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AST Specialisation and Partial Evaluation for Easy High-Performance Metaprogramming

1st Workshop on Meta-Programming Techniques and Reflection (META)

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Research Manager
Oracle Labs
November 2016

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Outline

- We are using a novel combination of techniques to create high performance implementations of existing languages
  - Truffle: framework for writing AST interpreters in Java
  - Graal: new dynamic (JIT) compiler for the JVM that knows about Truffle
- We've found that this combination of tools is particularly useful for easy, pervasive, consistent, high-performance metaprogramming implementations
- We'll show why this is and what it looks like
- We'll suggest what properties from Truffle and Graal could be useful to make sure future language implementation systems have

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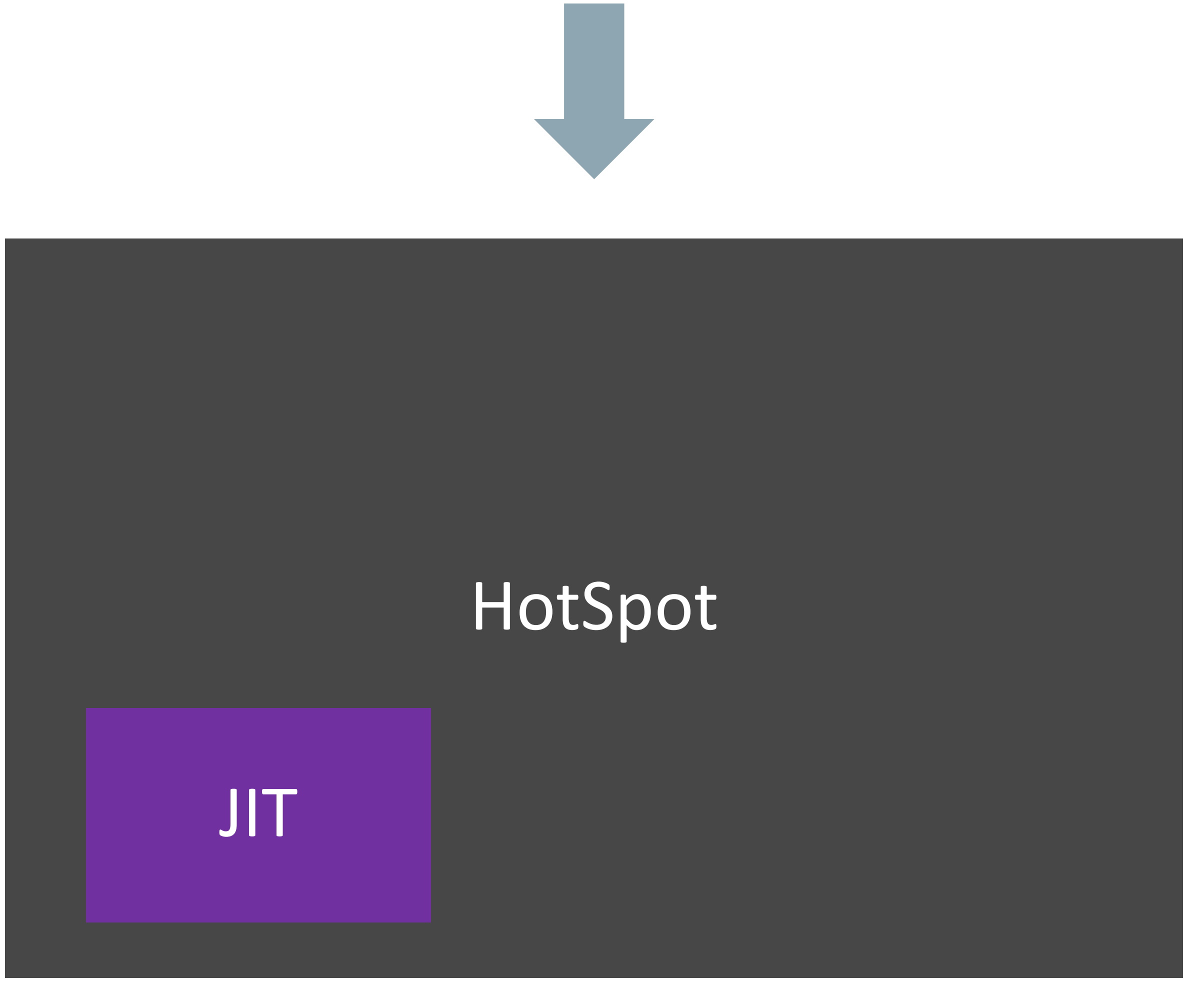
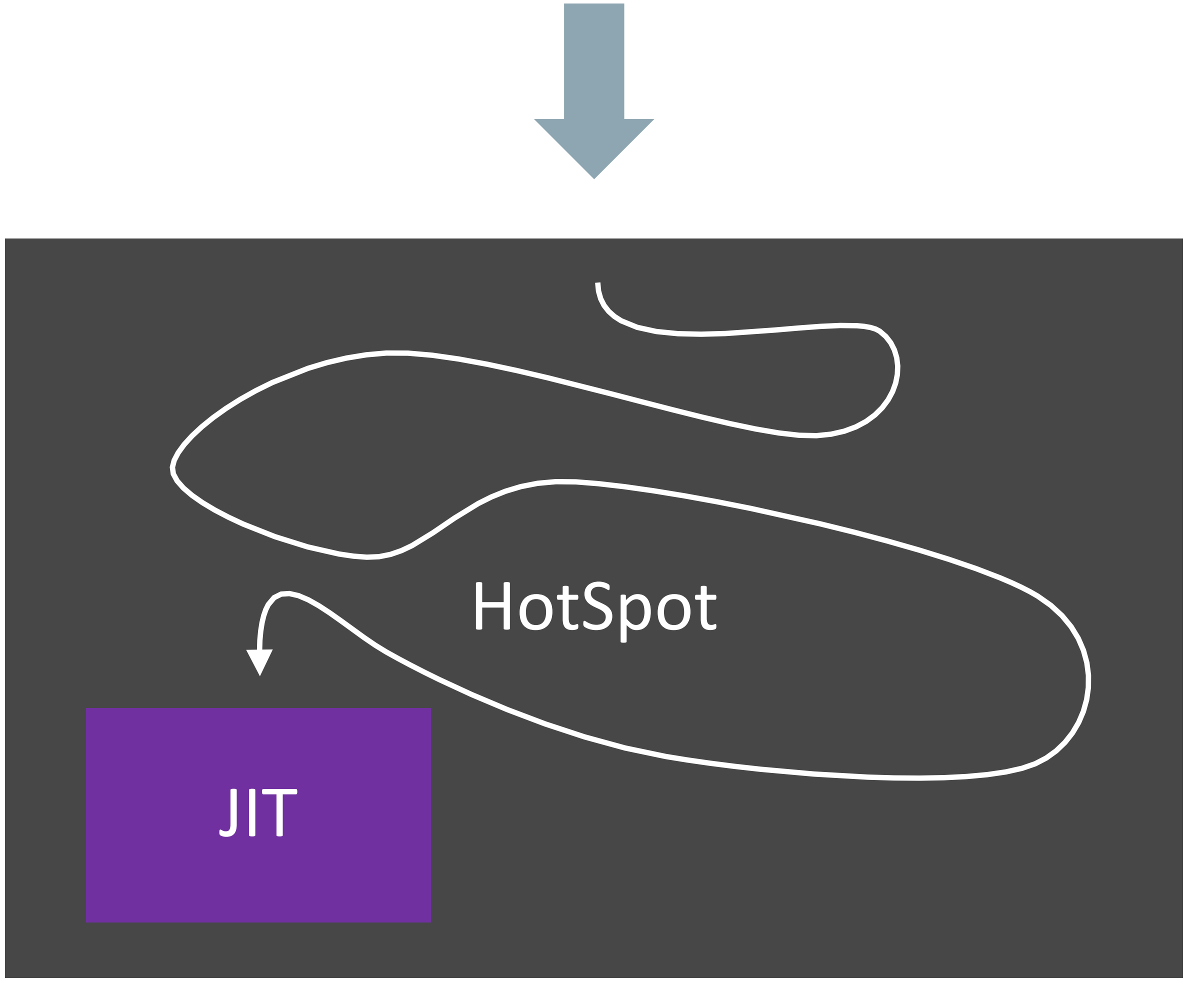
Truffle and Graal

HotSpot

HotSpot


HotSpot
JIT


HotSpot
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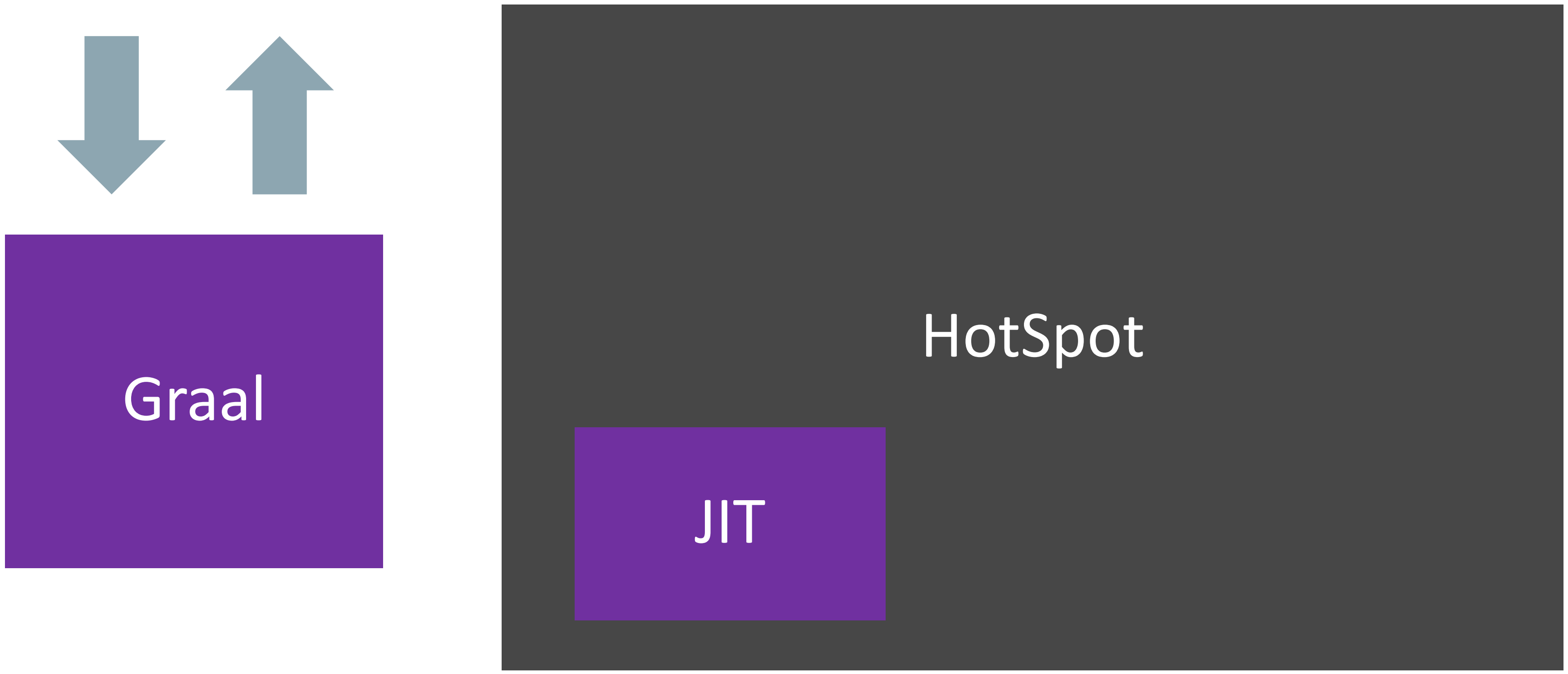
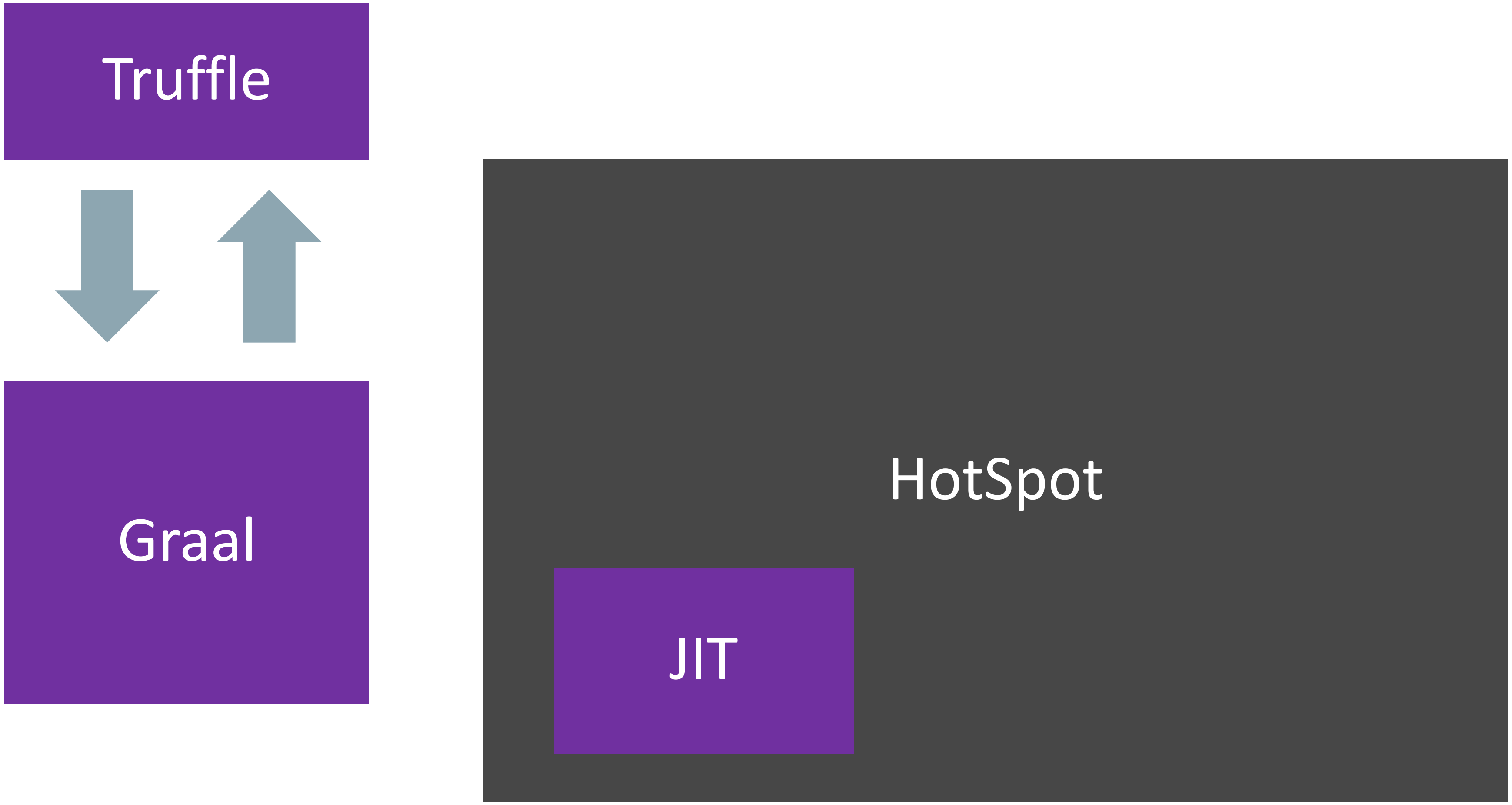
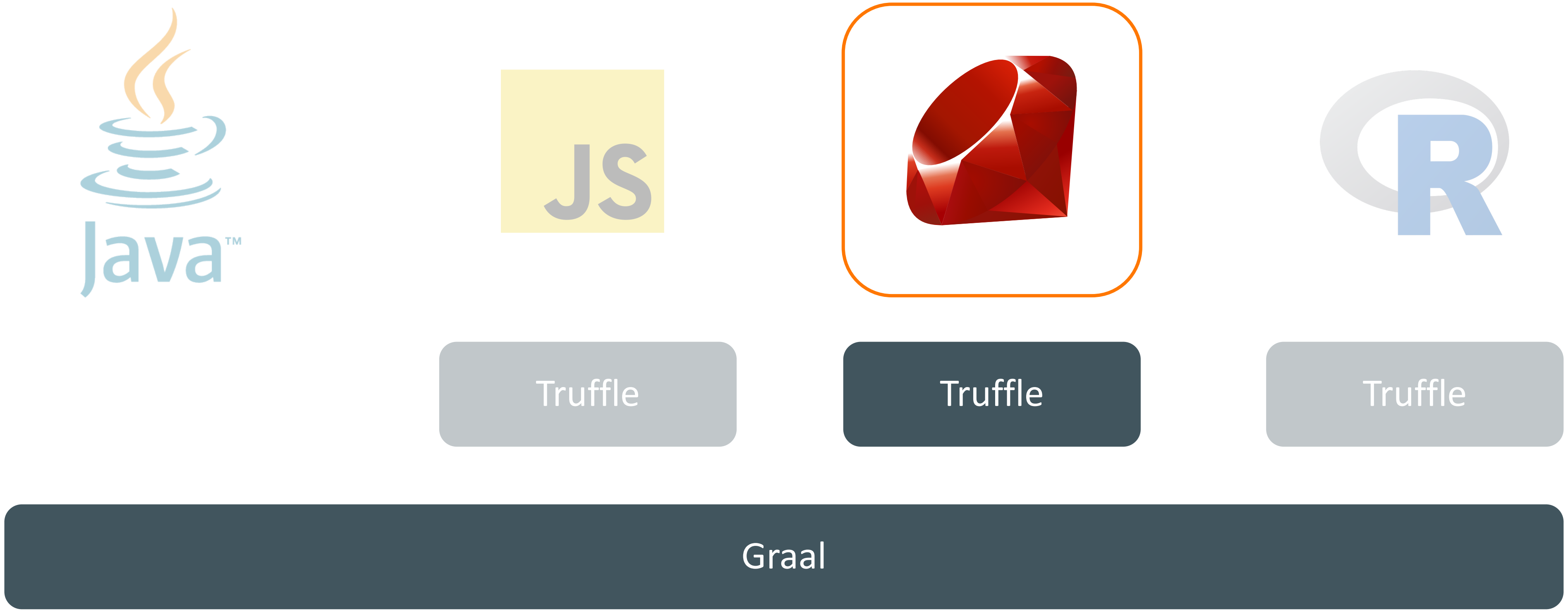

Graal
HotSpot
JIT


Truffle
Graal
HotSpot
JIT

Java

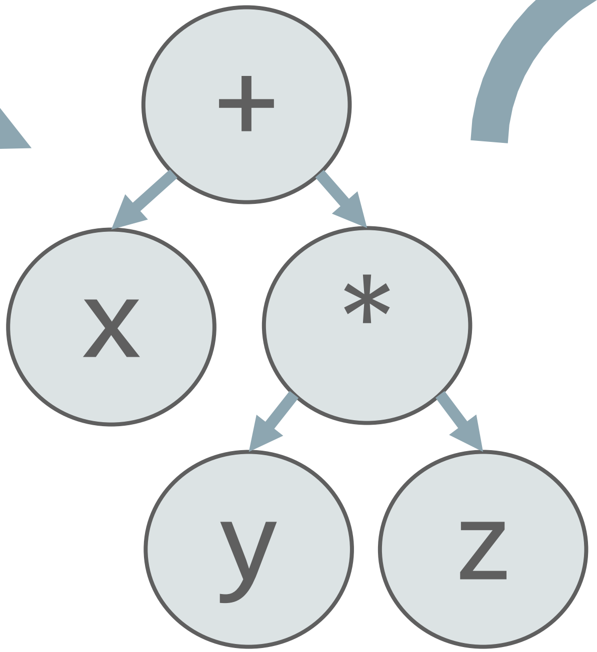
Truffle | Truffle | Truffle

Graal


Java™
JS
Truffle
Truffle
Truffle
Graal

Truffle for AST interpreters

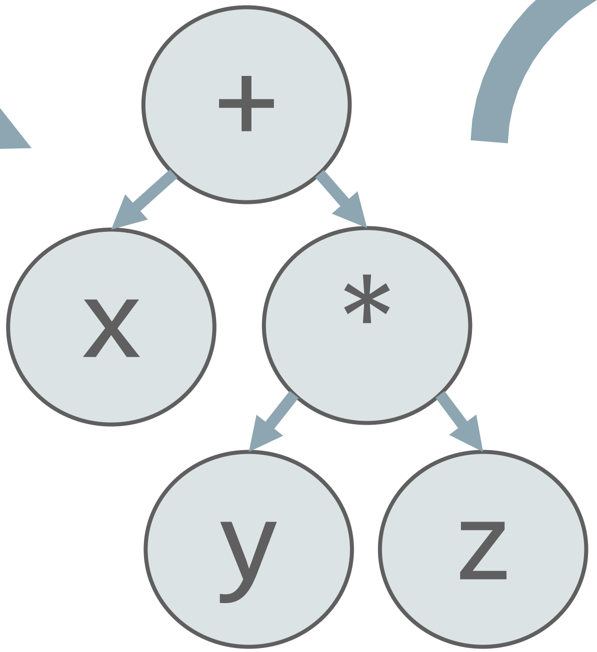
```
x + y * z
```




```
load_local x
load_local y
load_local z
call *
call +
```

```
pushq %rbp
movq  %rsp, %rbp
movq  %rdi, -8(%rbp)
movq  %rsi, -16(%rbp)
movq  %rdx, -24(%rbp)
movq  -16(%rbp), %rax
movl  %eax, %edx
movq  -24(%rbp), %rax
imull %edx, %eax
movq  -8(%rbp), %rdx
addl  %edx, %eax
popq  %rbp
ret
```

```
x + y * z
```

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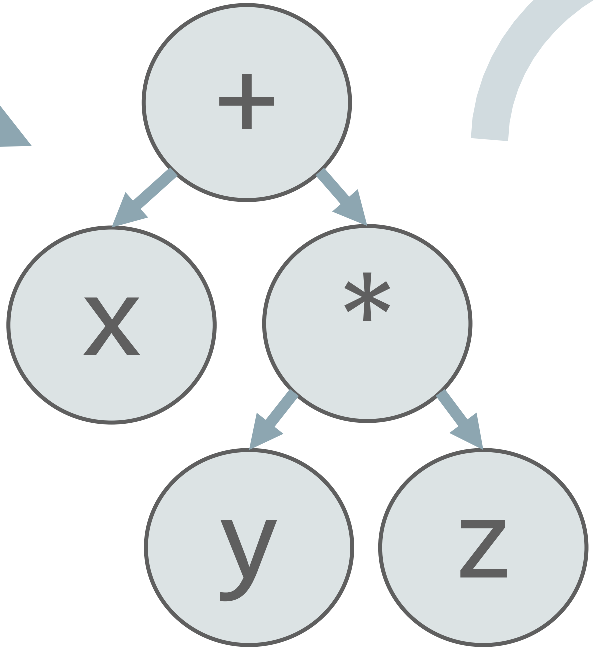


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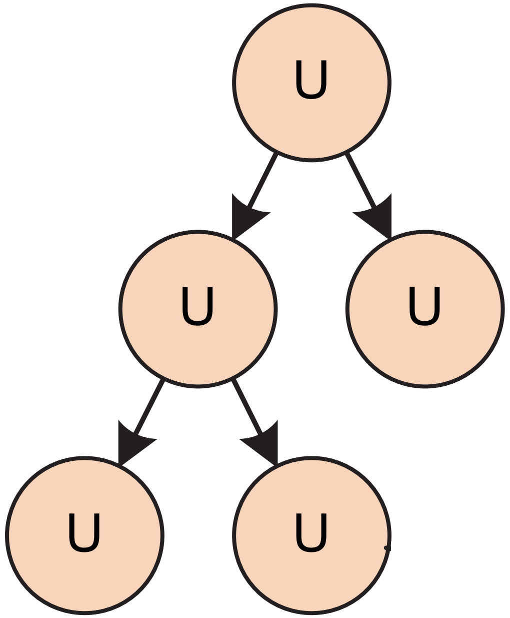
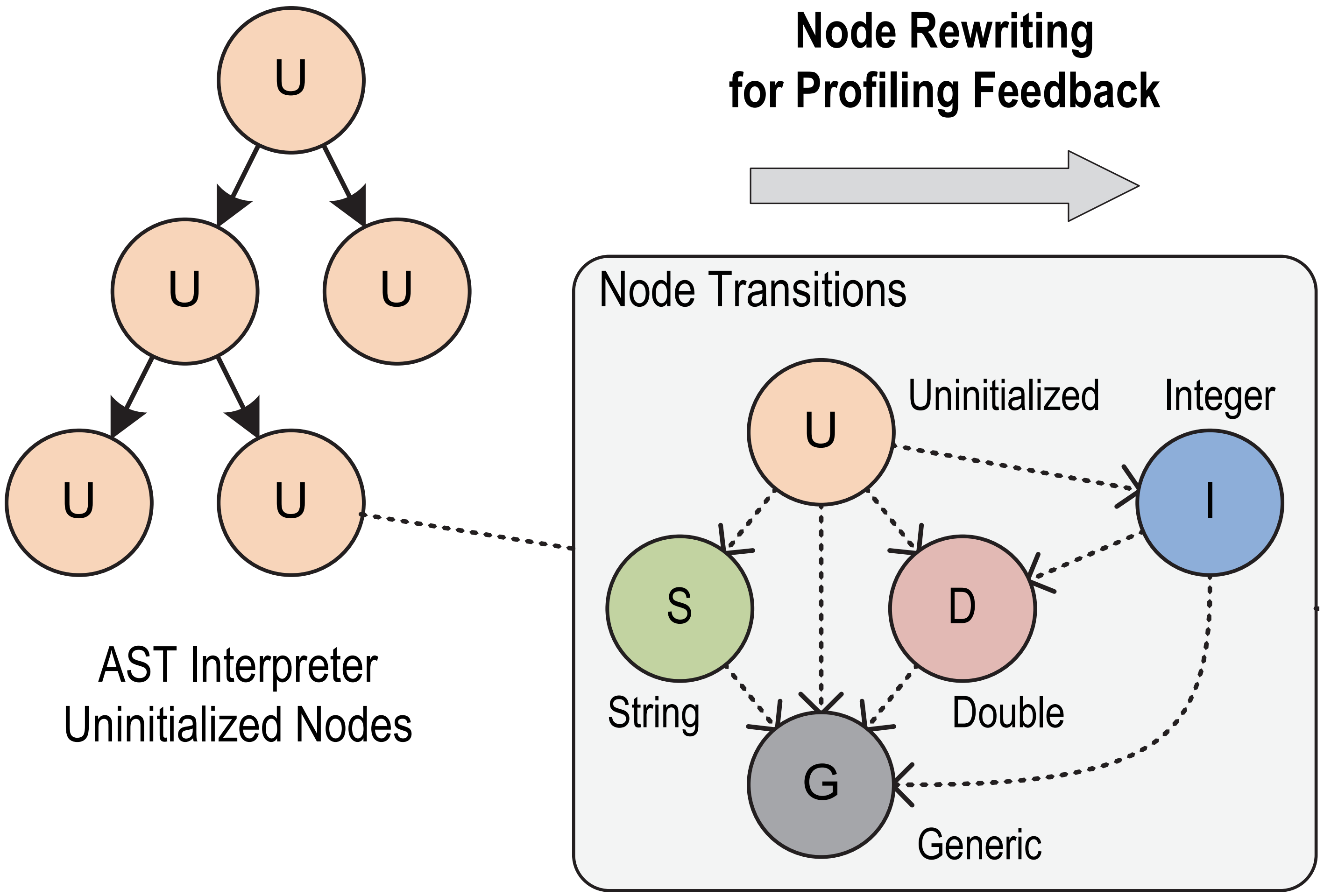
imull %edx, %eax
movq  -8(%rbp), %rdx
addl  %edx, %eax
popq  %rbp
ret
```



AST Interpreter
Uninitialized Nodes

T. Würthinger, C. Wimmer, A. Wöß, L. Stadler, G. Duboscq, C. Humer, G. Richards, D. Simon, and M. Wolczko. One VM to rule them all. In Proceedings of Onward!, 2013.



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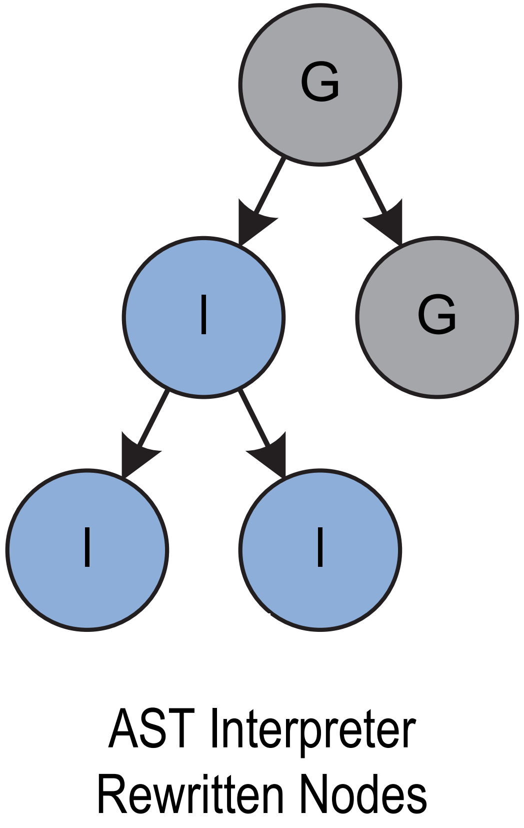
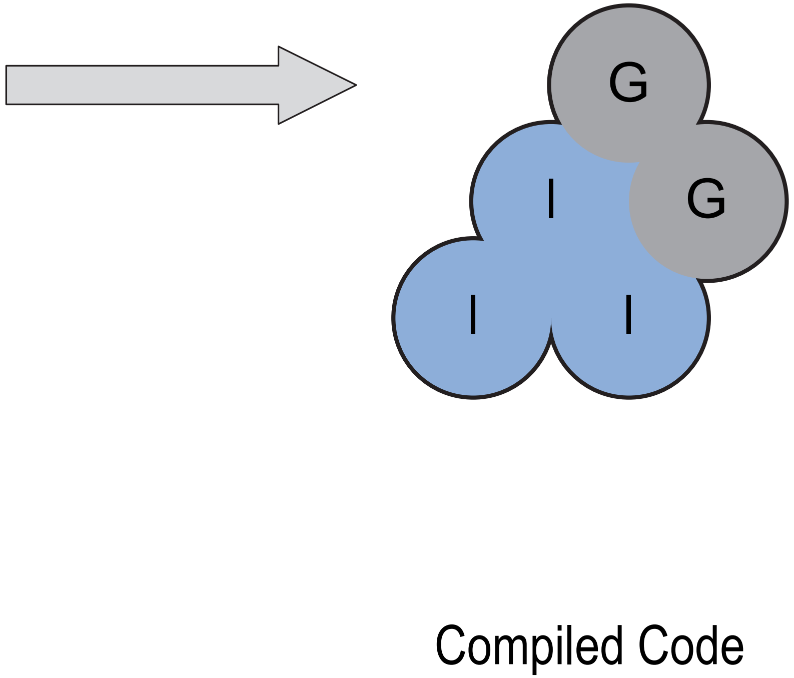
Graal for partial evaluation



Compilation using Partial Evaluation



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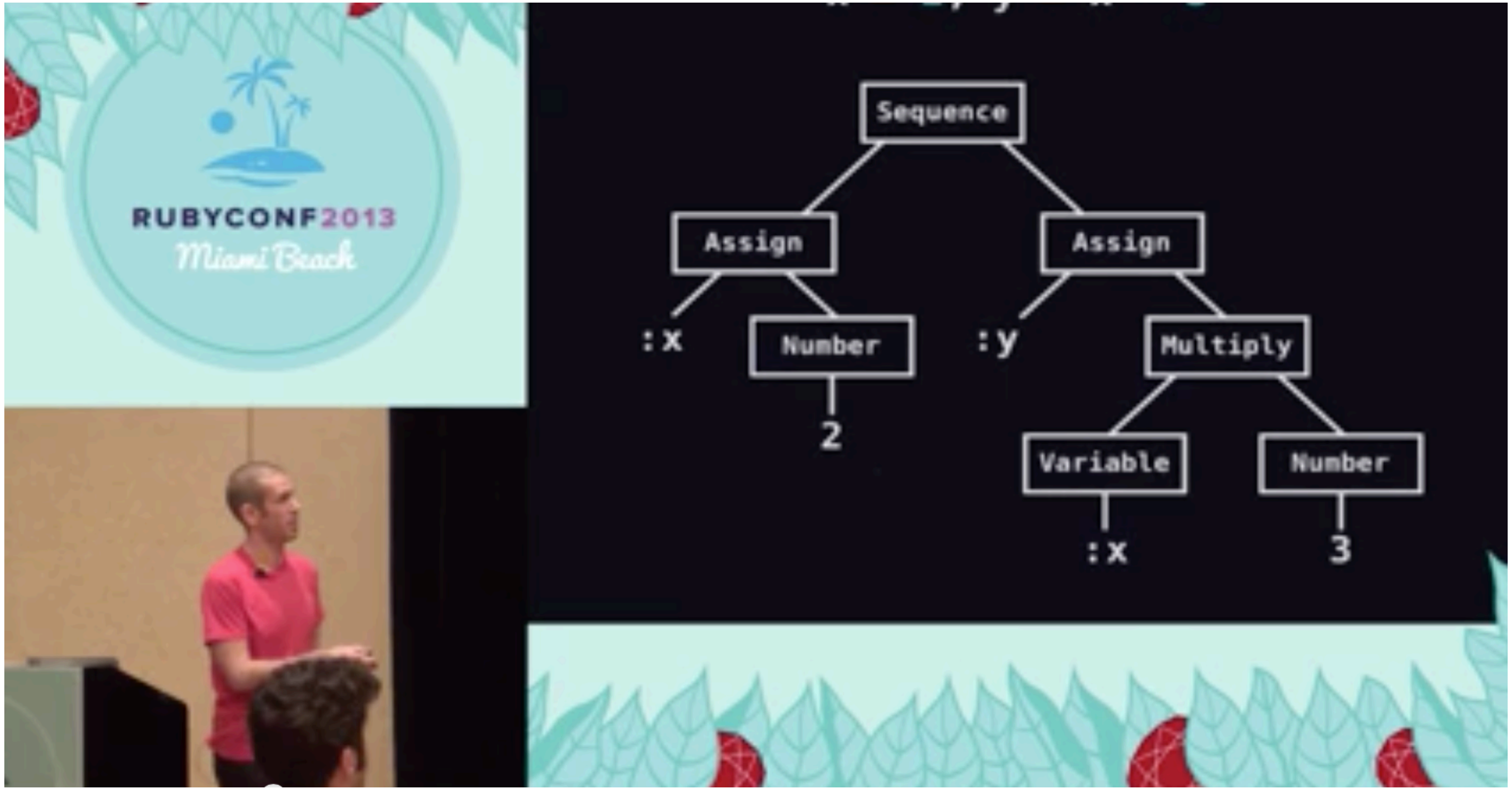

codon.com/compilers-for-free

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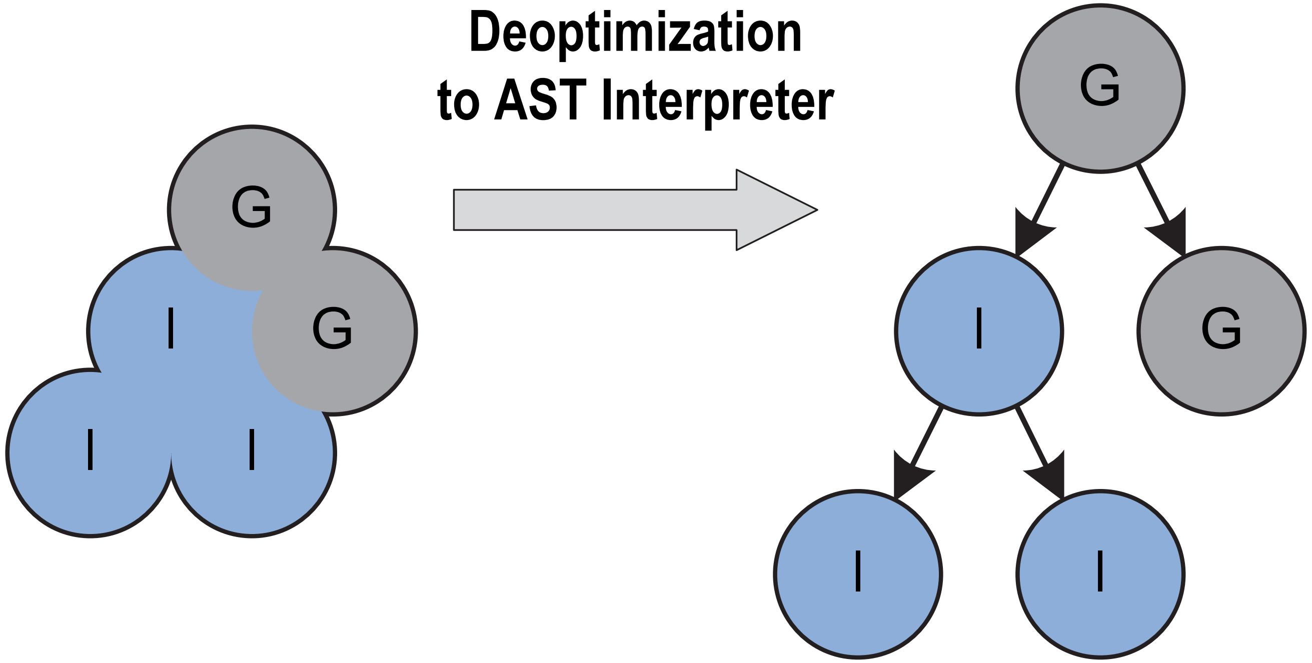

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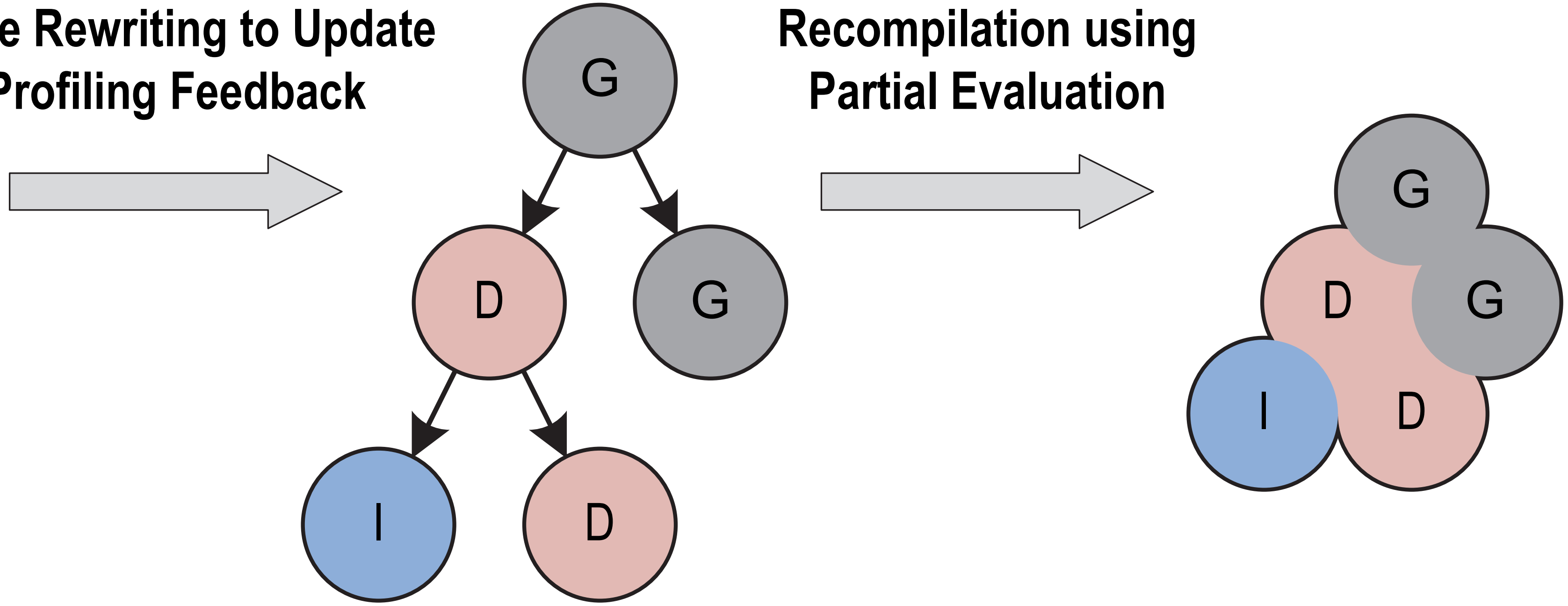
Node Rewriting to Update Profiling Feedback

Recompilation using Partial Evaluation



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Metaprogramming in Ruby

```
# Conventional send
object.method_name(arg1, arg2, ...)
# Metaprogramming send
object.send('method_name', arg1, arg2, ...)
```

```ruby
operator = exclude_end? ? :< : :<=
value.send(operator, last)
```

```
send("decode_png_resample_#{bit_depth}bit_value")
```

```ruby
def method_missing(method, *args)
  @encapsulated_value.send(method, *args)
end
```

```ruby
def method_missing(name, *args)
  if Color.respond_to?(name)
    return Color.send(name, *args)
  end
end
```

```
eval(generated_template, variables)
```

```
object.instance_variable_get('@variable_name')
object.instance_variable_set('@variable_name', value)
```

```ruby
def eql?(other)
  @hash.eql?(other.instance_variable_get(:@hash))
end
```

Foundational techniques

Caching

```ruby
a = [1, 2, 3]
puts a[2]
```

```ruby
h = {1=>a, 2=>b, 3=>c}
puts h[2]
```

Class	Method name	Method
Array	[]	Array#[]
Hash	[]	Hash#[]
…. more entries …		

one table per virtual machine, lots of entries

Inline caching

L. P. Deutsch and A. M. Schiffman. Efficient Implementation of the Smalltalk-80 System, 1984.

```
a = [1, 2, 3]
puts a[2]
```

```
h = {1=>a, 2=>b, 3=>c}
puts h[2]
```

Class	Method
Array	Array#[]

Class	Method
Hash	Hash#[]

one table per call site, one entry

one table per call site , one entry

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Polymorphic inline caching

```
x = random(a, h)
x[2]
```

Class	Method
Array	Array#[]

```
x = random(a, h)
x[2]
```

Class	Method
Hash	Hash#[]

one table per call site, one entry

one table per call site , one entry

Polymorphic inline caching

U. Hölzle, C. Chambers, and D. Ungar. Optimizing dynamically-typed object-oriented languages with polymorphic inline caches. In *ECOOP'91 European Conference on Object-Oriented Programming*, volume 512 of *Lecture Notes in Computer Science*. 1991.

```
x = random(a, h)
x[2]
```

Class	Method
Array	Array#[]
Hash	Hash#[]
…. more entries …	

one table per call site, multiple entries

```
x = random(a, h)
x[2]
```

Class	Method
Array	Array#[]
Hash	Hash#[]
…. more entries …	

one table per call site, multiple entries

Dispatch chains

S. Marr, C. Seaton, and S. Ducasse. Zero-overhead metaprogramming: Reflection and metaobject protocols fast and without compromises. In *Proceedings of the 36th ACM SIGPLAN Conference on Programming Language Design and Implementation*, 2015.

```
bit_depth = random(8, 16, 32)
send(image, "resample_#{bit_depth}bit")
```

Class	Method name	Method
Image	resample_8bit	Image#resample_8bit
Image	resample_16bit	Image#resample_16bit
Image	resample_32bit	Image#resample_32bit
	…. more entries …	

one table per call site, multiple entries

Why aren’t these a solution on their own?

Caches are currently implemented manually

```
struct rb_call_cache {
    /* inline cache: keys */
    rb_serial_t method_state;
    rb_serial_t class_serial;

    /* inline cache: values */
    const rb_callable_method_entry_t *me;

    vm_call_handler call;

    union {
      unsigned int index; /* used by ivar */
      enum method_missing_reason method_missing_reason; /* used by method_missing */
      int inc_sp; /* used by cfunc */
    } aux;
};
```

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You need somewhere to store an inline cache

```
a.foo(b)

a = [1, 2, 3]
a.sort

a.send(:foo, b)
```

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You need somewhere to store an inline cache

```
a.foo(b)

a = [1, 2, 3]
a.sort

a.send(:foo, b)
```

```
a <=> b
```

You need somewhere to store an inline cache

```ruby
a.foo(b)

a = [1, 2, 3]
a.sort

a.send(:foo, b)
```

```ruby
a.foo(b)
```

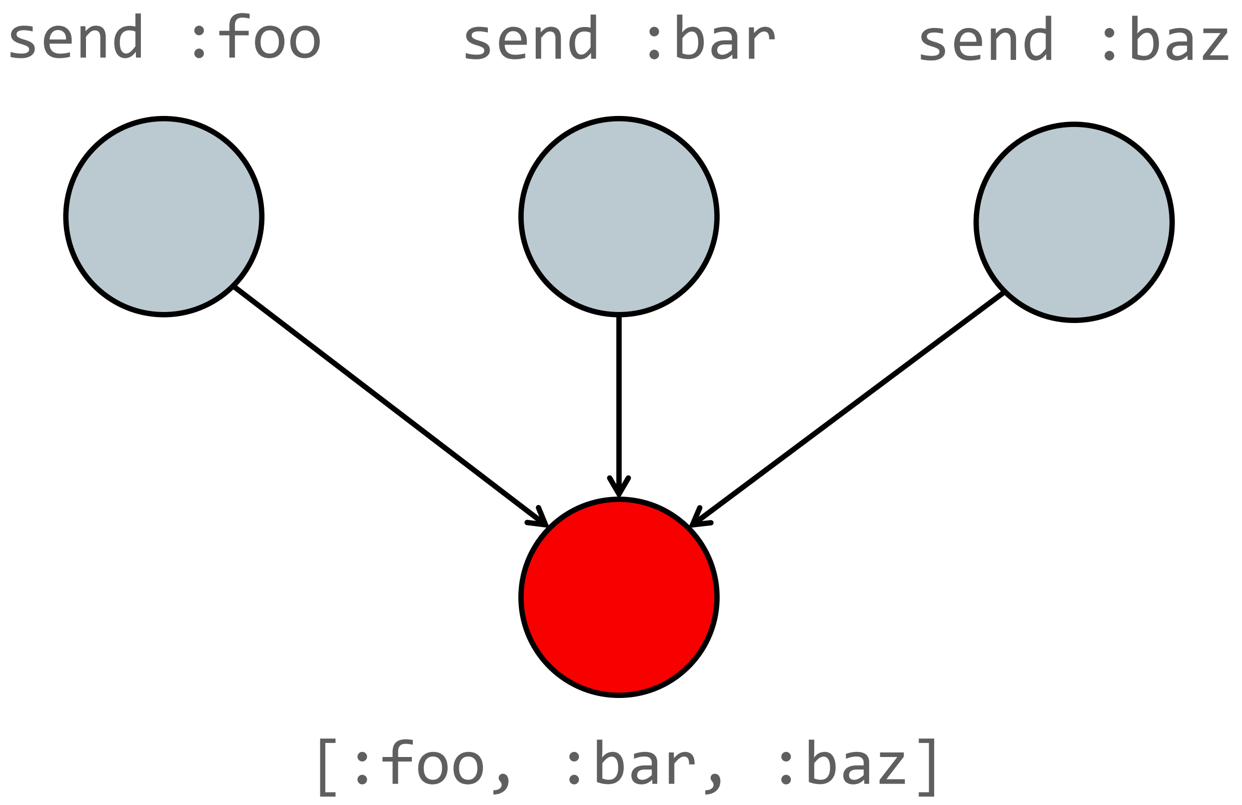
You need somewhere to store an inline cache

```java
@JRubyMethod(name = "send")
public static IRubyObject send(ThreadContext context, IRubyObject self, String name, IRubyObject[] args) {
    DynamicMethod method = searchMethod(name);
    return method.call(context, self, this, name, args);
}
```

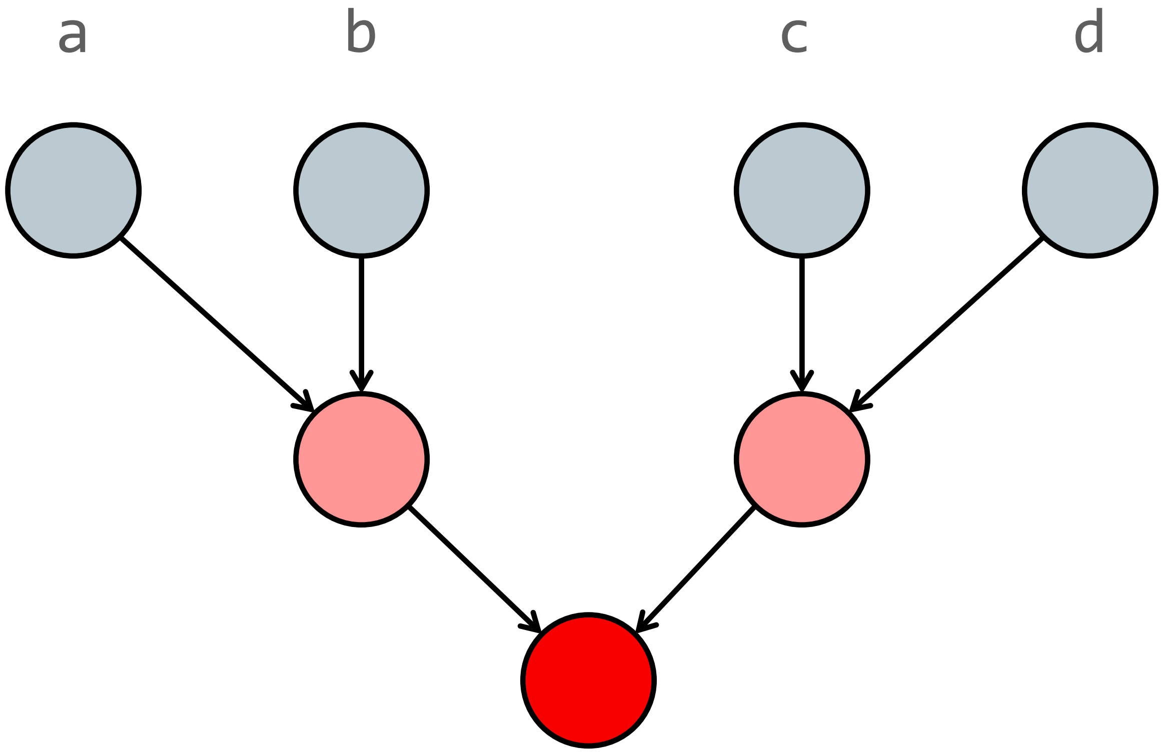
You need somewhere to store an inline cache

```
@JRubyMethod(name = "sort")
public static IRubyObject sort(ThreadContext context, IRubyObject array, String name) {
    ...
    Arrays.sort(newValues, 0, length, new Comparator() {
        public int compare(Object o1, Object o2) {
            DynamicMethod method = searchMethod("<=>");
            return method.call(context, self, this, name, o1, o2);
        }
    });
    ...
}
```

Caches quickly become megamorphic



Caches quickly become megamorphic



`[a, b, c, d]`

How Truffle and Graal make a difference

An easy place to store state

```
class SendNode extends Node {
  String methodName;
  Node receiverNode;

  public Object execute() {
    Object receiver = receiverNode.execute();
    Method method = receiver.lookup(methodName);
    return method.call();
  }
}
```

An easy place to store state

```java
class SendNode extends Node {
  String methodName;
  Node receiverNode;
  Class cachedClass;
  Method cachedMethod;

  public Object execute() {
    Object receiver = receiverNode.execute();
    if (receiver.getClass() != cachedClass) {
      cachedClass = receiver.getClass();
      cachedMethod = receiver.lookup(methodName);
    }
    return cachedMethod.call();
  }
}
```

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A DSL to write caches in just a couple of lines

```
@NodeChild("receiver")
class SendNode extends Node {
    String methodName;

    @Specialisation(guards = "receiver.getClass() == cachedClass")
    public Object execute(Object receiver,
                          @Cached("receiver.getClass()") Class cachedClass,
                          @Cached("receiver.lookup(methodName)") Method cachedMethod) {
        return method.call();
    }
}
```

A DSL to write caches in just a couple of lines

```
@NodeChildren({"receiver", "name"})
class SendNode extends Node {
    @Specialisation(guards = {"receiver.getClass() == cachedClass", "name.equals(cachedName)"})
    public Object execute(Object receiver,
                          String name,
                          @Cached("receiver.getClass()") Class cachedClass,
                          @Cached("name") String cachedName,
                          @Cached("receiver.lookup(name)") Method cachedMethod) {
        return method.call();
    }
}
```

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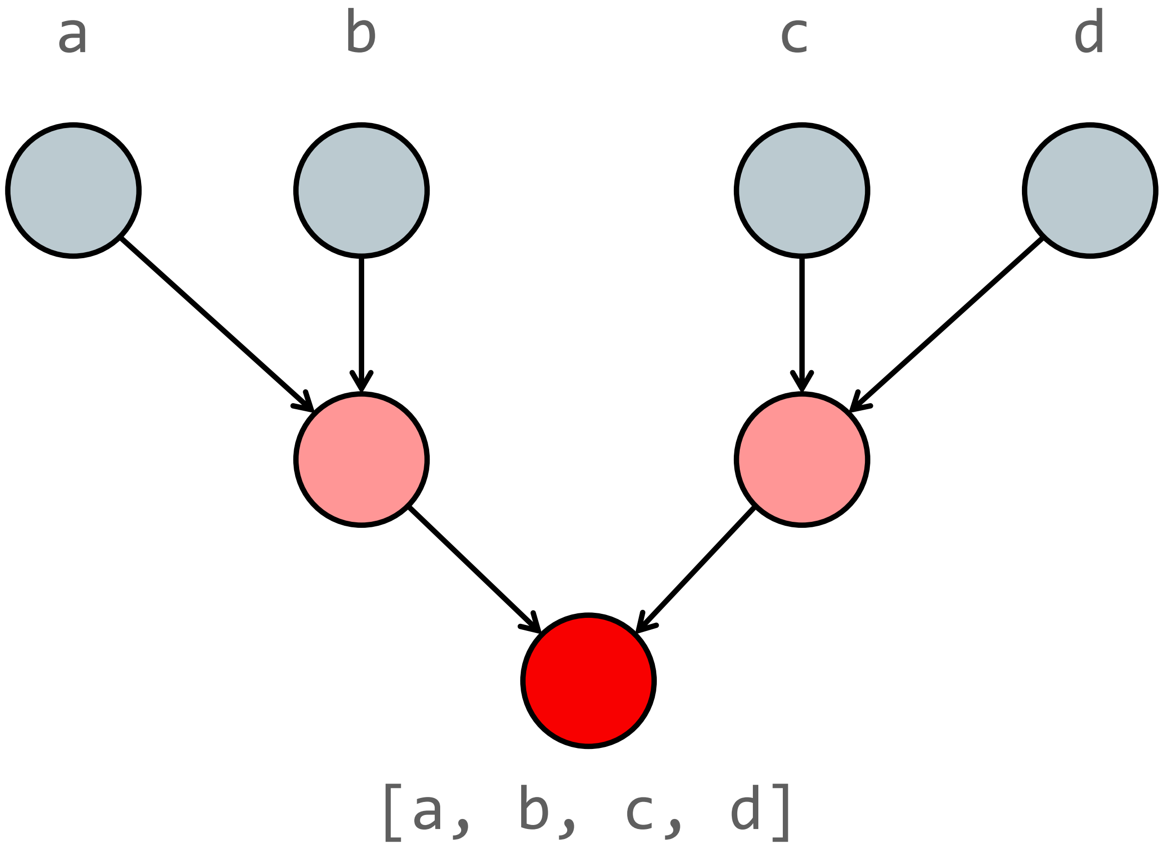
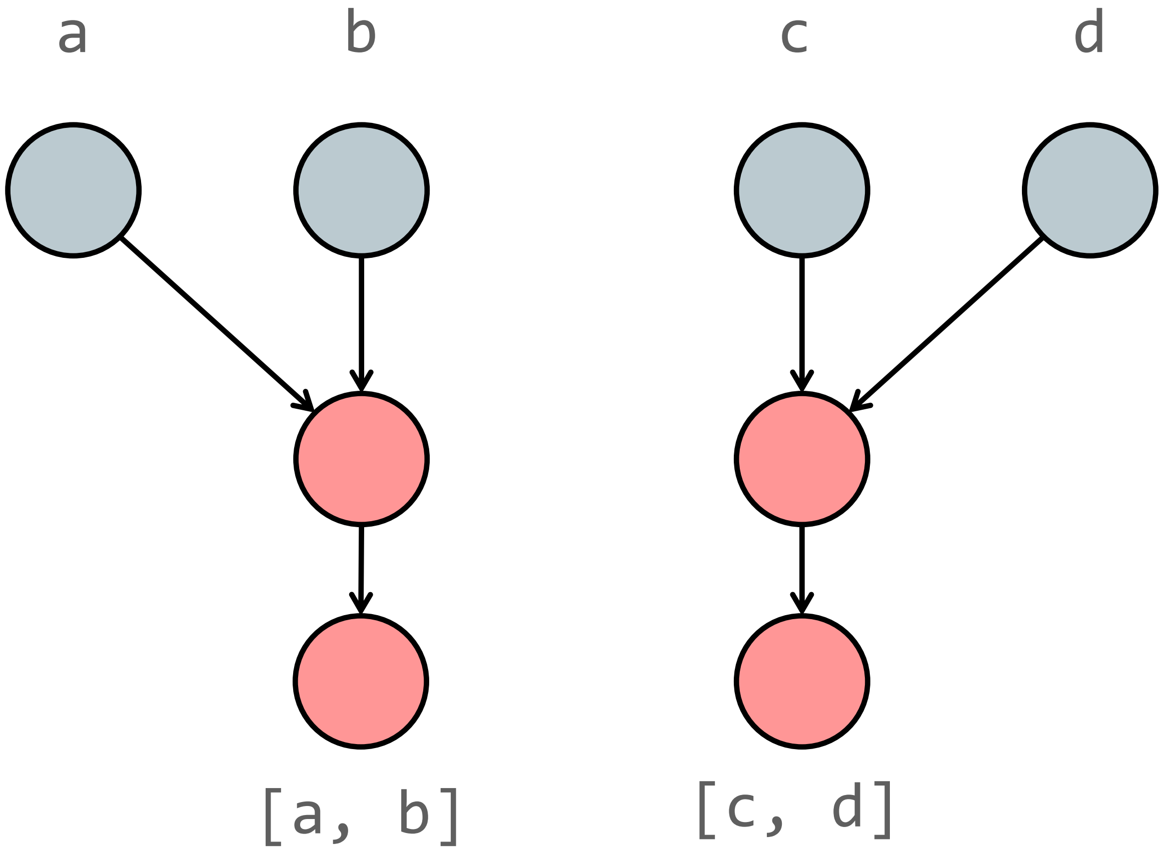
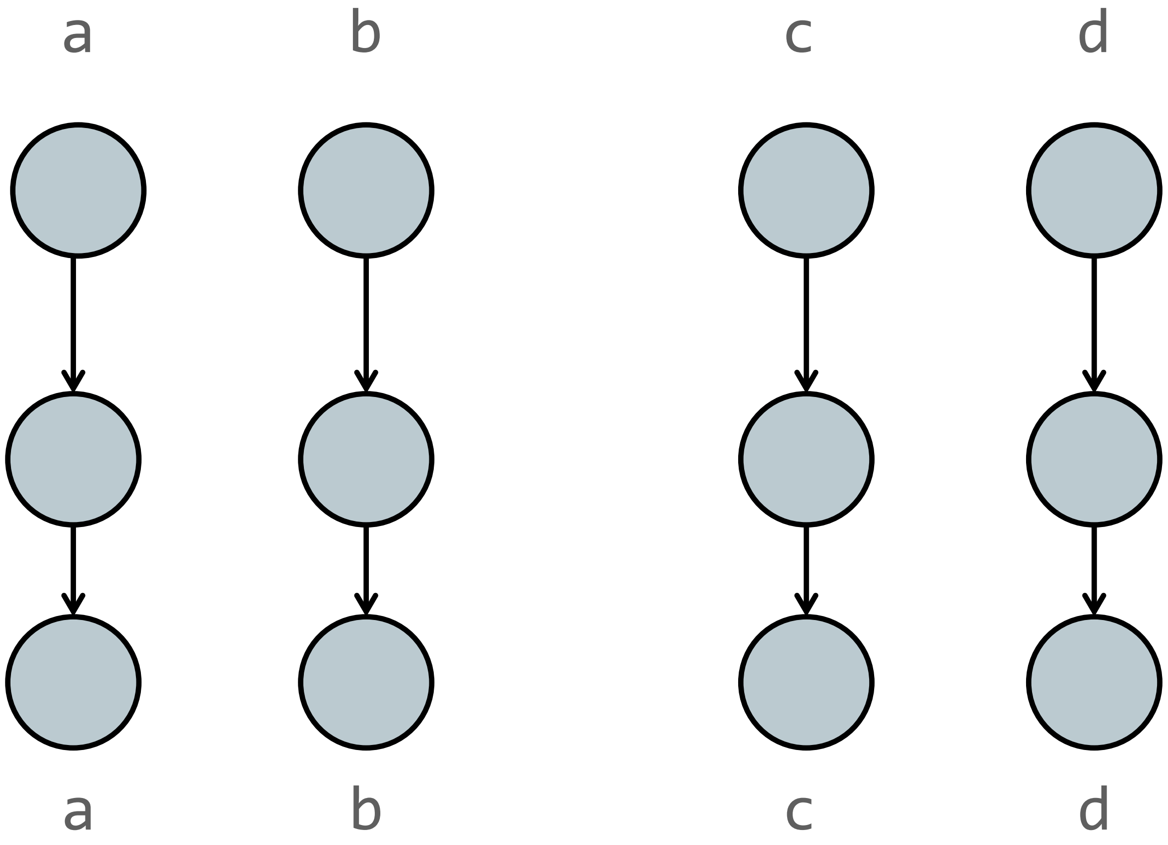
Automatic splitting to push caches down the call stack



Automatic splitting to push caches down the call stack



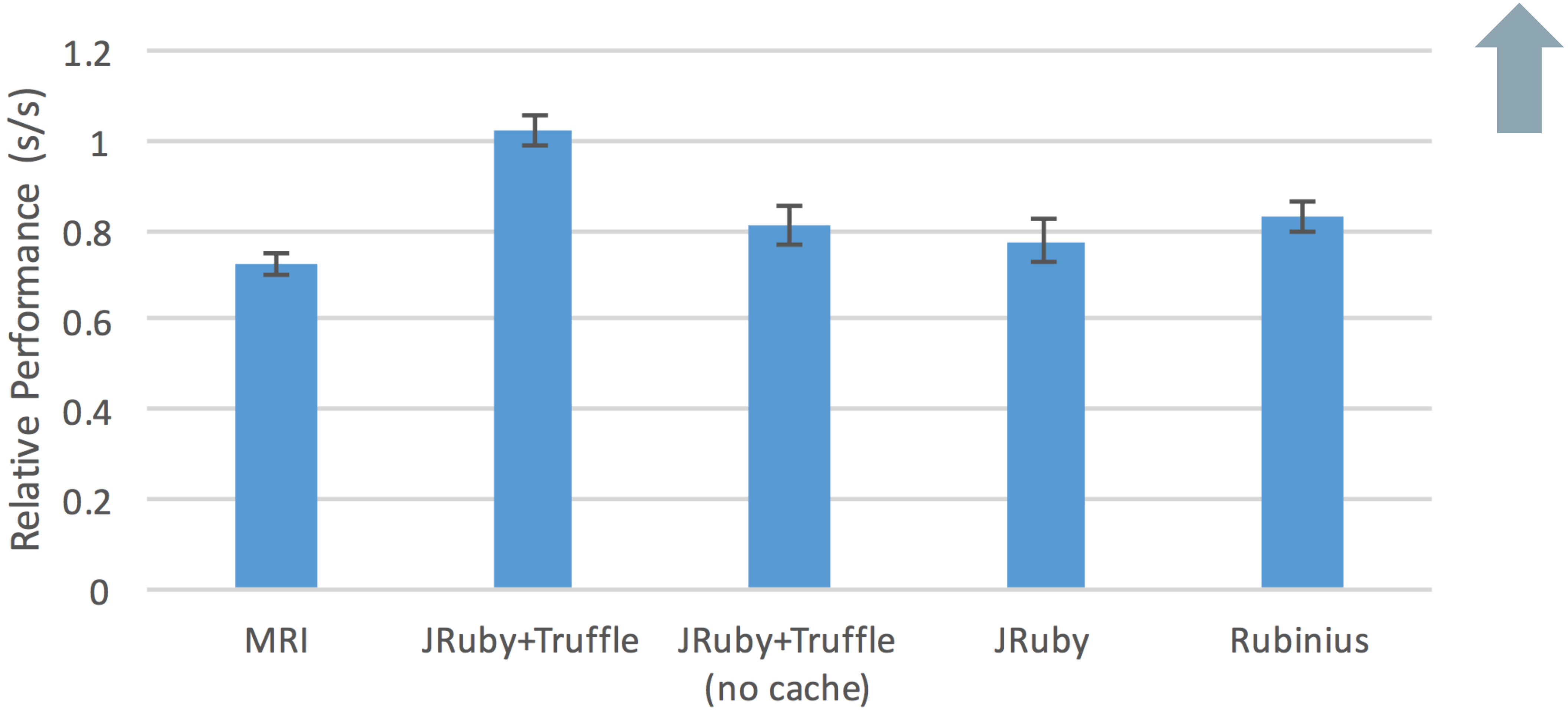
Automatic splitting to push caches down the call stack



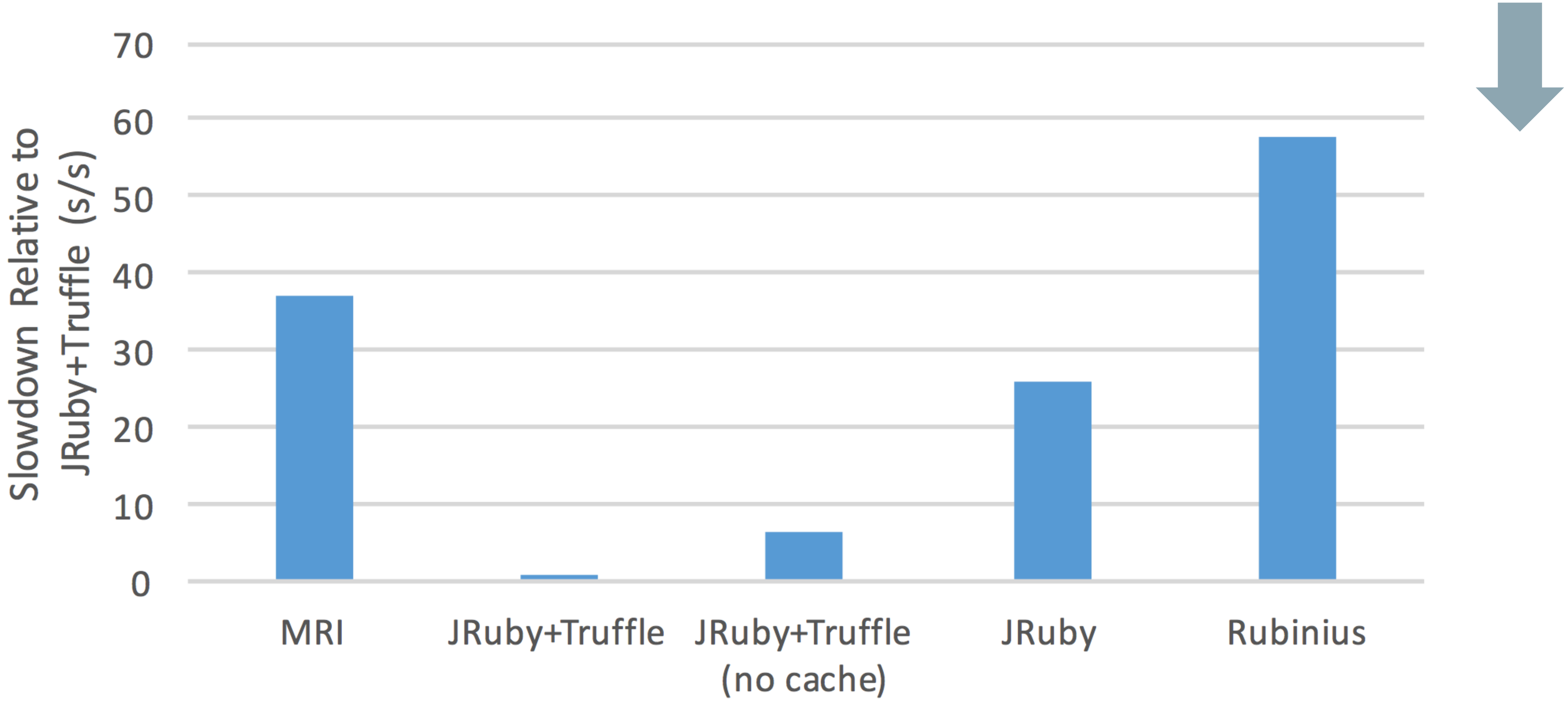
Results

```ruby
def eql?(other)
  @hash.eql?(other.instance_variable_get(:@hash))
end
```

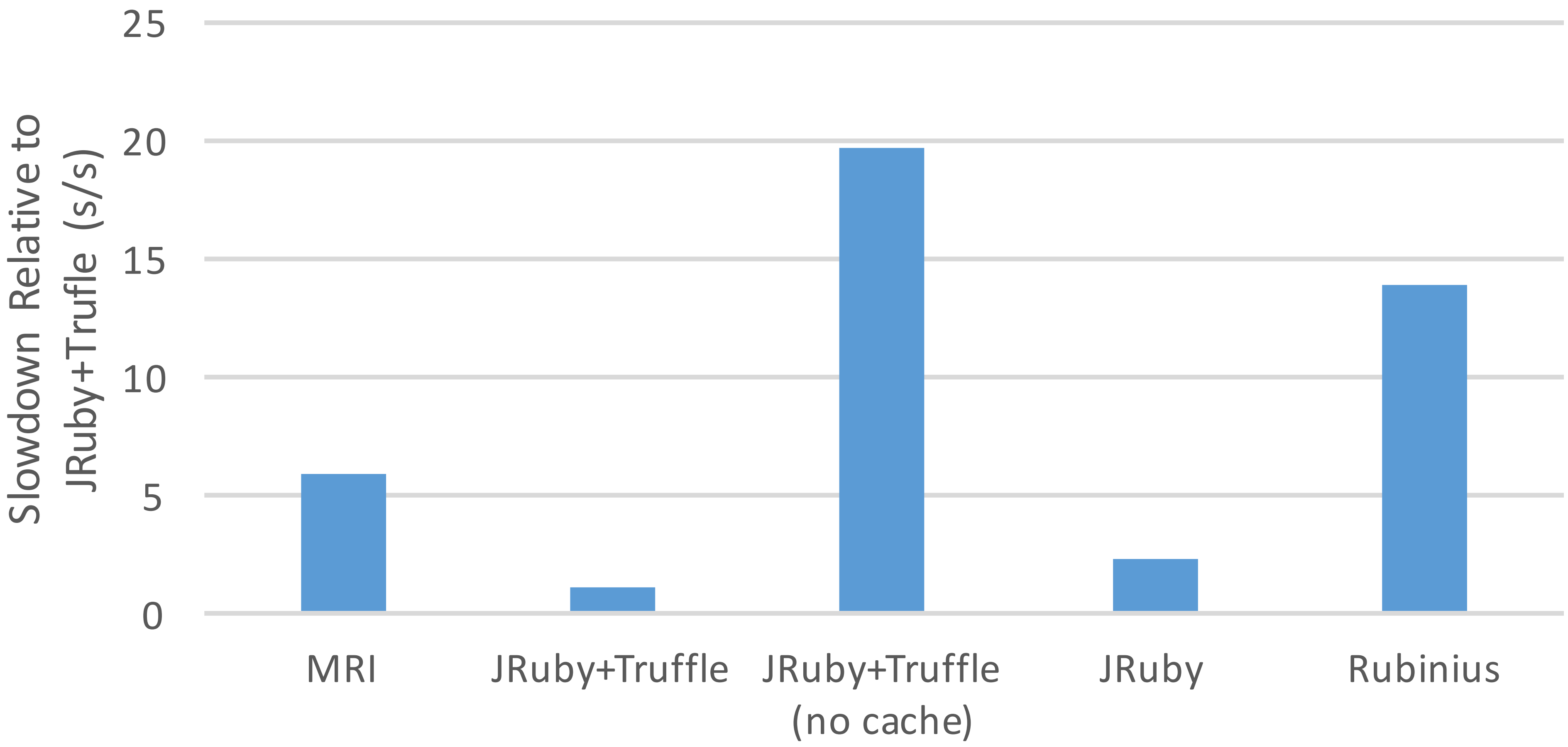
Relative performance of metaprogramming access to instance variables relative to conventional access



Slowdown of metaprogramming access to instance variables relative to JRuby+Truffle



Slowdown of `Set#eql?` relative to JRuby+Truffle



The important properties

Somewhere to store state

- Caching and profiling requires somewhere to store state
- Truffle's nodes are just Java objects, so you can store whatever you want in normal Java fields
- In Truffle you are almost always in a node, so you almost always have access to your state
  - Doesn't become inaccessible in compiled code

Low-effort caching

- Truffle's DSL makes it easy to add sophisticated polymorphic inline caches anywhere
- This is implemented using the state that we just mentioned
- Guards can be arbitrary Java expressions, or zero-overhead mutable flags using deoptimisation
- Supports an arbitrary number of guards

Dynamic optimisation

- Dynamic optimisation (JIT compilation) comes for free from Graal
- Partial evaluation removes degrees of freedom that aren’t used
  - Allows us to add degrees of freedom to handle metaprogramming without worrying

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Dynamic *de*optimisation

- Allows us to make speculative optimisations and reverse them if they were wrong
- Allows functionality not used to be ‘turned off’ until it is needed
- Allows local variables to be lowered all the way to registers while still letting frames be accessed as if they were objects

Automatic inlining and splitting

- Removes the overhead of intermediate methods calls and indirection used in metaprogramming
- Allows state to be ‘pushed down’ the call stack to reduce polymorphism

Programmatic access to frames

- Allows local variables to be read and written from outside method activations
- Whole frames represented as objects
- Access to the list of frames currently on the stack

Conclusions

- We already knew how to make most (not all) of Ruby's metaprogramming functionality fast
- Existing mature Ruby implementations don't apply this knowledge
- Why? Because it was hard in practice to do it consistently and pervasively that they never got around to it

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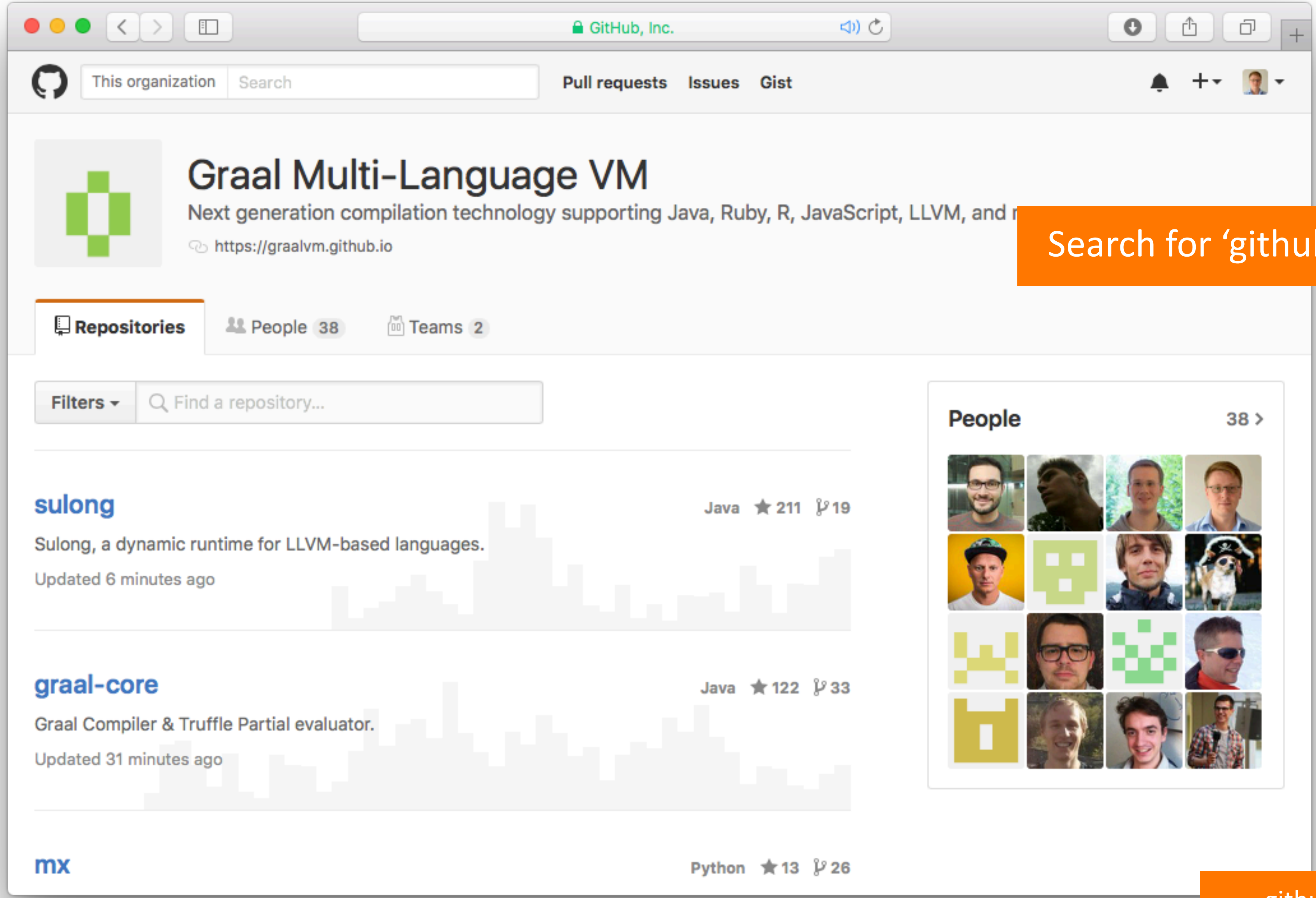
Conclusions

- Truffle and Graal make it so much easier
- We’ve identified what we think are the key properties that enable this
- I think Truffle and Graal are the only systems to provide effective implementations of these
- If you are implementing a metaprogramming language, use Truffle and Graal
- If you’re making a new language implementation system, perhaps incorporate these same properties

Where to find more information

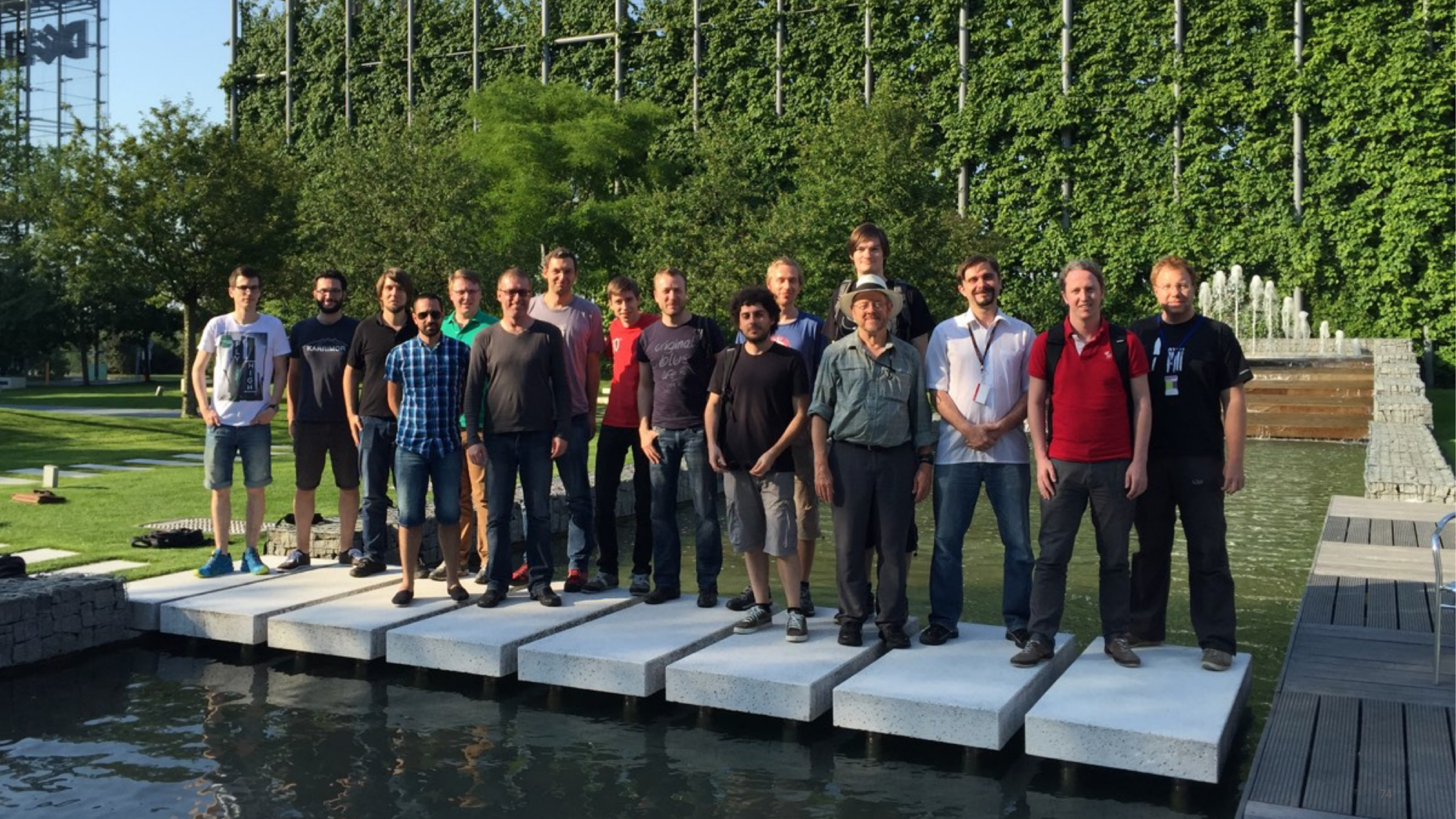


Search for 'github graalvm'

github.com/graalvm

Truffle and Graal: Fast Programming Languages With Modest Effort

Thursday, 14:20, Matterhorn 3 (this room)
SPLASH-I
Adam Welc


FLY
HIGH
KARRIMOR
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Acknowledgements

Oracle
Danilo Ansaloni
Stefan Anzinger
Cosmin Basca
Daniele Bonetta
Matthias Brantner
Petr Chalupa
Jürgen Christ
Laurent Daynès
Gilles Duboscq
Martin Entlicher
Brandon Fish
Bastian Hossbach
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