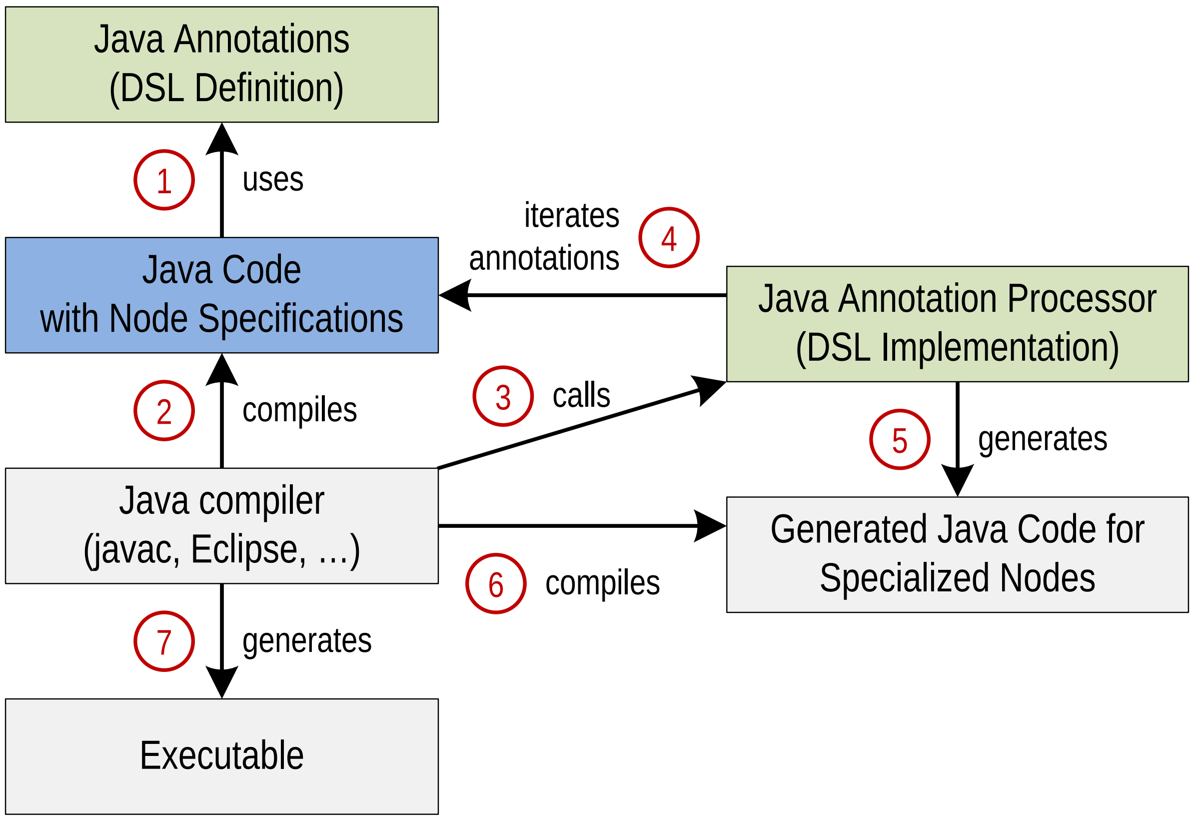
Truffle DSL Workflow



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

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

Frame Management

```
public interface Frame {
  FrameDescriptor getFrameDescriptor();
  Object[] getArguments();

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

  Object getValue(FrameSlot slot);

  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

ORACLE

Local Variables

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

  protected abstract FrameSlot getSlot();

  @Specialization(guards = "isLongOrIllegal(frame)")
  protected long writeLong(VirtualFrame frame, long value) {
    getSlot().setKind(FrameSlotKind.Long);
    frame.setLong(getSlot(), value);
    return value;
  }
  protected boolean isLongOrIllegal(VirtualFrame frame) {
    return getSlot().getKind() == FrameSlotKind.Long || getSlot().getKind() == FrameSlotKind.Illegal;
  }
  ...

  @Specialization(contains = {"writeLong", "writeBoolean"})
  protected Object write(VirtualFrame frame, Object value) {
    getSlot().setKind(FrameSlotKind.Object);
    frame.setObject(getSlot(), value);
    return value;
  }
}
```

`setKind()` is a no-op if kind is already `Long`

If we cannot specialize on a single primitive type, we switch to Object for all reads and writes

ORACLE

Local Variables

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

  protected abstract FrameSlot getSlot();

  @Specialization(guards = "isLong(frame)")
  protected long readLong(VirtualFrame frame) {
    return FrameUtil.getLongSafe(frame, getSlot());
  }
  protected boolean isLong(VirtualFrame frame) {
    return getSlot().getKind() == FrameSlotKind.Long;
  }
  ...

  @Specialization(contains = {"readLong", "readBoolean"})
  protected Object readObject(VirtualFrame frame) {
    if (!frame.isObject(getSlot())) {
      CompilerDirectives.transferToInterpreter();
      Object result = frame.getValue(getSlot());
      frame.setObject(getSlot(), result);
      return result;
    }

    return FrameUtil.getObjectSafe(frame, getSlot());
  }
```

The guard ensure the frame slot contains a primitive long value

Slow path: we can still have frames with primitive values written before we switched the local variable to the kind Object

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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

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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()`
  - `@TruffleBoundary`
    - Marks a method that is not important for performance, i.e., not part of partial evaluation
  - `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

Slow Path Annotation

```
public abstract class SLPrintlnBuiltin extends SLBuiltinNode {

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

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

When compiling, the output stream is a constant

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

Compiler Assertions

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

- CompilerAsserts.partialEvaluationConstant()
  - Checks that the passed in value is a compile-time constant early during partial evaluation
- CompilerAsserts.compilationConstant()
  - Checks that the passed in value is a compile-time constant (not as strict as partialEvaluationConstant)
  - 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

Compilation

SL source code:

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

Machine code for loop:

```
     mov  r14, 0
     mov  r13, 0
     jmp  L2
L1:  safepoint
     mov  rax, r13
     add  rax, r14
     jo   L3
     inc  r13
     mov  r14, rax
L2:  cmp  r13, rbp
     jle  L1
     ...
L3:  call transferToInterpreter
```

Run this example:

```
./sl -dump -disassemble tests/SumPrint.sl
```

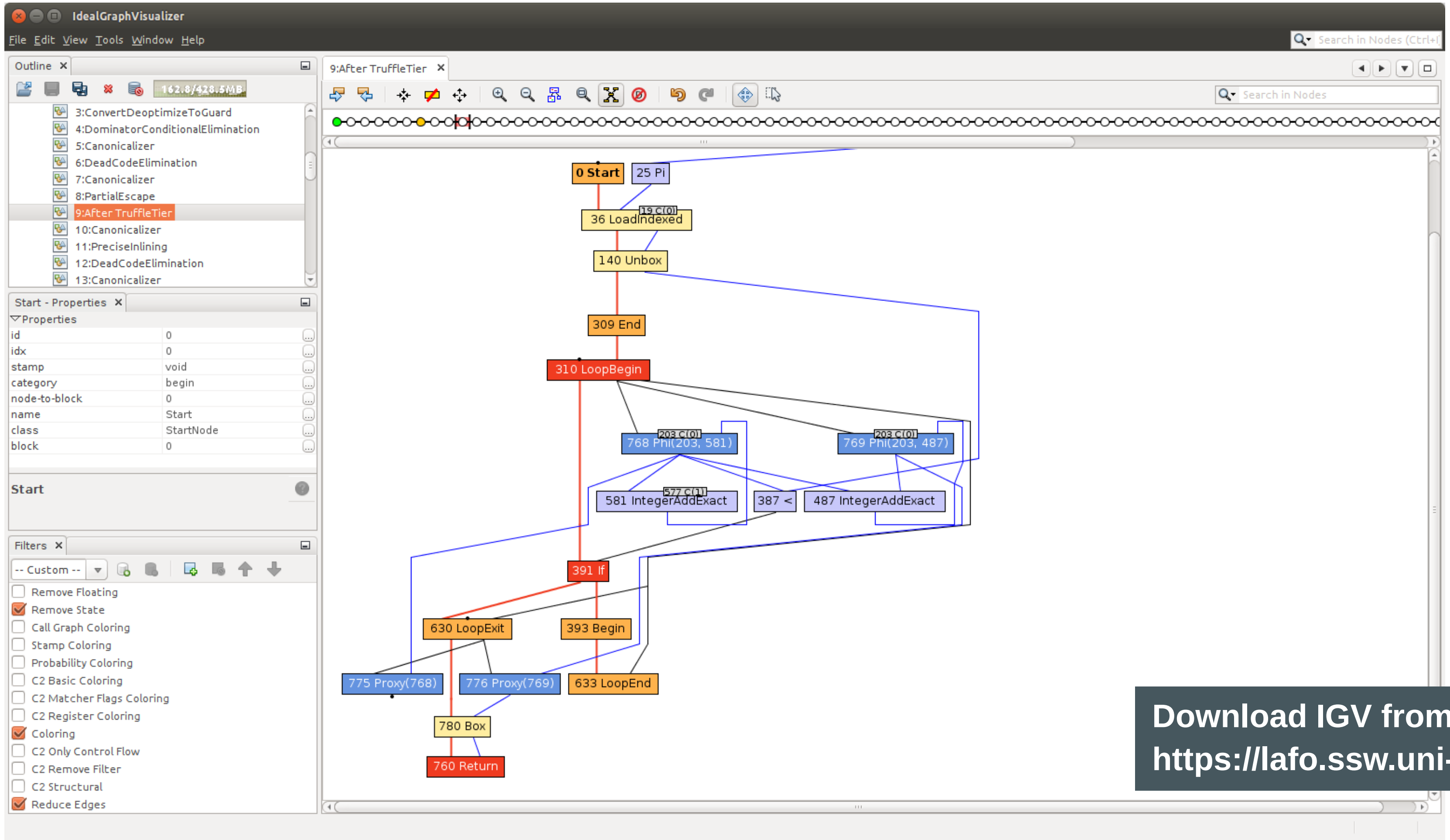
Truffle compilation printing is enabled

Background compilation is disabled

Graph dumping to IGV is enabled

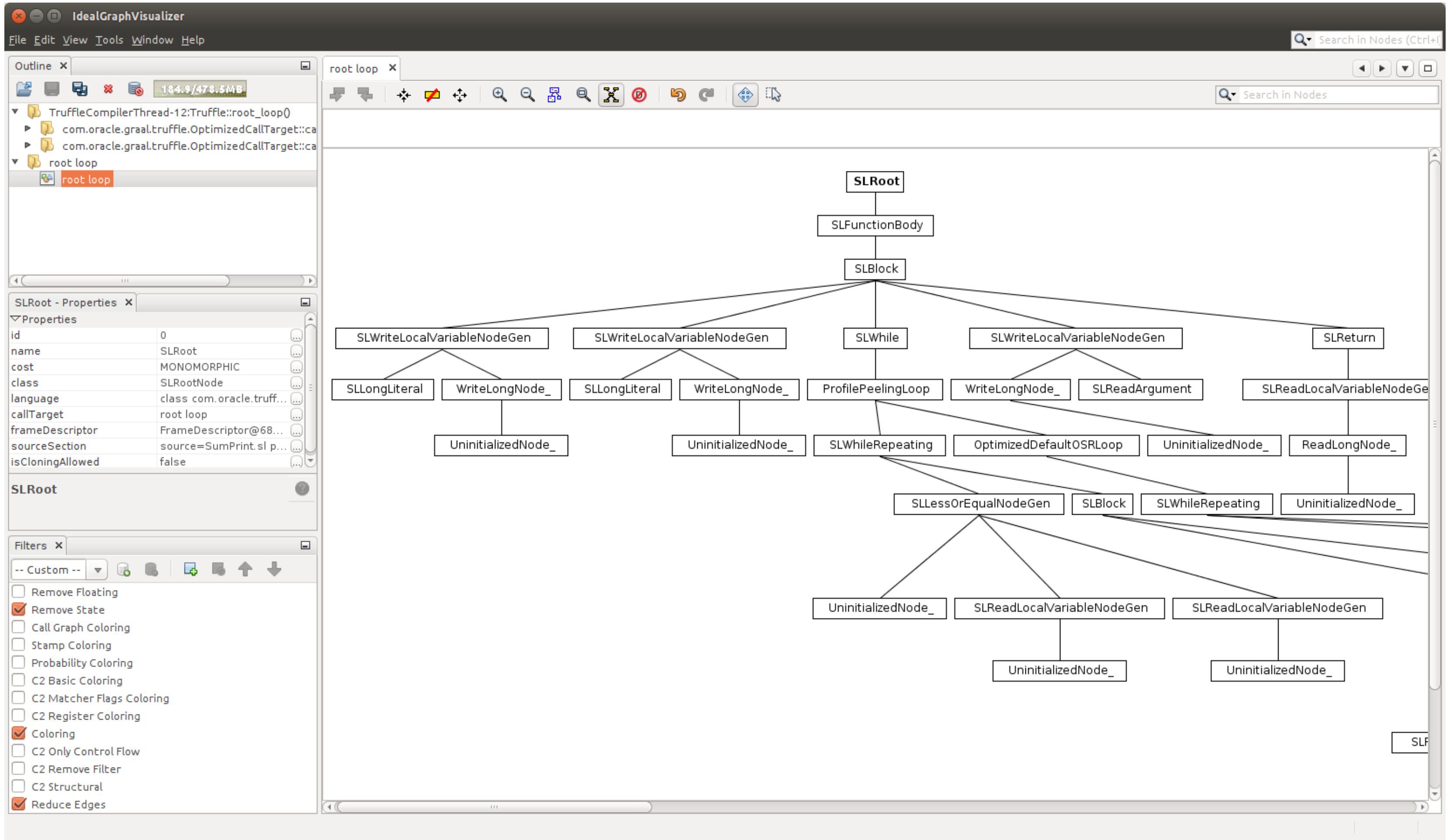
Disassembling is enabled

Visualization Tools: IGV



Download IGV from https://lafo.ssw.uni-linz.ac.at/pub/idealgraphvisualizer

Visualization Tools: IGV



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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
  - Use profiles or `@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
  - 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 slower

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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 that it is 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 specialization
  - Build chain of multiple cached functions

Example: Simple Polymorphic Inline Cache

```
public abstract class ANode extends Node {

    public abstract Object execute(Object operand);

    @Specialization(limit = "3",
                    guards = "operand == cachedOperand")
    protected Object doCached(AType operand,
                    @Cached("operand") AType cachedOperand) {
        // implementation
        return cachedOperand;
    }

    @Specialization(contains = "doCached")
    protected Object doGeneric(AType operand) {
        // implementation
        return operand;
    }
}
```

The `cachedOperand` is a compile time constant

Up to 3 compile time constants are cached

The generic case contains all cached cases, so the 4th unique value removes the cache chain

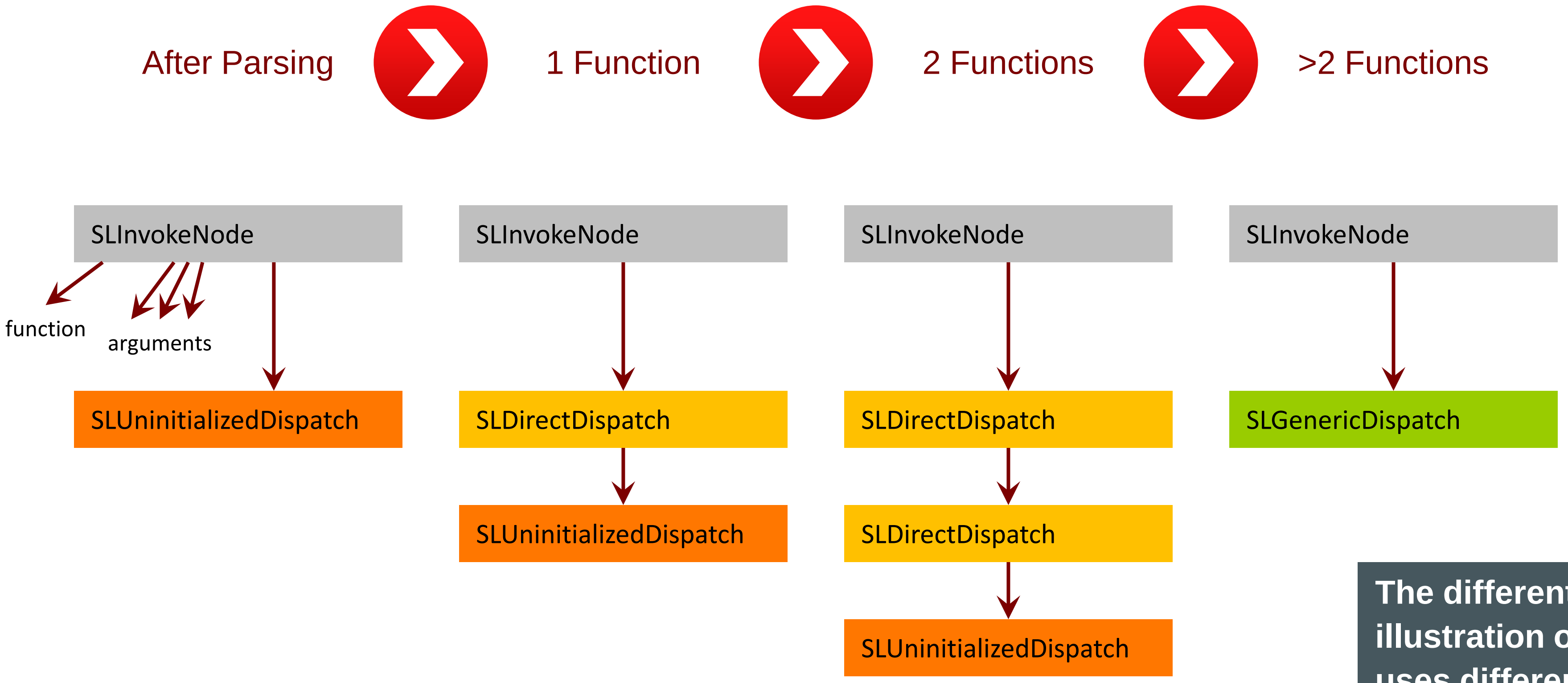
The `operand` is no longer a compile time constant

The `@Cached` annotation leads to a `final` field in the generated code

Compile time constants are usually the starting point for more constant folding

Polymorphic Inline Cache for Function Dispatch

Example of cache with length 2



The different dispatch nodes are for illustration only, the generated code uses different names

Invoke Node

```
public final class SLInvokeNode extends SLExpressionNode {

  @Child private SLExpressionNode functionNode;
  @Children private final SLExpressionNode[] argumentNodes;
  @Child private SLDispatchNode dispatchNode;

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

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

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

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

Dispatch Node

```
public abstract class SLDispatchNode extends Node {

  public abstract Object executeDispatch(VirtualFrame frame, Object function, Object[] arguments);

  @Specialization(limit = "2",
                  guards = "function == cachedFunction",
                  assumptions = "cachedFunction.getCallTargetStable()")
  protected static Object doDirect(VirtualFrame frame, SLFunction function, Object[] arguments,
                  @Cached("function") SLFunction cachedFunction,
                  @Cached("create(cachedFunction.getCallTarget())") DirectCallNode callNode) {

    return callNode.call(frame, arguments);
  }

  @Specialization(contains = "doDirect")
  protected static Object doIndirect(VirtualFrame frame, SLFunction function, Object[] arguments,
                  @Cached("create()") IndirectCallNode callNode) {

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

Separation of concerns: this node builds the inline cache chain

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Code Created from Guards and @Cached Parameters

Code creating the `doDirect` inline cache (runs infrequently):

```
if (number of doDirect inline cache entries < 2) {
if (function instanceof SLFunction) {
cachedFunction = (SLFunction) function;
if (function == cachedFunction) {
callNode = DirectCallNode.create(cachedFunction.getCallTarget());
assumption1 = cachedFunction.getCallTargetStable();
if (assumption1.isValid()) {
create and add new doDirect inline cache entry
```

Code checking the inline cache (runs frequently):

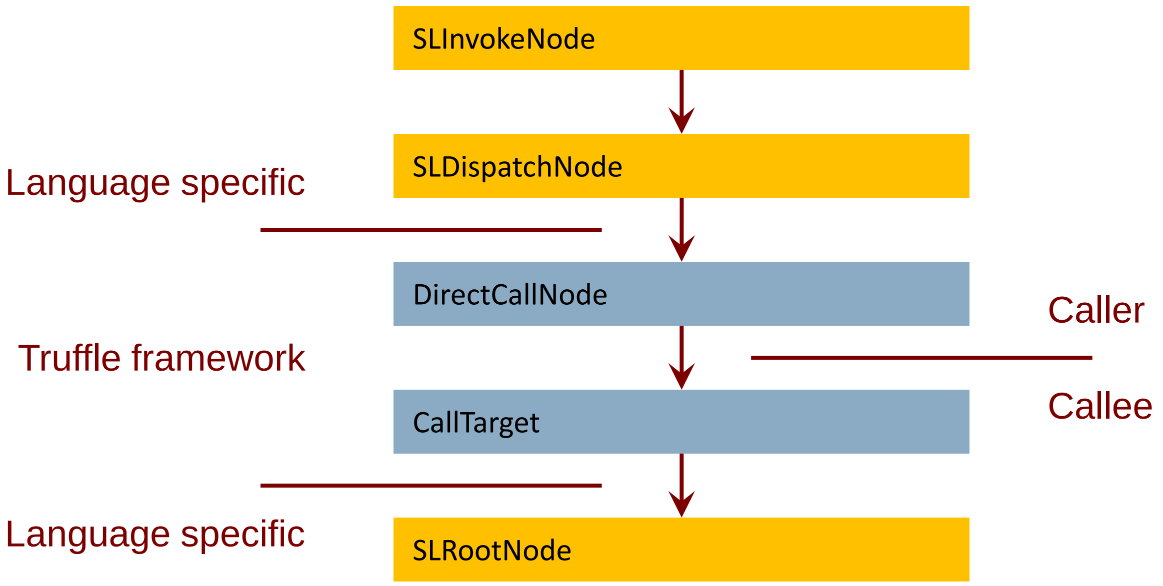
```
assumption1.check();
if (function instanceof SLFunction) {
if (function == cachedFunction)) {
callNode.call(frame, arguments);
```

Code that is compiled to a no-op is marked ~~strikethrough~~

The inline cache check is only one comparison with a compile time constant

Partial evaluation can go across function boundary (function inlining) because `callNode` with its `callTarget` is `final`

Language Nodes vs. Truffle Framework Nodes



Truffle framework code triggers compilation, function inlining, …

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

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Function Redefinition (2)

```
public abstract class SLDefineFunctionBuiltin extends SLBuiltinNode {

  @TruffleBoundary
  @Specialization
  public String defineFunction(String code) {
    Source source = Source.fromText(code, "[defineFunction]");
    getContext().getFunctionRegistry().register(Parser.parseSL(source));
    return code;
  }
}
```

Why `@TruffleBoundary`? 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 final String name;
  private RootCallTarget callTarget;
  private Assumption callTargetStable;

  protected SLFunction(String name) {
    this.name = name;
    this.callTarget = Truffle.getRuntime().createCallTarget(new SLUndefinedFunctionRootNode(name));
    this.callTargetStable = Truffle.getRuntime().createAssumption(name);
  }

  protected void setCallTarget(RootCallTarget callTarget) {
    this.callTarget = callTarget;
    this.callTargetStable.invalidate();
    this.callTargetStable = Truffle.getRuntime().createAssumption(name);
  }
}
```

The utility class `CyclicAssumption` simplifies this code

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] = SLWriteLocalVariableNode<writeLong>(name = "a")
        valueNode = SLReadArgumentNode(index = 0)
      bodyNodes[1] = SLWriteLocalVariableNode<writeLong>(name = "b")
        valueNode = SLReadArgumentNode(index = 1)
      bodyNodes[2] = SLReturnNode
        valueNode = SLAddNode<addLong>
          leftNode = SLReadLocalVariableNode<readLong>(name = "a")
          rightNode = SLReadLocalVariableNode<readLong>(name = "b")
```

Function Inlining vs. Function Splitting

- 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
  - Partial evaluation does not stop at `DirectCallNode`, but continues into next `CallTarget`
  - All later optimizations see the big combined tree, without further work
- Function splitting creates a new, uninitialized copy of an AST
  - Specialization in the context of a particular caller
  - Useful to avoid polymorphic specializations and to keep polymorphic inline caches shorter
  - Function inlining can inline a better specialized AST
  - Result: context sensitive profiling information
- Function inlining and function splitting are language independent
  - The Truffle framework is doing it automatically for you

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Compilation with Inlined Function

SL source code without call:

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

Machine code for loop without call:

```
     mov   r14, 0
     mov   r13, 0
     jmp   L2
L1:  safepoint
     mov   rax, r13
     add   rax, r14
     jo    L3
     inc   r13
     mov   r14, rax
L2:  cmp   r13, rbp
     jle   L1
     ...
L3:  call  transferToInterpreter
```

SL source code with call:

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

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

Machine code for loop with call:

```
     mov   r14, 0
     mov   r13, 0
     jmp   L2
L1:  safepoint
     mov   rax, r13
     add   rax, r14
     jo    L3
     inc   r13
     mov   r14, rax
L2:  cmp   r13, rbp
     jle   L1
     ...
L3:  call  transferToInterpreter
```

Truffle gives you function inlining for free!

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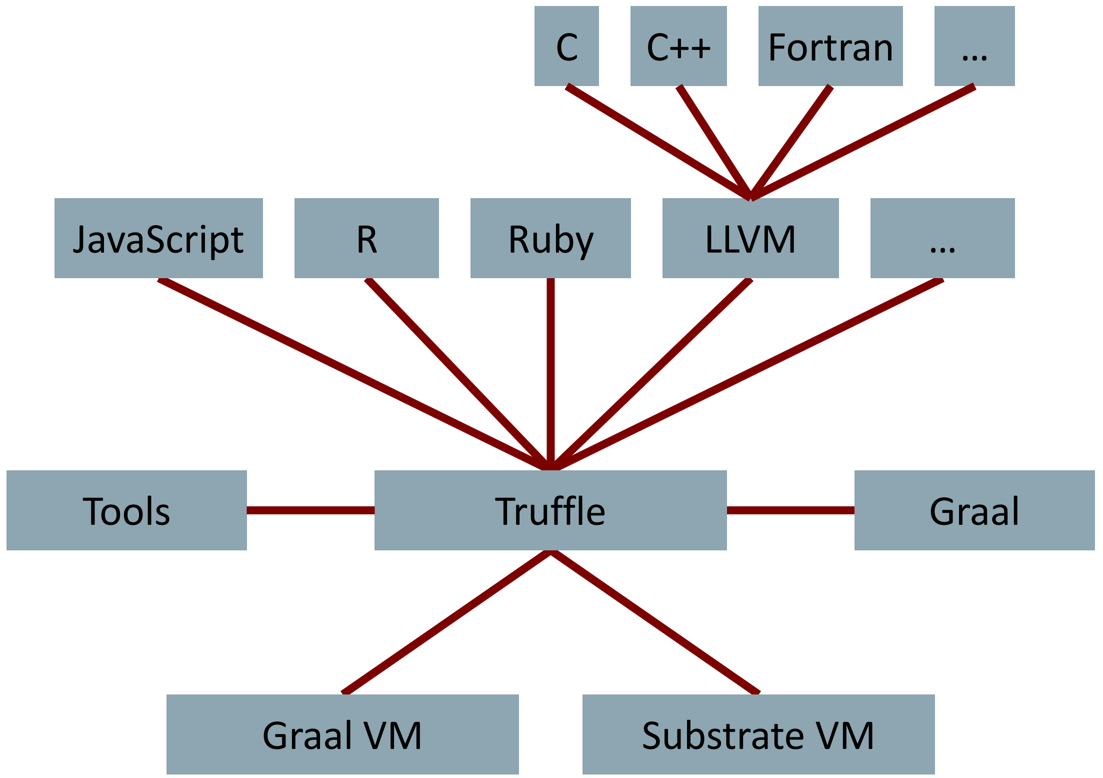
Truffle as an Internal DSL

- The base VM, Graal, is based on partial evaluation without code generation
  - Annotations are only used to denote fields that should be viewed as final by the partial evaluator
- Initial language implementations included a lot of boilerplate
  - E.g. multiple execute() methods that differed only in argument/return types
    - To specialize for types
  - Complicated, handwritten logic to choose and combine specializations
- Truffle DSL
  - Implemented purely within Java, using annotations
  - Annotation processor reads annotations, generates additional code
- Case study: partial JavaScript interpreter
  - 3500 LOC in Java → 1000 LOC in Java + Truffle annotations
  - Ran faster (more consistent optimizations) and less error-prone

Overall System Structure

Interpreter for every language

Common API separates language implementation, optimization system, and tools (debugger)

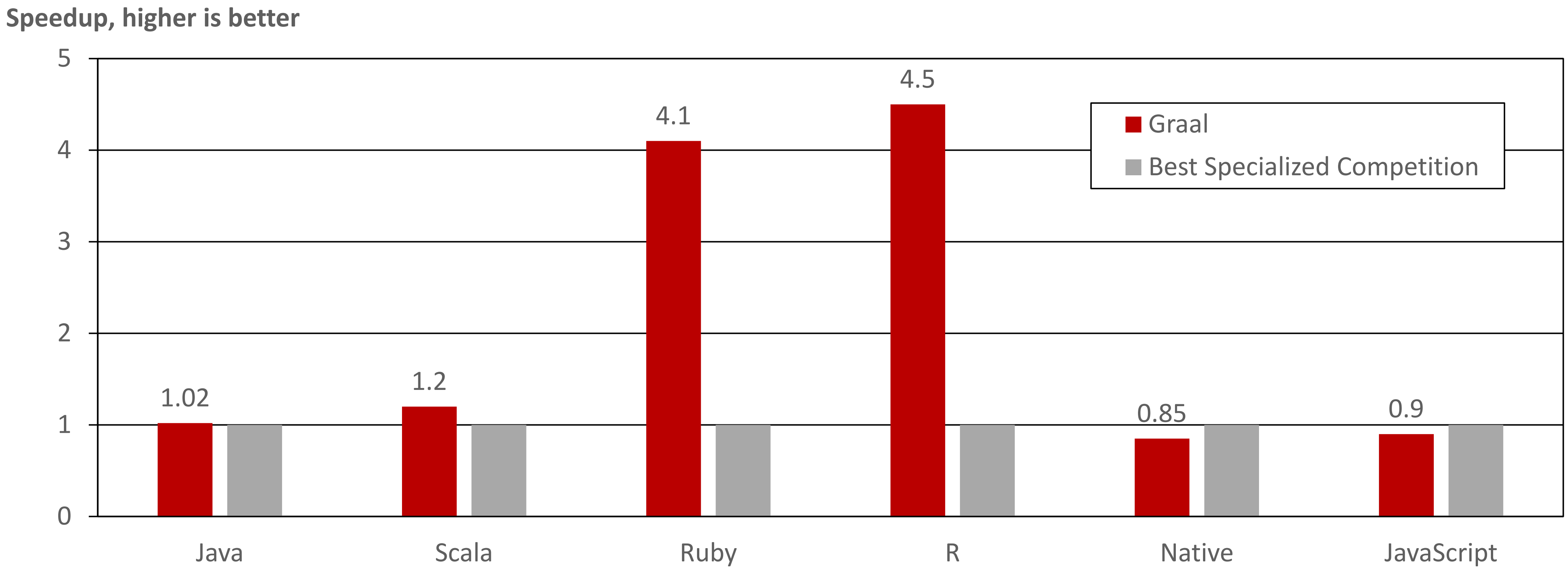


Language agnostic dynamic compiler

Integrate with Java applications

Low-footprint VM, also suitable for embedding

Performance: Graal VM



Performance relative to:
HotSpot/Server, HotSpot/Server running JRuby, GNU R, LLVM AOT compiled, V8

Demonstration

Tools

Tools: We Don't Have It All

(Especially for Debuggers)

- Difficult to build
  - Platform specific
  - Violate system abstractions
  - Limited access to execution state
- Productivity tradeoffs for programmers
  - Performance – disabled optimizations
  - Functionality – inhibited language features
  - Complexity – language implementation requirements
  - Inconvenience – nonstandard context (debug flags)

Tools: We Can Have It All

- Build tool support into the Truffle API
  - High-performance implementation
  - Many languages: any Truffle language can be tool-ready with minimal effort
  - Reduced implementation effort

- Generalized *instrumentation* support
  1. Access to execution state & events
  2. Minimal runtime overhead
  3. Reduced implementation effort (for languages *and* tools)

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Implementation Effort: Language Implementors

- Treat AST syntax nodes specially
  - Precise source attribution
  - Enable probing
  - Ensure stability

- Add default tags, e.g., Statement, Call, ...
  - Sufficient for many tools
  - Can be extended, adjusted, or replaced dynamically by other tools

- Implement debugging support methods, e.g.
  - Eval a string in context of any stack frame
  - Display language-specific values, method names, …

- More to be added to support new tools & services

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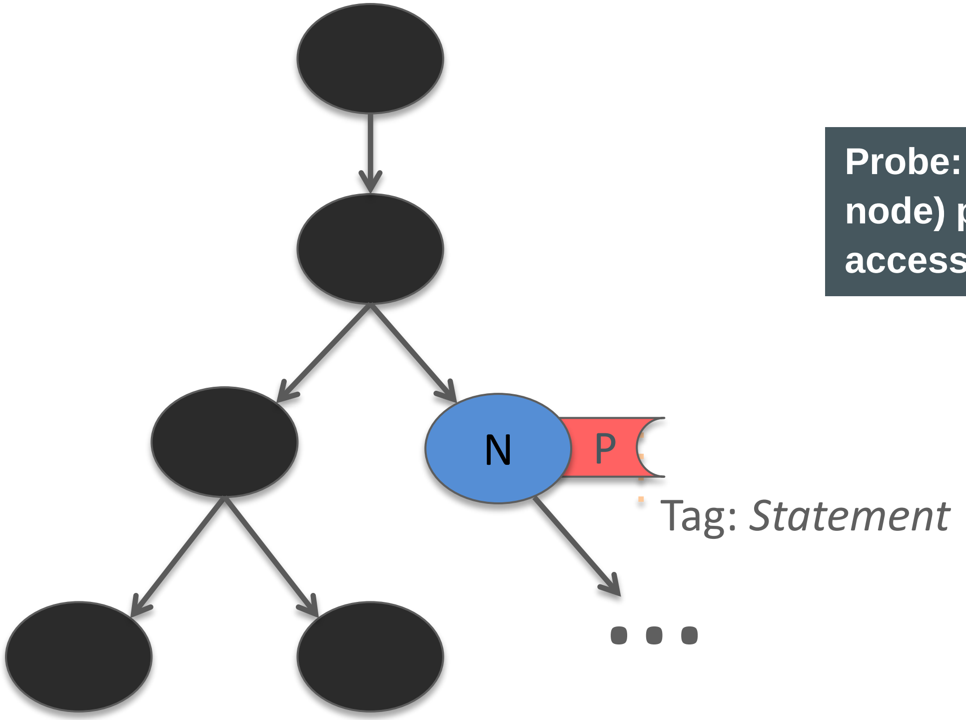
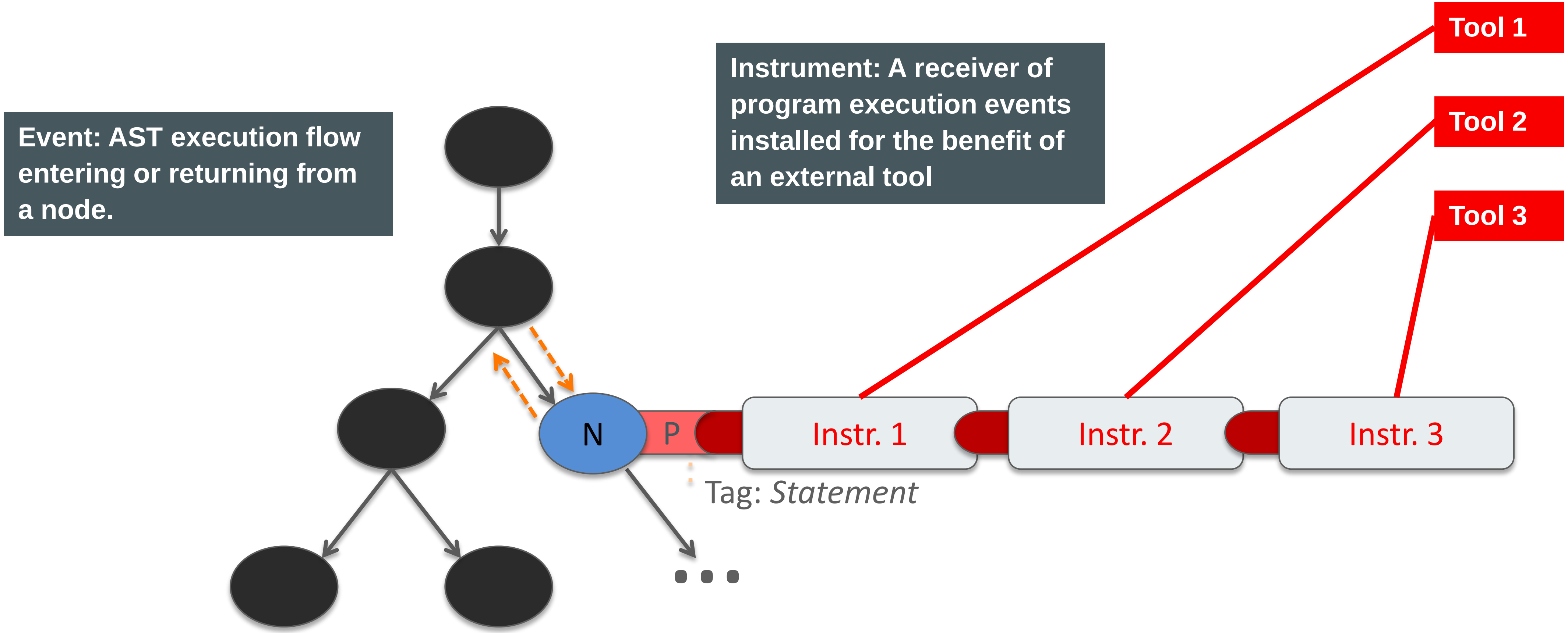
"Mark Up" Important AST Nodes for Instrumentation



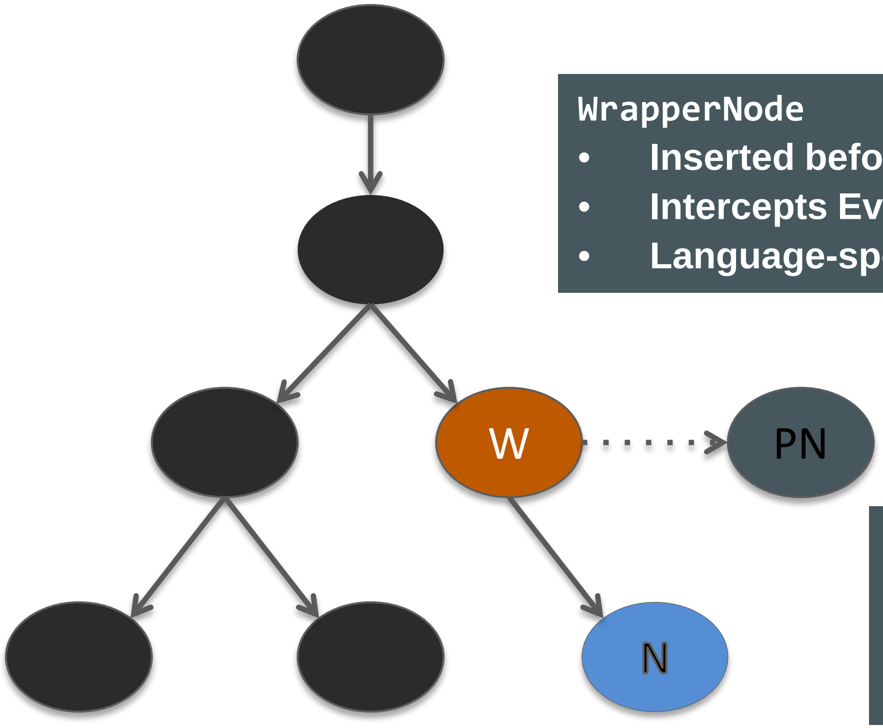
Probe: A program location (AST node) prepared to give tools access to execution state.

Tag: An annotation for configuring tool behavior at a Probe. Multiple tags, possibly tool-specific, are allowed.

Access to Execution Events



Implementation: Nodes



`WrapperNode`
- Inserted before any execution
- Intercepts Events
- Language-specific Type

`ProbeNode`
- Manages “instrument chain” dynamically
- Propagates Events
- Instrumentation Type

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More Details on Instrumentation and Debugging

http://dx.doi.org/10.1145/2843915.2843917

Building Debuggers and Other Tools: We Can "Have it All"

Position Paper ICOOOLPS '15

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Abstract

Software development tools that "instrument" running programs, notably debuggers, are presumed to demand difficult tradeoffs among *performance*, *functionality*, *implementation complexity*, and *user convenience*. A fundamental change in our thinking about such tools makes that presumption obsolete.

By building instrumentation directly into the core of a high-performance language implementation framework, tool-support can be *always on*, with confidence that optimization will apply uniformly to instrumentation and result in near zero overhead. Tools can be always available (and fast), not only for end user programmers, but also for language implementors throughout development.

2. Roadblocks

Why is it so difficult to have tools that are as good and timely as our programming languages? Why can't we "have it all"?

2.1 Tribes

One perspective is historical and cultural. Concerns about program execution speed (utilization of *expensive machines*) came long before concerns about software development rate and correctness (utilization of *expensive people*).

Our legacy is that people who write compilers and people who build developer tools essentially belong to different *tribes*, each with its own technologies and priorities[1]. More significantly, each

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Node Tags

```
@Instrumentable(factory = SLStatementNodeWrapper.class)
public abstract class SLStatementNode extends Node {

  private boolean hasStatementTag;
  private boolean hasRootTag;

  @Override
  protected boolean isTaggedWith(Class<?> tag) {
      if (tag == StandardTags.StatementTag.class) {
          return hasStatementTag;
      } else if (tag == StandardTags.RootTag.class) {
          return hasRootTag;
      }
      return false;
  }
}
```

Annotation generates type-specialized `WrapperNode`

The set of tags is extensible, tools can provide new tags

Example: Debugger

Simple command line debugger is in Truffle development repository: https://github.com/graalvm/truffle#hacking-truffle

```
mx repl
==> GraalVM Polyglot Debugger 0.9
Copyright (c) 2013-6, Oracle and/or its affiliates
    Languages supported (type "lang <name>" to set default)
    JS ver. 0.9
    SL ver. 0.12
()  loads LoopPrint.sl
Frame 0 in LoopPrint.sl
      1  function loop(n) {
      2    i = 0;
      3    while (i < n) {
      4      i = i + 1;
      5    }
      6    return i;
      7  }
      8
      9  function main() {
-->  10    i = 0;
     11    while (i < 20) {
     12      loop(1000);
     13      i = i + 1;
     14    }
     15    println(loop(1000));
     16  }
```

```
(<1> LoopPrint.sl:10)( SL ) break 4
==> breakpoint 0 set at LoopPrint.sl:4
(<1> LoopPrint.sl:10)( SL ) continue
Frame 0 in LoopPrint.sl
[...]
-->   4      i = i + 1;
[...]
(<1> LoopPrint.sl:4)( SL ) frame
==> Frame 0:
    #0: n = 1000
    #1: i = 0
(<1> LoopPrint.sl:4)( SL ) step
Frame 0 in LoopPrint.sl
[...]
-->   3    while (i < n) {
[...]
(<1> LoopPrint.sl:3)( SL ) frame
==> Frame 0:
    #0: n = 1000
    #1: i = 1
(<1> LoopPrint.sl:3)( SL ) backtrace
==>   0: at LoopPrint.sl:3 in root loop    line="  while (i <
      1: at LoopPrint.sl:12~ in root main    line="    loop(1
```

NetBeans Debugger

- NetBeans has experimental Truffle debugging support
- Download latest nightly build of NetBeans
  - This demo uses nightly build 201606100002
- Install Truffle plugin
  - Tools -> Plugins -> Available Plugins -> search for "Truffle"
  - Install "Truffle Debugging Support"
- Start SL in debug mode
  - `sl -debug tests/SumObject.sl`
- Manually insert `debugger;` statement into SumObject.sl
- Attach NetBeans debugger to port 8000

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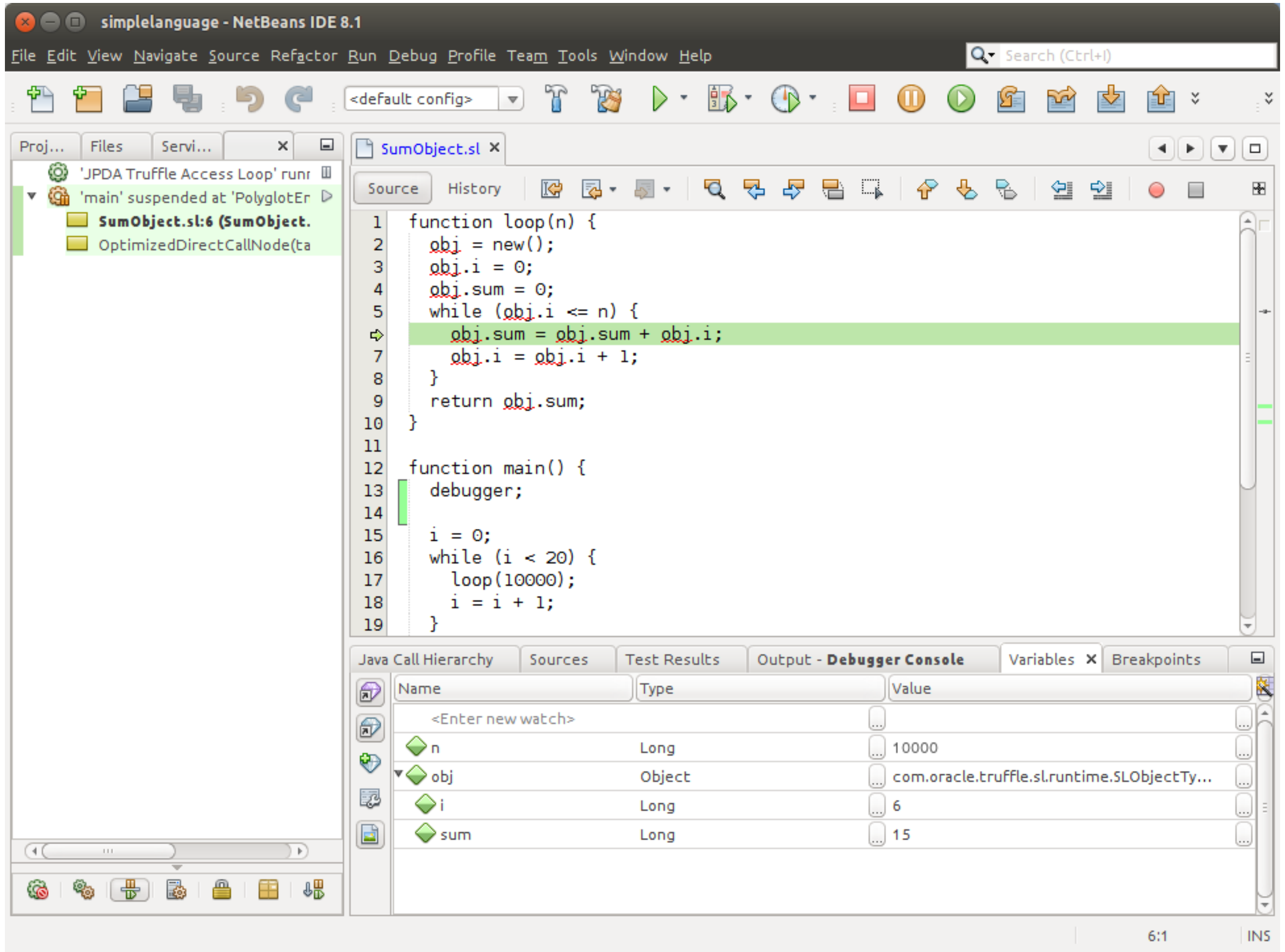
Example: NetBeans Debugger




```
sl -debug tests/SumObject.sl
```

`debugger;` statement sets a breakpoint manually because NetBeans does not know .sl files

Stepping and Variables view work as expected

Stacktrace view has small rendering issues

Bibliography

- Wurthinger et al. Practical Partial Evaluation for High-Performance Dynamic Language Runtimes. PLDI, 2017.
- Humer et al. A Domain-Specific Language for Building Self-Optimizing AST Interpreters. GPCE, 2014.
- Y. Futamura. Partial Evaluation of Computation Process—An Approach to a Compiler-Compiler. Systems, Computers, Controls 2(5):721-728, 1971
- Christian Wimmer. One VM to Rule Them All Tutorial. PLDI 2016.
- Christian Wimmer. Graal Tutorial. PLDI 2017.
- Interesting comparison: tracing-based metacompilation (e.g. PyPy)
  - Bolz et al. Tracing the meta-level: PyPy's tracing JIT compiler. ICOOLPS 2009.
  - Stefan Marr and Stéphane Ducasse. Tracing vs. Partial Evaluation: Comparing Meta-Compilation Approaches for Self-Optimizing Interpreters. OOPSLA 2015.