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What makes TruffleRuby run Optcarrot 9 times faster than MRI?

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Outline

1. Optcarrot
2. TruffleRuby
3. Optimizations

Optcarrot

Nintendo Entertainment System emulator

Optcarrot

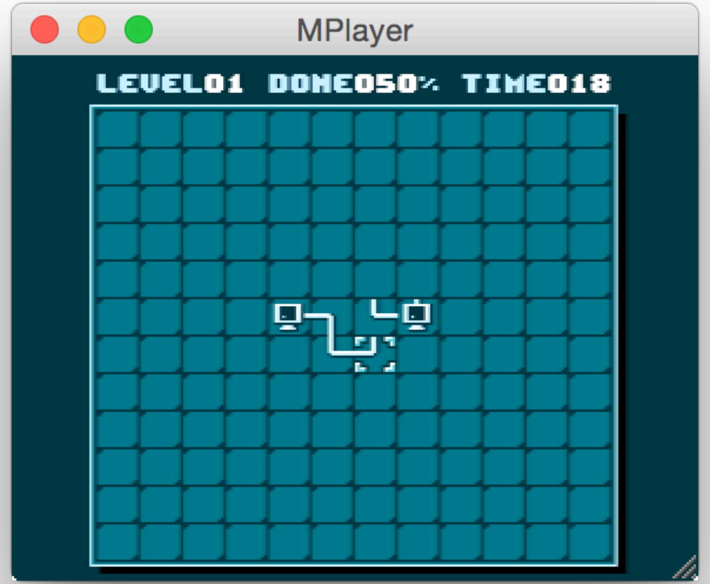
- **NES** Emulator
  - 8-bit, CPU, PPU, 2kB RAM, 2kB VRAM
  - Released in 1983
  - github.com/mame/optcarrot
- A benchmark created to drive Ruby MRI 3x3 improvements
- It runs the Lan Master game

Nintendo Entertainment System

https://en.wikipedia.org/wiki/Nintendo_Entertainment_System#/media/File:NES-Console-Set.jpg

Lets play

- Using:
  - MRI
  - TruffleRuby



Lan Master

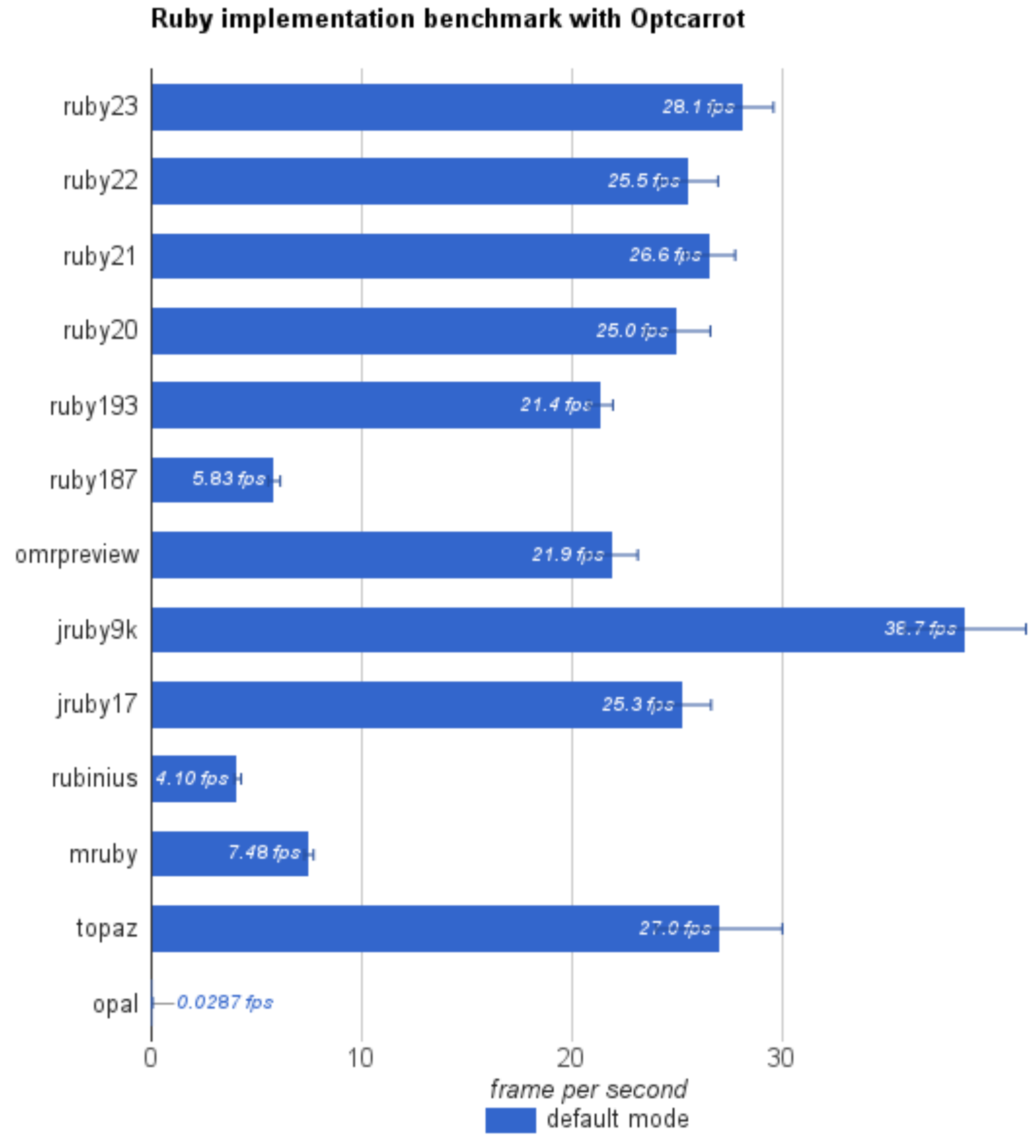
MRI 2.4.0

TruffleRuby

Results

Published results

- Without TruffleRuby
- 180 frames



https://raw.githubusercontent.com/mame/optcarrot/master/doc/benchmark-default.png

Benchmarking

- Implementations:
  - MRI 2.0
  - MRI 2.4
  - JRuby, 9.0 indy server
  - TruffleRuby, GraalVM 0.19
- Options
  - 6000 frames
  - Headless

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Benchmarking

9.5 times faster

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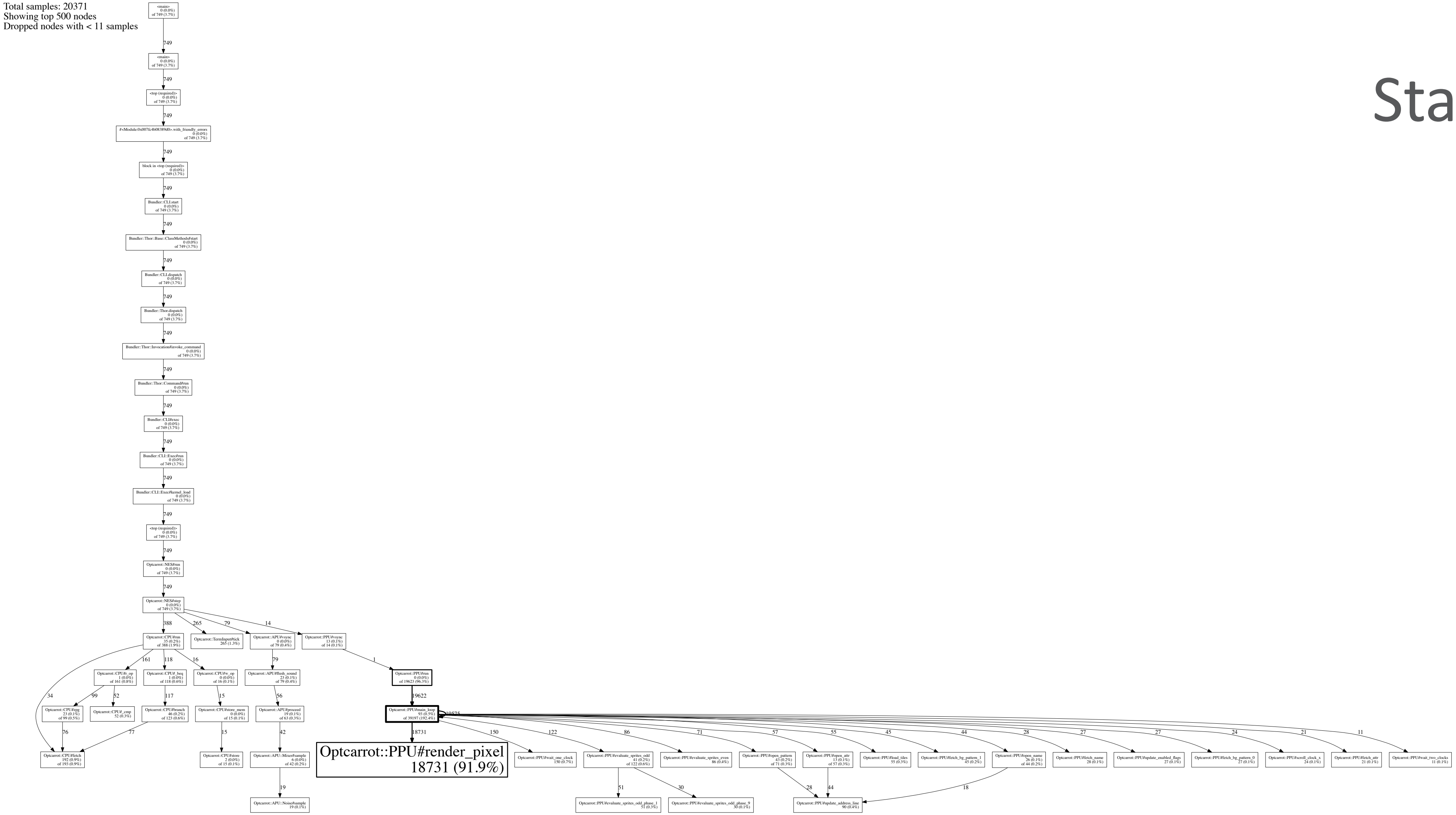
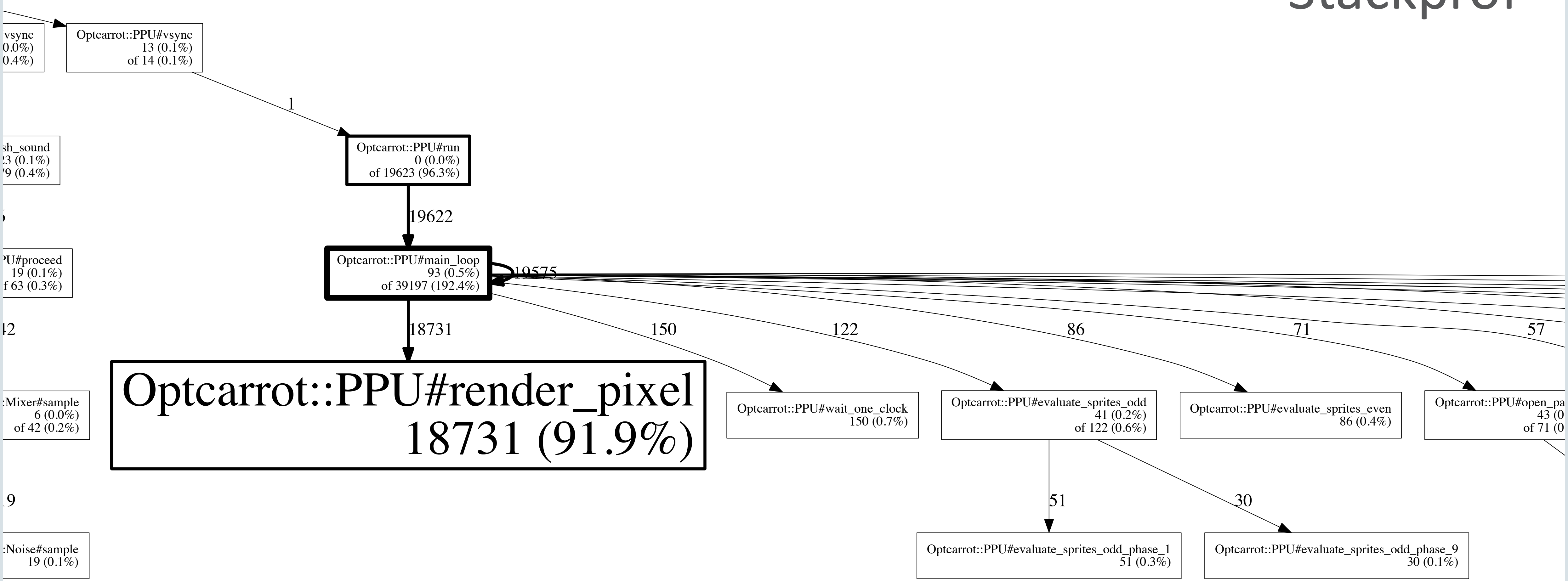
Optcarrot

Closer look

Stackprof

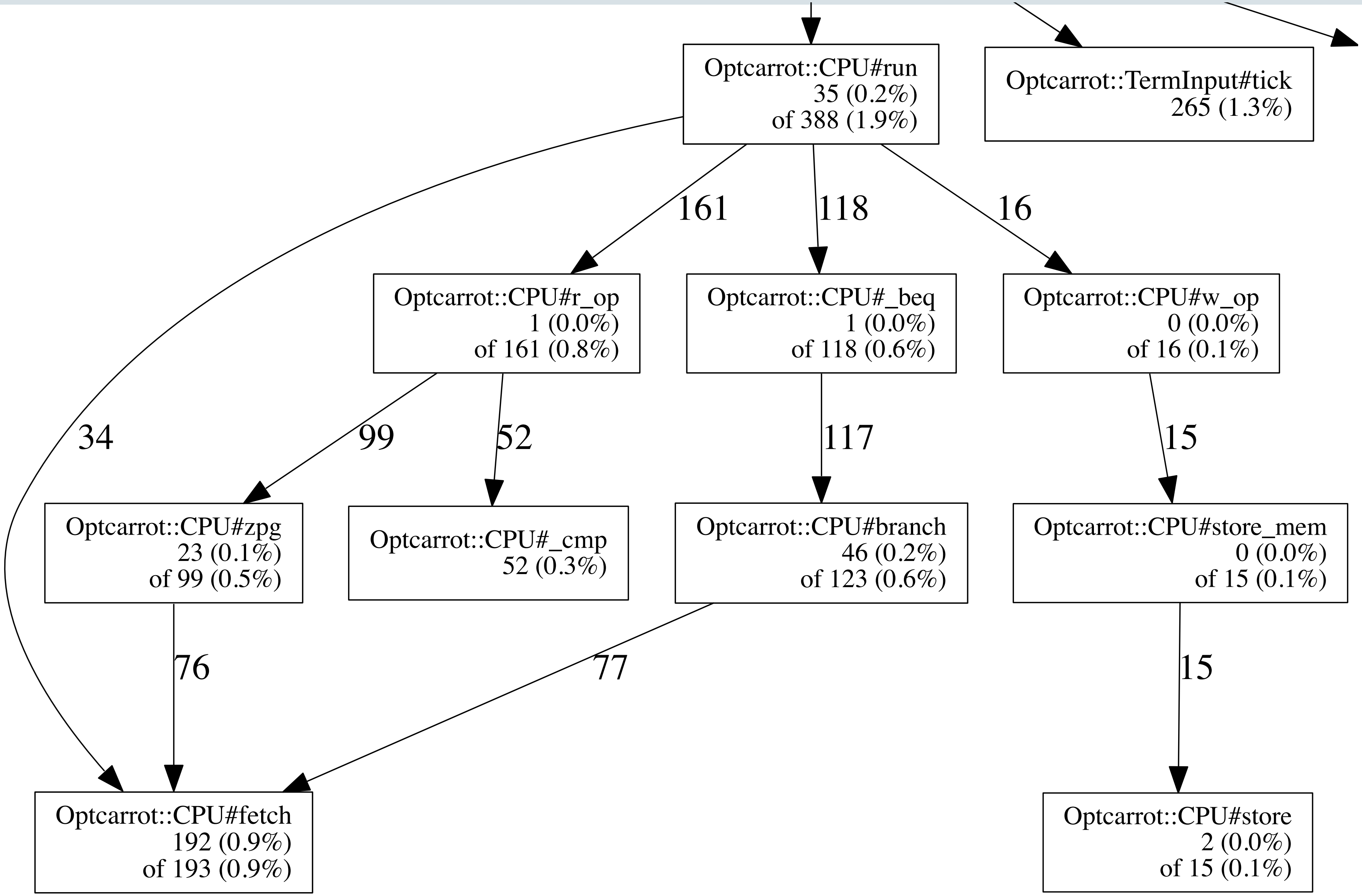

Total samples: 20371
Showing top 500 nodes
Dropped nodes with < 11 samples
Optcarrot::PPU#render_pixel
18731 (91.9%)

Stackprof



vsync
0.0%)
0.4%)
Optcarrot::PPU#vsync
13 (0.1%)
of 14 (0.1%)
1
sh_sound
3 (0.1%)
9 (0.4%)
Optcarrot::PPU#run
0 (0.0%)
of 19623 (96.3%)
19622
U#proceed
19 (0.1%)
f 63 (0.3%)
Optcarrot::PPU#main_loop
93 (0.5%)
of 39197 (192.4%)
19575
18731
150
122
86
71
57
Mixer#sample
6 (0.0%)
of 42 (0.2%)
Optcarrot::PPU#render_pixel
18731 (91.9%)
Optcarrot::PPU#wait_one_clock
150 (0.7%)
Optcarrot::PPU#evaluate_sprites_odd
41 (0.2%)
of 122 (0.6%)
Optcarrot::PPU#evaluate_sprites_even
86 (0.4%)
Optcarrot::PPU#open_pa
43 (0
of 71 (0
51
30
Noise#sample
19 (0.1%)
Optcarrot::PPU#evaluate_sprites_odd_phase_1
51 (0.3%)
Optcarrot::PPU#evaluate_sprites_odd_phase_9
30 (0.1%)

Stackprof



Optcarrot::CPU#run
35 (0.2%)
of 388 (1.9%)
Optcarrot::TermInput#tick
265 (1.3%)
161
118
16
34
Optcarrot::CPU#r_op
1 (0.0%)
of 161 (0.8%)
Optcarrot::CPU#_beq
1 (0.0%)
of 118 (0.6%)
Optcarrot::CPU#w_op
0 (0.0%)
of 16 (0.1%)
99
52
117
15
Optcarrot::CPU#zpg
23 (0.1%)
of 99 (0.5%)
Optcarrot::CPU#_cmp
52 (0.3%)
Optcarrot::CPU#branch
46 (0.2%)
of 123 (0.6%)
Optcarrot::CPU#store_mem
0 (0.0%)
of 15 (0.1%)
76
77
15
Optcarrot::CPU#fetch
192 (0.9%)
of 193 (0.9%)
Optcarrot::CPU#store
2 (0.0%)
of 15 (0.1%)

PPU – Source code

```
def render_pixel
 if @any_show
  pixel = @bg_enabled ? @bg_pixels[@hclk % 8] : 0
  if @sp_active && (sprite = @sp_map[@hclk])
   if pixel % 4 == 0
    pixel = sprite[2]
   else
    @sp_zero_hit = true if sprite[1] && @hclk != 255
    pixel = sprite[2] unless sprite[0]
   end
  end
 else
  pixel = @scroll_addr_5_14 & 0x3f00 == 0x3f00 ? @scroll_addr_0_4 : 0
  @bg_pixels[@hclk % 8] = 0
 end
 @output_pixels << @output_color[pixel]
end
```

- Instance variable reads and writes
- Fixnum operations
- Array
  - Access
  - Append

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CPU – Source code

```
op_r :_ldx, :imm

def r_op(instr, mode)
  send(mode, true, false)
  send(instr)
end

def imm(_read, _write)
  @data = fetch(@_pc)
  @_pc += 1
  @clk += CLK_2
end

def _ldx
  @_p_nz = @_x = @data
end
```

- Instance variable reads and writes
- Integer operations
- Method calls
- Dynamic method calls
  - #send

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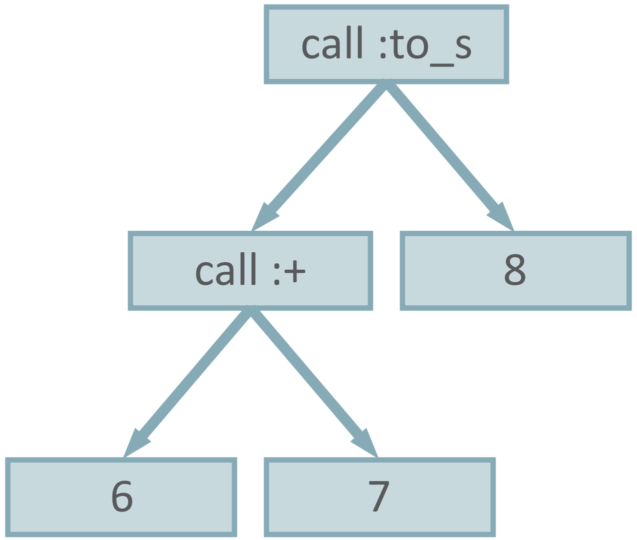
TruffleRuby

How does it work?

AST – Abstract Syntax Tree

```
def a_method
  (6 + 7).to_s(8)
end
```

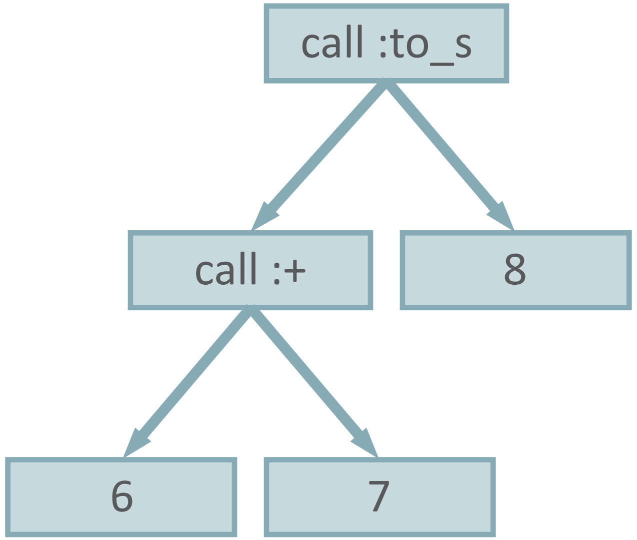


AST Interpreter

- Each node is an object with execute method

```
class LiteralNode
  def initialize(value)
    @value = value
  end

  def execute
    @value
  end
end
```



AST Interpreter

```
class MethodCallNode
  def initialize(name, receiver, arguments)
    @name, @receiver, @arguments = name, receiver, arguments
  end

  def execute
    receiver = @receiver.execute
    method = lookup_method receiver, @name
    method.call receiver, *@arguments.map(&:execute)
  end
end
```

- Greatly simplified

Self-optimizing AST Interpreter

```ruby
class UninitialisedMethodCallNode
  def initialize(name, receiver, arguments)
    @name, @receiver, @arguments = name, receiver, arguments; end
  def execute
    method = lookup_method @receiver.execute, @name
    self.replace(CachedMethodCallNode.new method, @receiver, @arguments).execute; end
end

class CachedMethodCallNode
  def initialize(method, receiver, arguments)
    @method, @receiver, @arguments = method, receiver, arguments; end
  def execute
    @method.call @receiver.execute, *@arguments.map(&:execute); end
end
```

- Node replacement
- Monomorphic cache
  - Method lookup is expensive
- Greatly simplified

Partial evaluation

- Eliminates overhead of nodes
- Evaluates constants
  - Final fields
  - Compilation final fields
- Result is a compilation unit for Compiler

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Partial evaluation

```
class CachedMethodCallNode
  attr_final :method, :receiver, :arguments
  def initialize(method, receiver, arguments)
    @method, @receiver, @arguments = method, receiver, arguments; end
  def execute
    @method.call @receiver.execute, *@arguments.map(&:execute); end
end

class LiteralNode
  attr_final :value
  def initialize(value)
    @value = value; end
  def execute
    @value; end
end
```

- Final fields
  - Let's assume Ruby has them for the example

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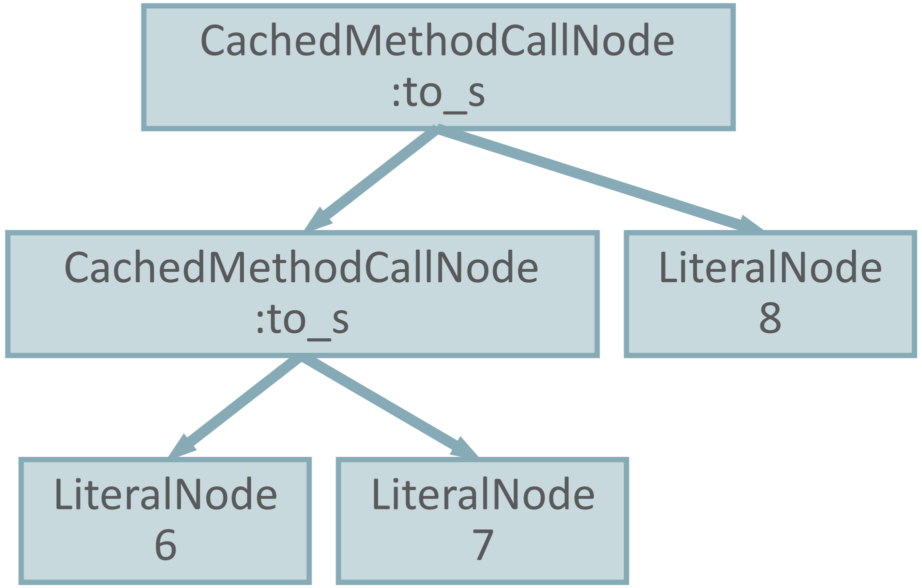
Partial evaluation



.[] represents existing values

```
@method.call @receiver.execute, *@arguments.map(&:execute)
@method.call @receiver.execute, *[LiteralNode[8]].map(&:execute)
@method.call @receiver.execute, LiteralNode[8].execute
@method.call @receiver.execute, 8
@method.call receiver = @receiver.execute, 8

receiver = @receiver.execute
receiver = @method.call @receiver.execute,
                 *@arguments.map(&:execute)
receiver = @method.call @receiver.execute, 7
receiver = @method.call LiteralNode[6].execute, 7
receiver = @method.call 6, 7
receiver = direct_call(Method[Integer, :+], 6, 7)

@method.call receiver = direct_call(Method[Integer, :+], 6, 7), 8
@method.call direct_call(Method[Integer, :+], 6, 7), 8
direct_call(Method[Integer, :to_s],
        direct_call(Method[Integer, :+], 6, 7),
        8)
```

Compilation

```
direct_call(
        Method[Integer, :to_s],
        direct_call(Method[Integer, :+], 6, 7),
        8)
```

- Compiled by Graal compiler
- Next time the compiled code is called instead of interpreting the AST
  - No longer calls the 5 execute methods on the nodes
  - Any overhead of the self-optimizing AST interpreter is eliminated

TruffleRuby example

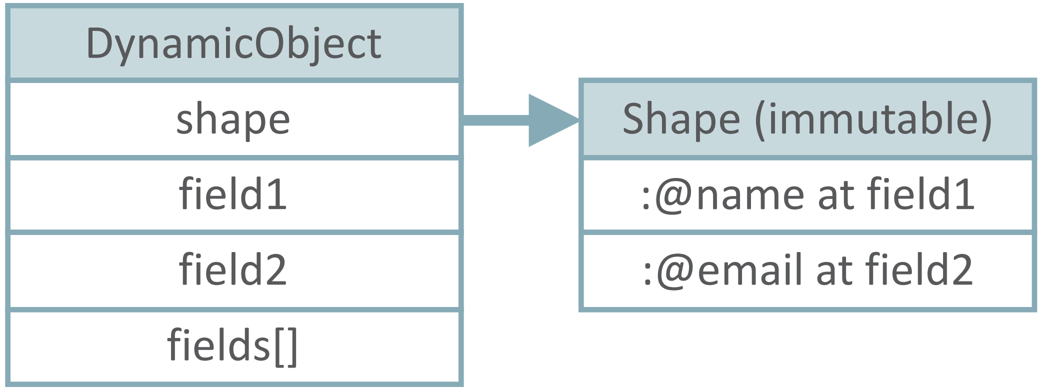
```
@CoreMethod(names = "+", required = 1)
public abstract static class AddNode extends CoreMethodArrayArgumentsNode {
  public abstract Object executeBuiltin(VirtualFrame frame, Object... arguments);

  @Specialization(rewriteOn = ArithmeticException.class)
  public int add(int a, int b) { return Math.addExact(a, b); }

  @Specialization
  public long addWithOverflow(int a, int b) { return (long) a + (long) b; }

  @Specialization(rewriteOn = ArithmeticException.class)
  public long add(long a, long b) { return Math.addExact(a, b); }

  @Specialization
  public Object addWithOverflow(long a, long b) {
    return fixnumOrBignum(BigInteger.valueOf(a).add(BigInteger.valueOf(b)));
  }
  // ...
```

- Fixnum#+
- DSL
- Annotation processor
  - Generates node for each specialization
  - Creates polymorphic chain for more specializations
- Type specialization

Instance variable access

Instance variable access

- Ruby objects are DynamicObjects
  - Or a primitive type like int, long, float if possible
- Values of instance variables are stored in DynamicObject
- Shape defines mapping between instance variable names and fields



Instance variable access – Implementation

```
public abstract class ReadObjectFieldNode extends RubyBaseNode {
  private final Object defaultValue;
  protected final Object name;

  public ReadObjectFieldNode(Object name, Object defaultValue) {
    this.name = name;
    this.defaultValue = defaultValue;
  }
  @Specialization(guards = "receiver.getShape() == cachedShape", limit = "getCacheLimit()")
  protected Object readObjectFieldCached(DynamicObject receiver,
          @Cached("receiver.getShape()") Shape cachedShape,
          @Cached("cachedShape.getProperty(name)") Property cachedProperty) {
    if (cachedProperty != null) {
      return cachedProperty.get(receiver, cachedShape);
    } else {
      return defaultValue;
    }
  }
```

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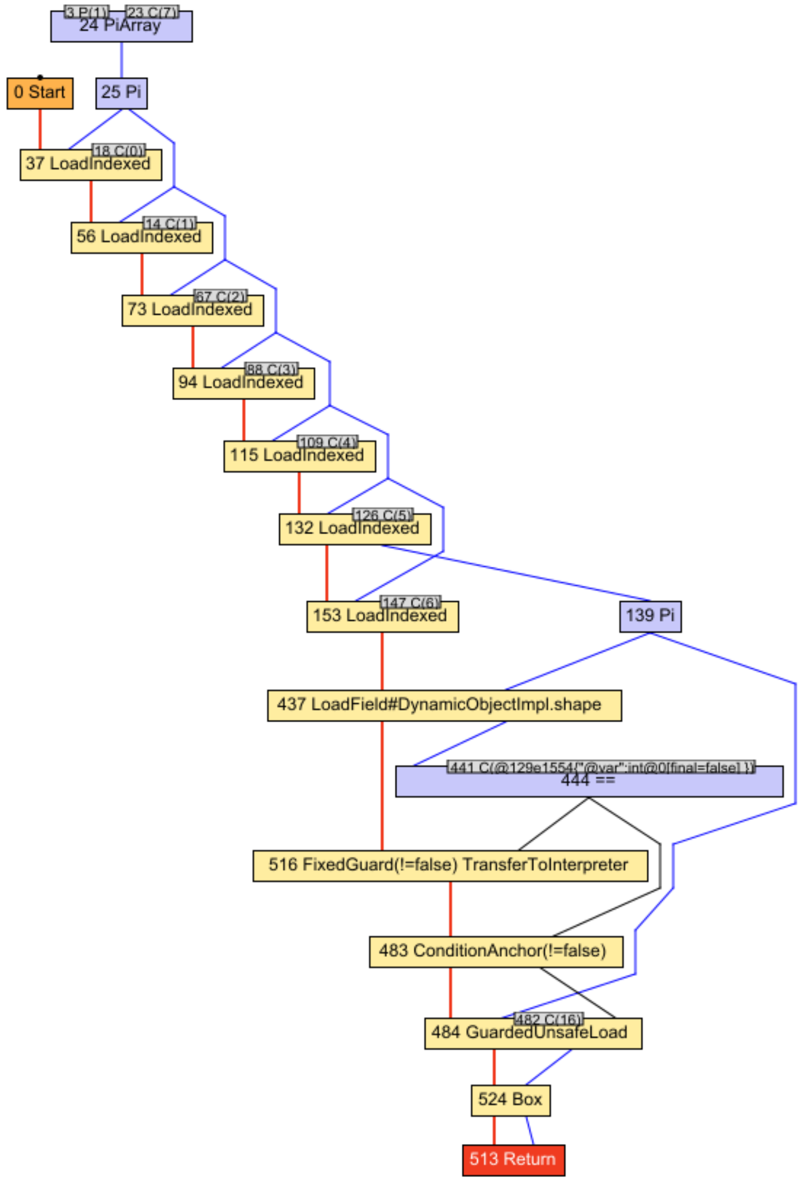
Instance variable read – IGV

def ***read;*** **@var; end**

- After specialization it only:
  - Reads arguments
    - Including self object
  - Reads the shape of self
  - Ensures it's a correct shape against a constant
  - Read the value of instance variable from a constant offset in self object



Instance variable access – IGV

```
# zero-page addressing
def zpg(read, write)
 @addr = fetch(@_pc)
 @_pc += 1
 @clk += CLK_3
 if read
  @data = @ram[@addr]
  @clk += CLK_2 if write
 end
end
```

- Many accesses to instance variables
- Checks are merged
  - Only access to a constant offset remains

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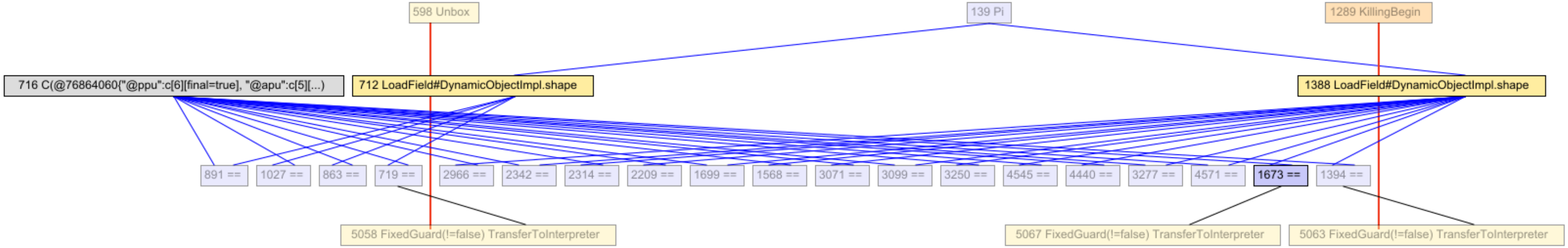
Instance variable access – IGV



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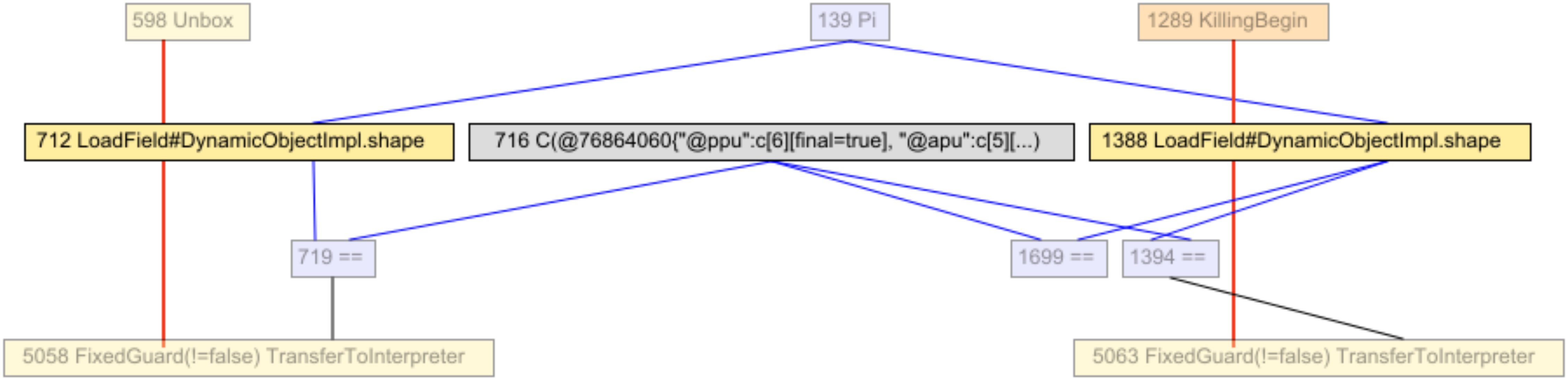
Instance variable access – IGV



Splitting

CPU – Source code

```
loop { send(*DISPATCH[@opcode]) }
# send :op_r, :_ldx, :imm

def r_op(instr, mode)
  send(mode, true, false)
  send(instr)
end

def imm(_read, _write)
  @data = fetch(@_pc)
  @_pc += 1
  @clk += CLK_2
end

def _ldx
  @_p_nz = @_x = @data
end
```

- Send – dynamic method call
- Optimized with 2-dimensional polymorphic inline cache
  - Caches already called methods by name and receiver

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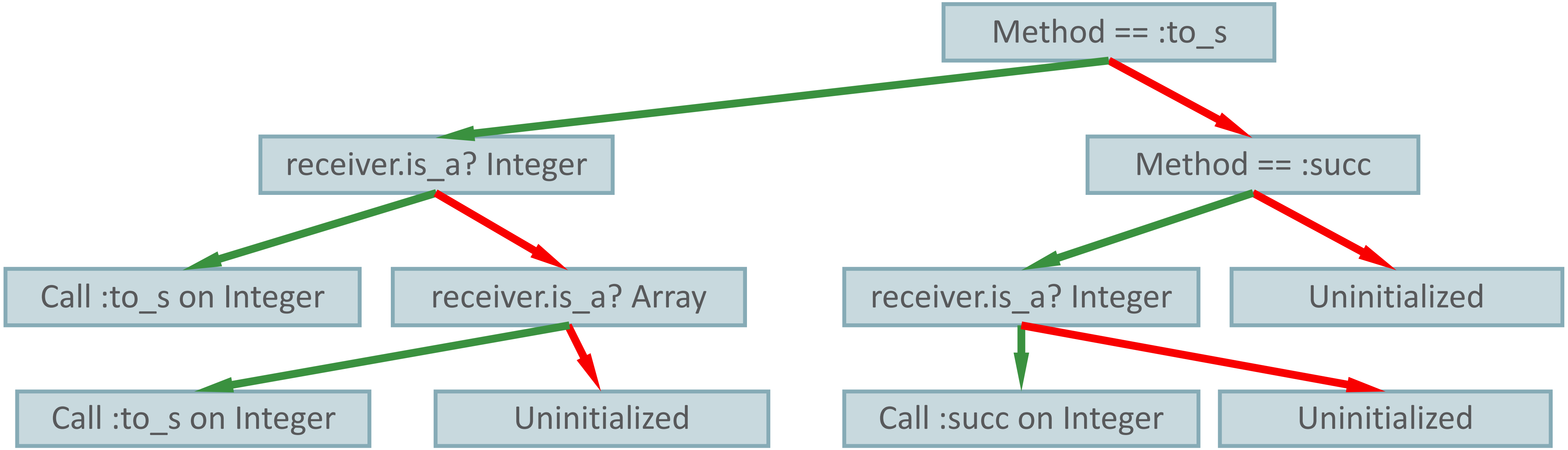
Two dimensional polymorphic inline cache



Why split?

```
def r_op(instr, mode)
  send(mode, true, false)
  send(instr)
end

def imm(_read, _write)
  @data = fetch(@_pc)
  @_pc += 1
  @clk += CLK_2
end

def _ldx
  @_p_nz = @_x = @data
end
```

- There are 2 sends in r_op
- Each has to have its own cache to specialize effectively
  - Modes: #abs, #imm, #zpg, #ind_y, #abs_x
  - Instructions: #_ida, #_and, #_cmp, #_ldx, #_ldy, #_adc, #_ora
- Only finds the method in the cache
  - Avoids expensive method lookup in Ruby modules/classes

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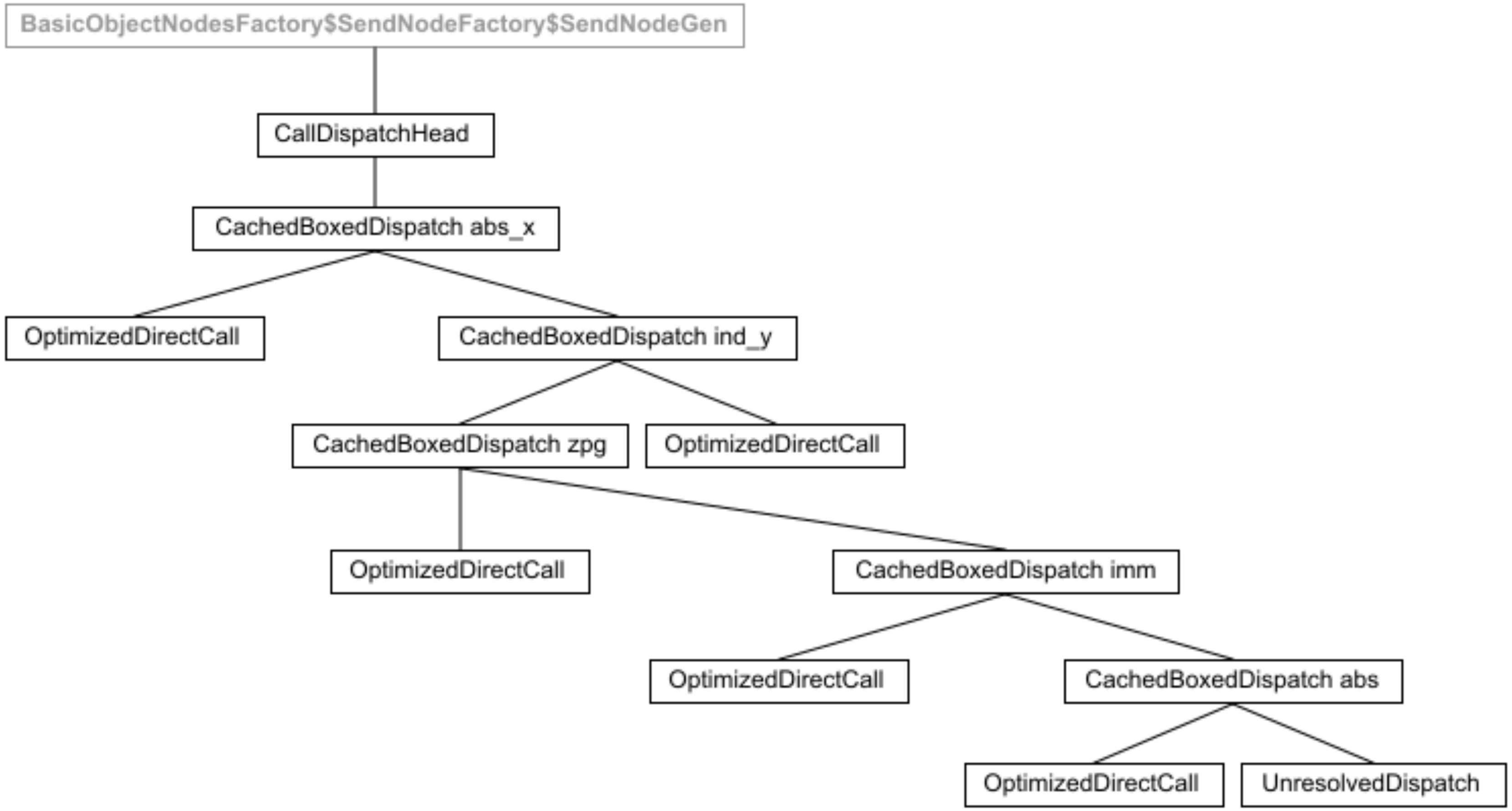
The cache representation in the IGV



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Splitting – summary

- Applied to all methods
- Important for core Ruby methods
  - #each, #step, #==, #to_s
- Avoids megamorphic nodes
- Truffle framework does it automatically

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Inlining

Why inlining?

- Splitting ensures methods are specialized in their calling context
- They are optimized independently
  - Same guards cannot be merged across methods
  - Same code cannot be eliminated across methods
- Compiler cannot see into called methods
  - Cannot move things above or bellow method invocations

Why inlining?

- Methods and blocks are inlined into their callers
  - The already specialized and split AST replaces the direct method call
- Creates big chunk of code – compilation unit
  - Can be analyzed and optimized by compiler together
  - More optimizations can be applied
    - Guards merged
    - Repeated and dead code eliminated
- Truffle framework does it automatically

Examples

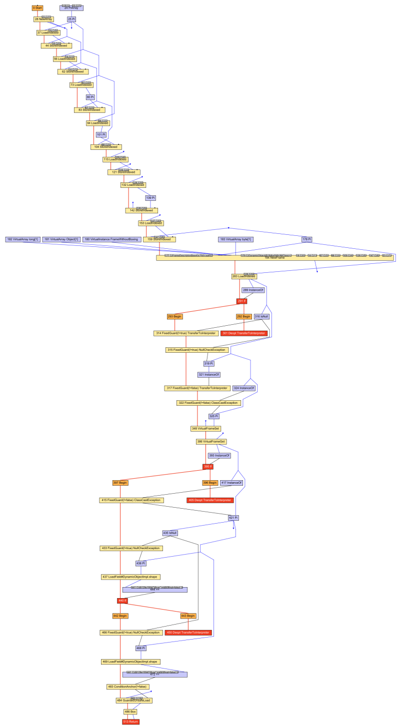
- A Fixnum #+ method is turned into just 2 instructions %addi, %jo after inlining in the calling method
- Ruby blocks
  - Is a very important abstraction in Ruby
  - Are used abundantly
  - Can be fully inlined in TruffleRuby

Block inlining

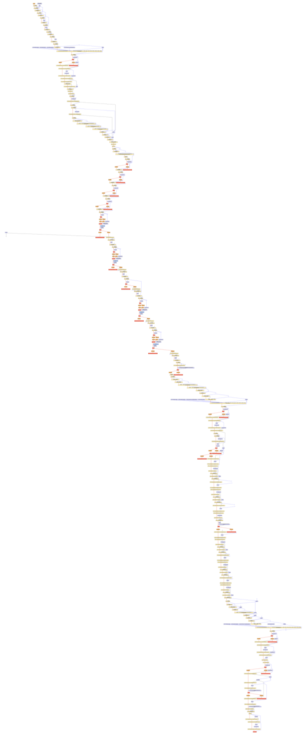
```ruby
def read
  @var
end
```

```ruby
def block
  -> { @var }.call
end
```

Block inlining

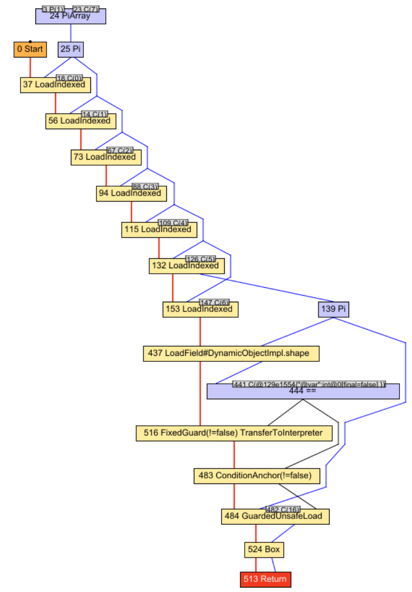


#read method before optimizations

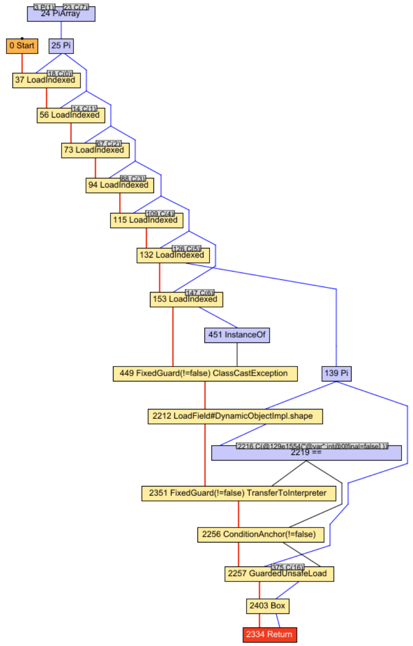


#block method before optimizations

Block inlining



#read method after optimizations



#block method after optimizations

Conclusion

What makes TruffleRuby run Optcarrot 9 times faster than MRI?

- Combination of several optimizations
  - Quick instance variable access
  - Truffle
    - Splitting
    - Inlining
    - Partial evaluation
  - Graal
    - High quality compiler

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