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Maxine: A JVM Written in Java

Michael Haupt
Oracle Labs
Potsdam, Germany

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Speaker's Background

Technische Universität
Darmstadt, 2001–2006

Doctoral research, Steamloom
(virtual machine support for
aspect-oriented programming)

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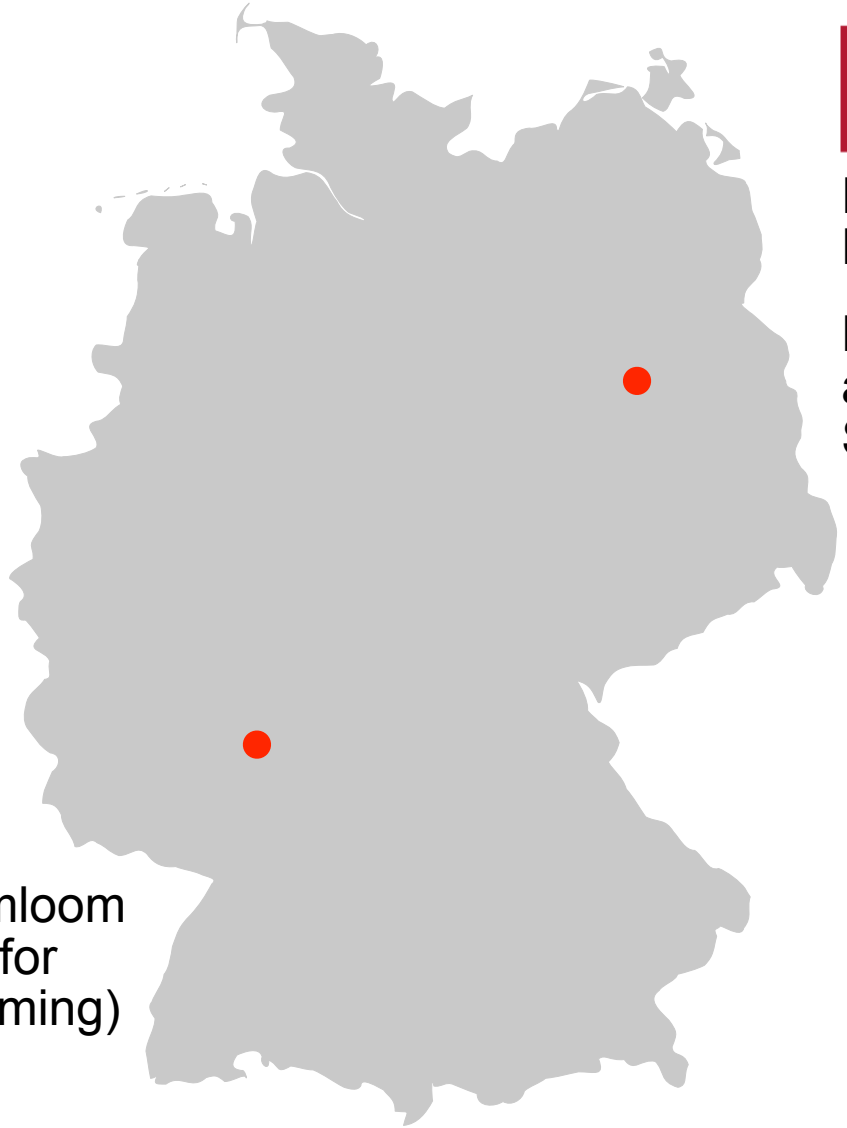

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Postdoc, virtual machine
architecture disentangling,
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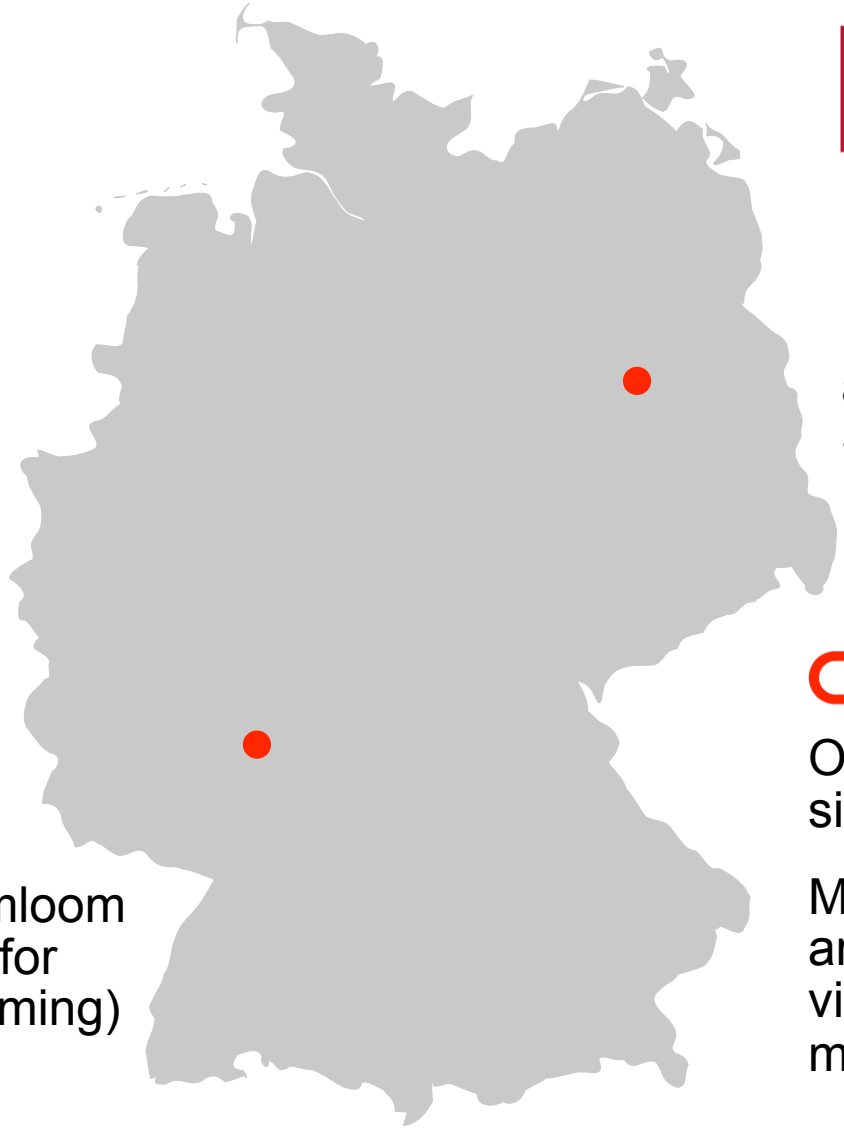

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ORACLE

Oracle Labs, Potsdam,
since 2011

Maxine team, virtual machine
architecture, multi-language
virtual machines, code cache
management, JSR292

Who Needs a JVM?

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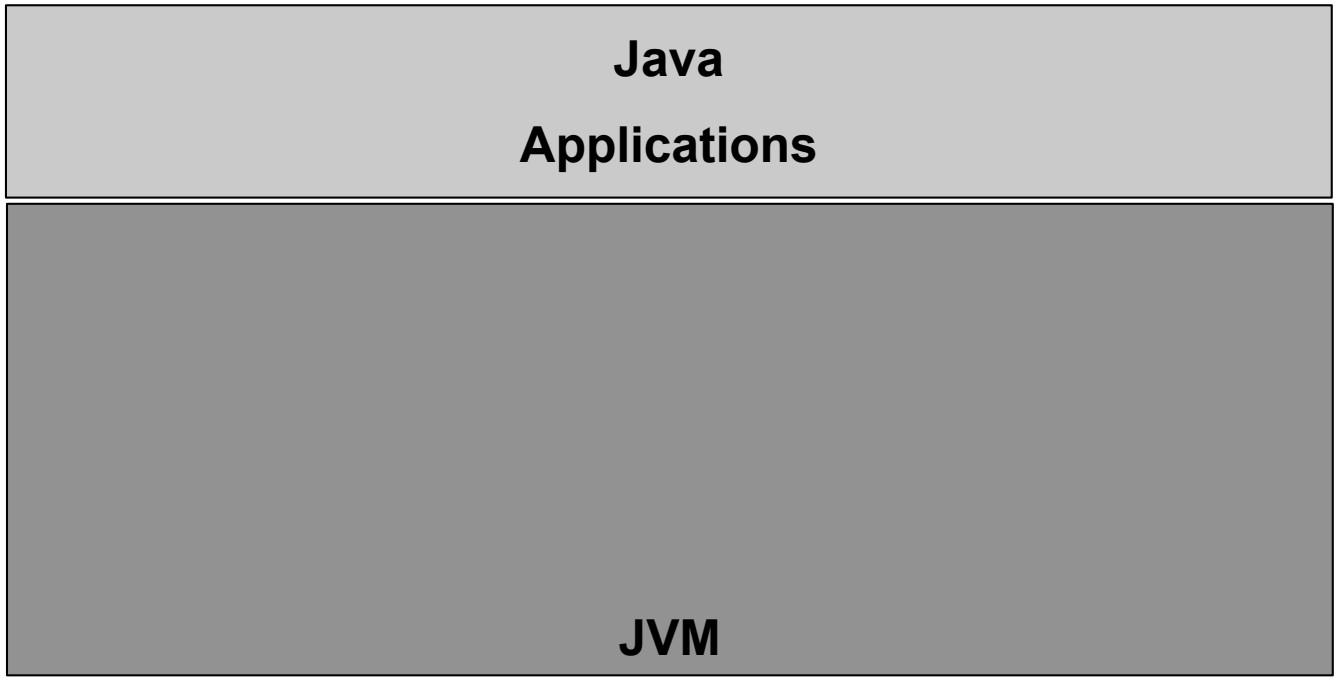
application developers, end users ✔



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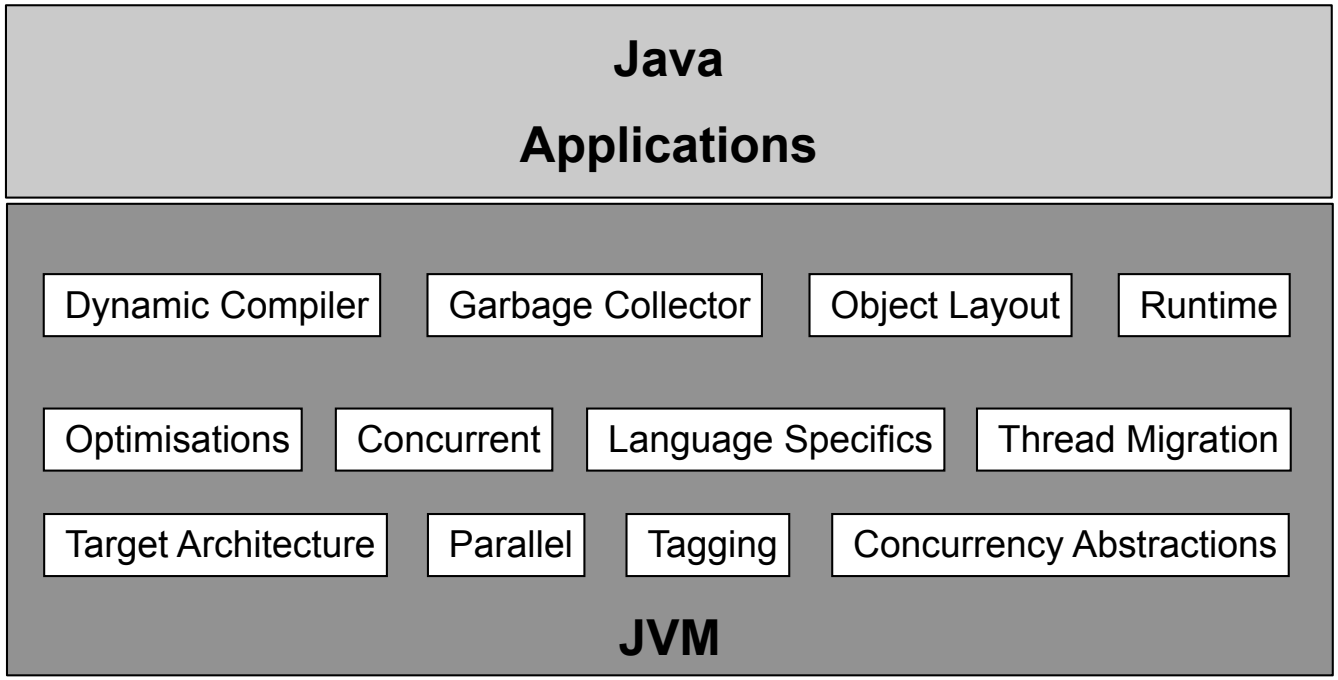

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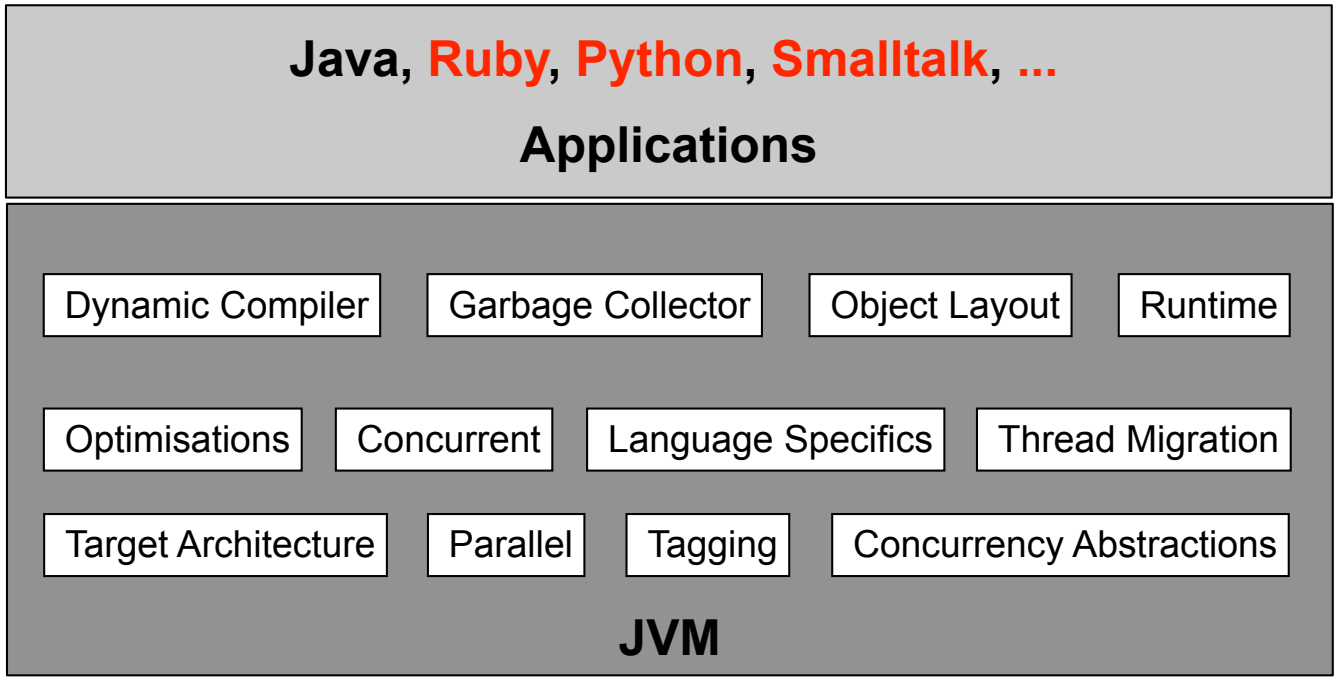

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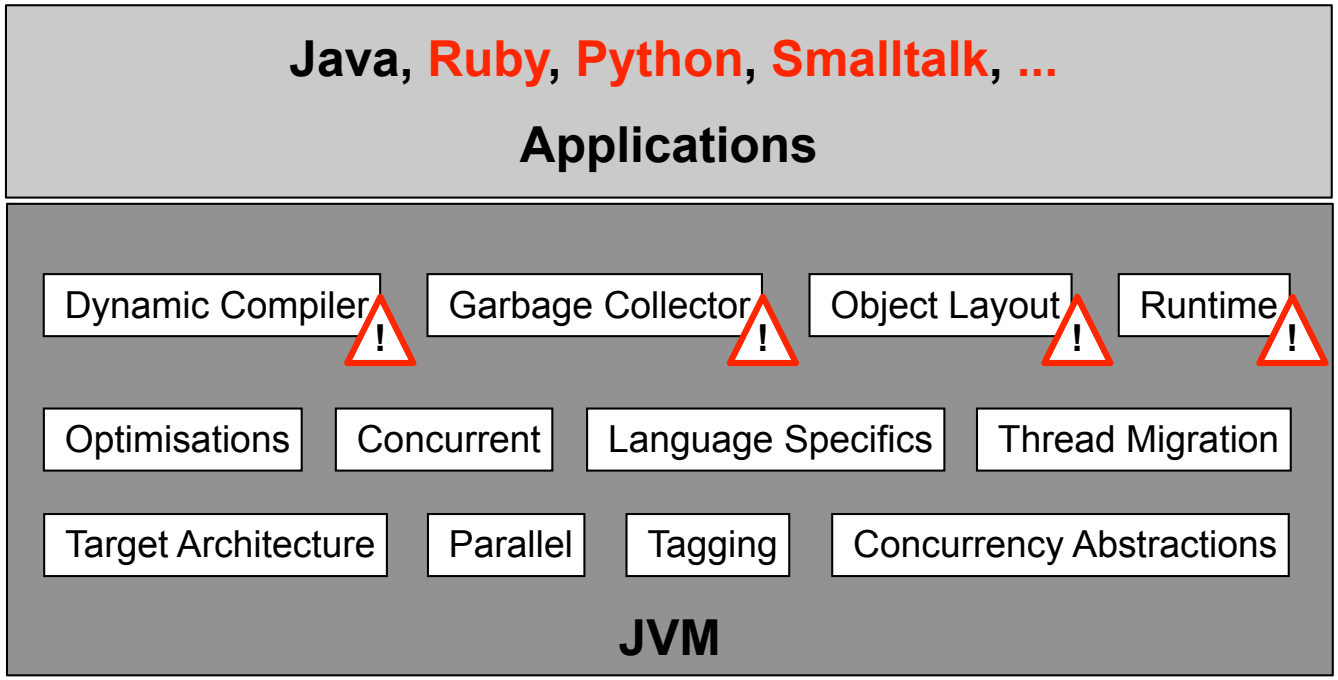

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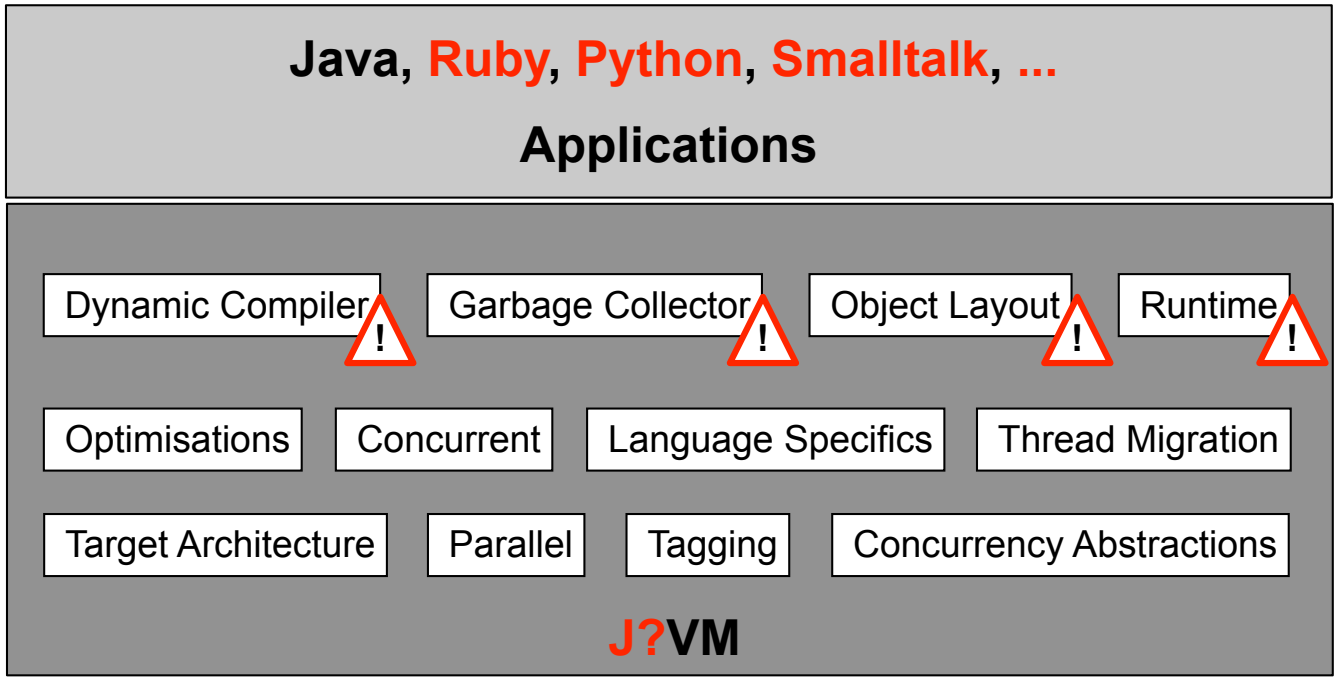
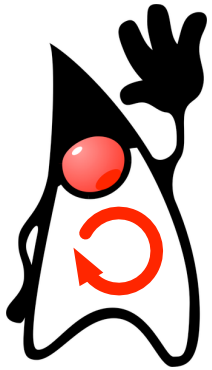


Maxine



almost 100 % Java

use unmodified JDK

meta-circularity studies

Home page: http://wikis.oracle.com/display/MaxineVM/Home

Source (GPLv2): https://hg.kenai.com/hg/maxine~maxine

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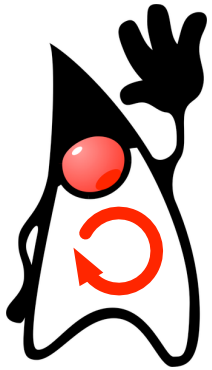

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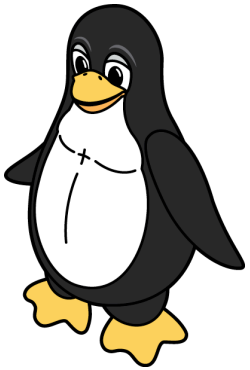

supported on 64-bit x86

Solaris, Mac OS X, Linux

Virtual Edition: Xen

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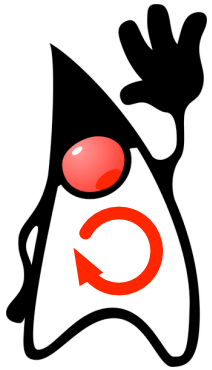

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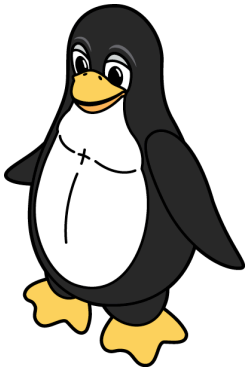

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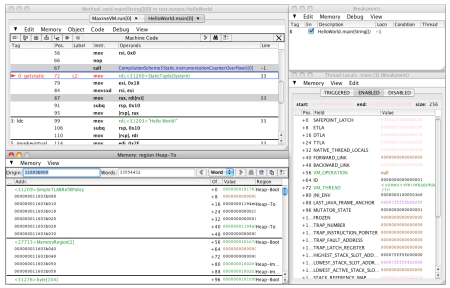

full IDE support

(Eclipse, NetBeans)

tooling: Inspector

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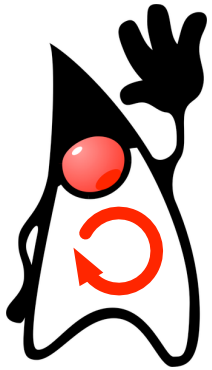

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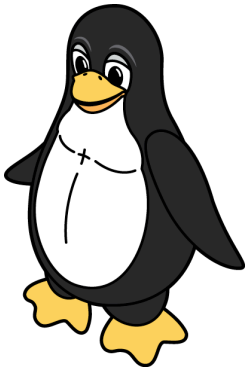

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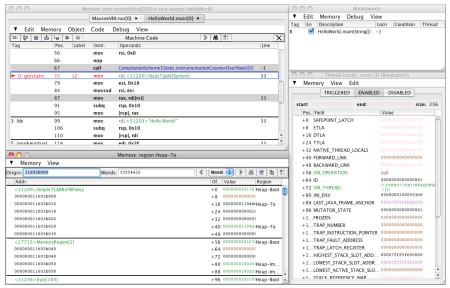

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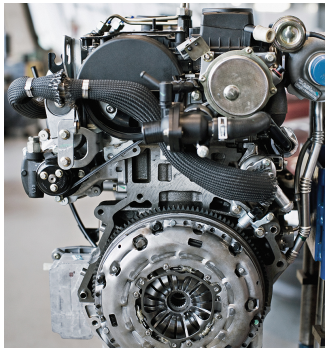

dynamic compilation only

semi-space GC

modular architecture

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VM Research Group at Oracle Labs

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Daynès

Mario
Wolczko

Director

Mick
Jordan

Michael
Van De Vanter

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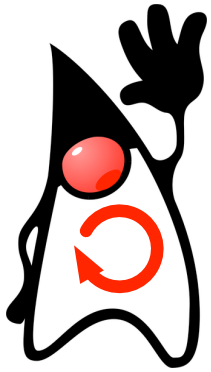
Why Java?

language
- reflection
- annotations

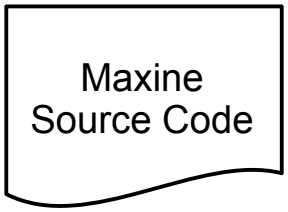
JDK
- rich and powerful API
- inclusion in VM



VM architecture
- uniform representation
- same compiler chain

ecosystem
- IDE support
- tooling

Bootstrapping Maxine



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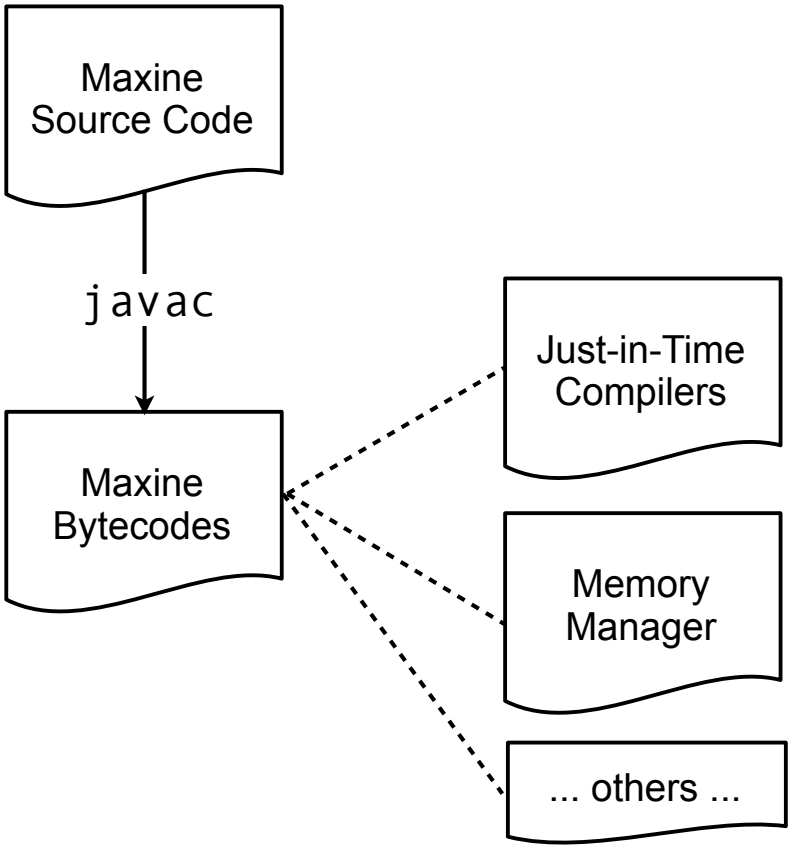

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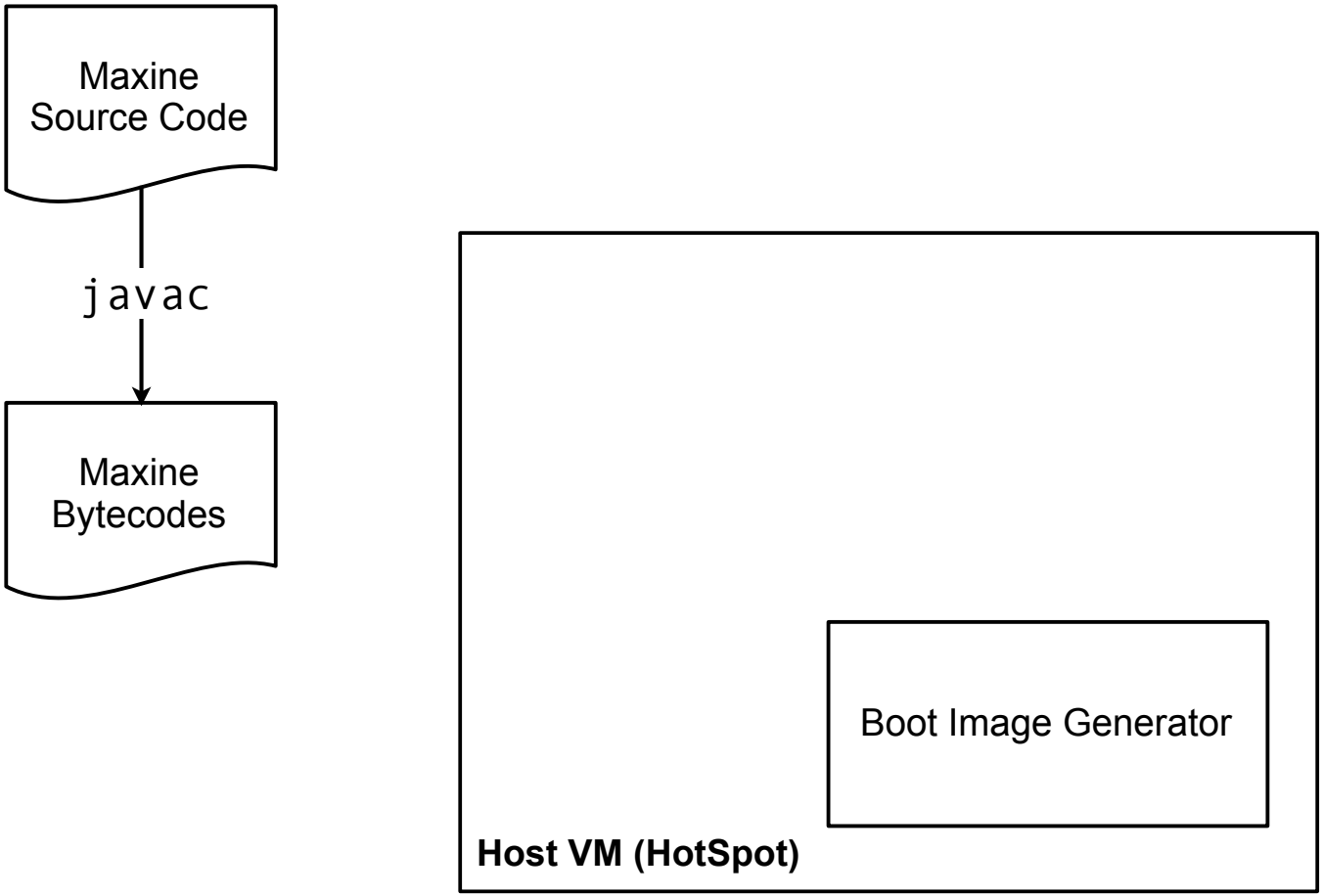

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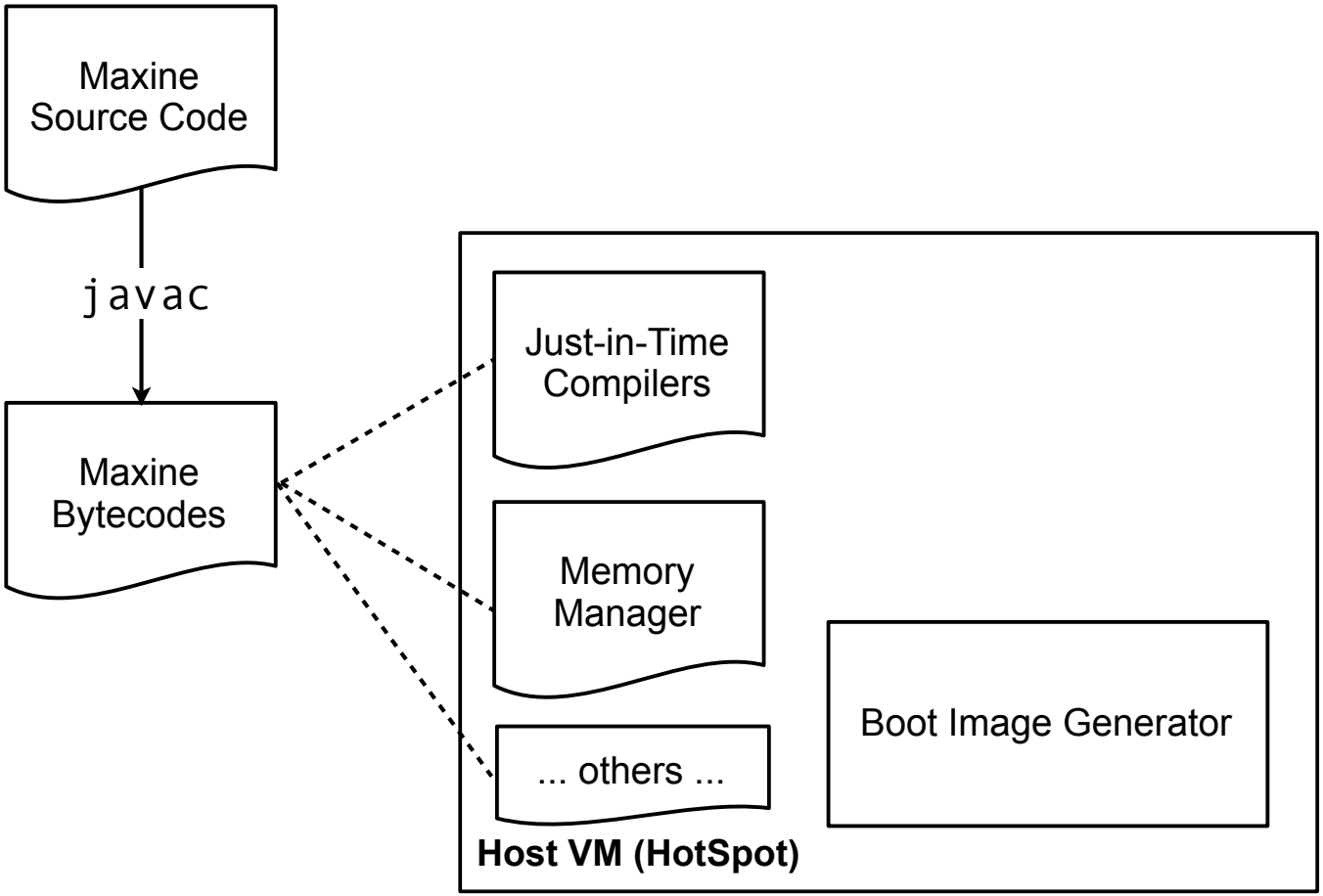

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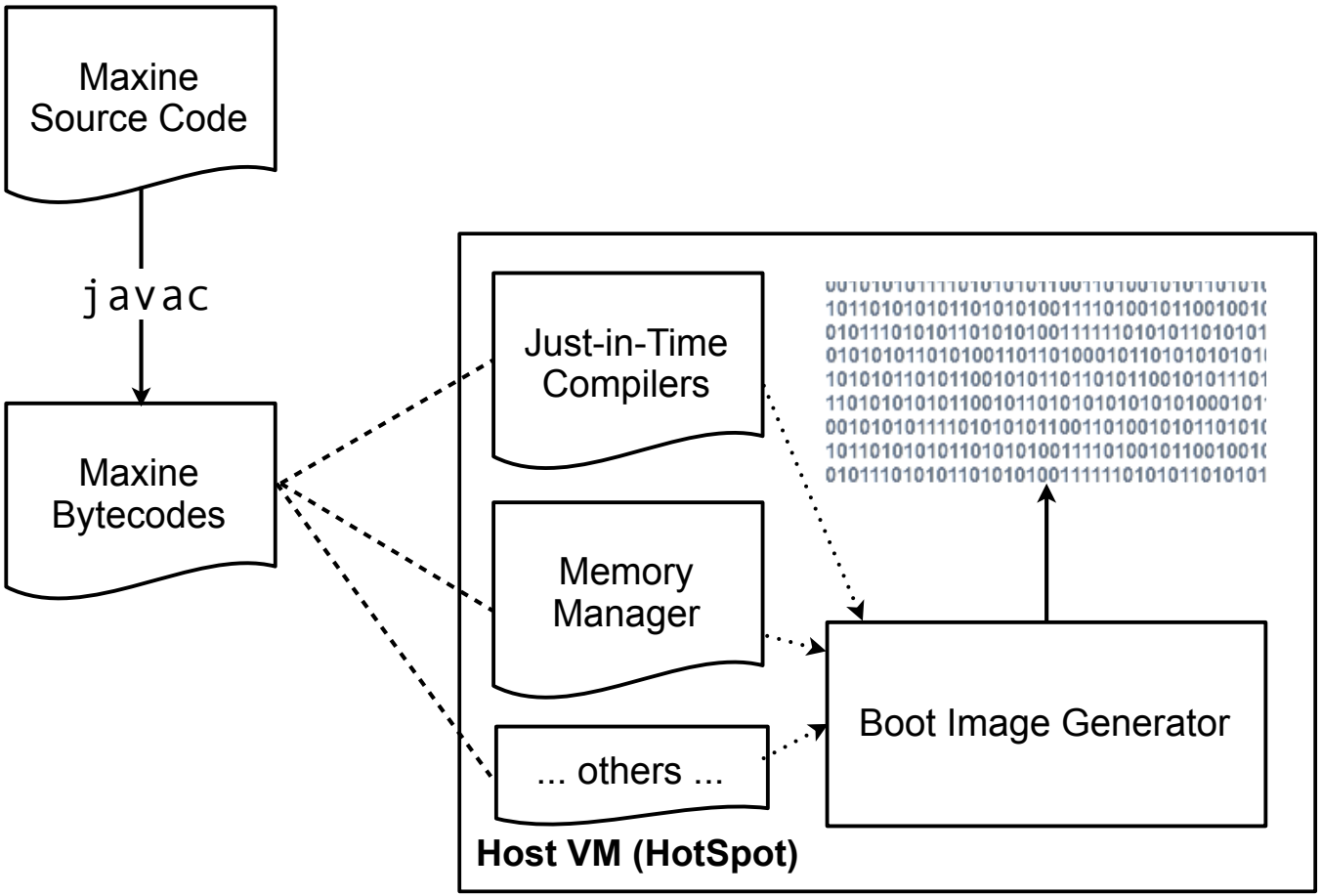

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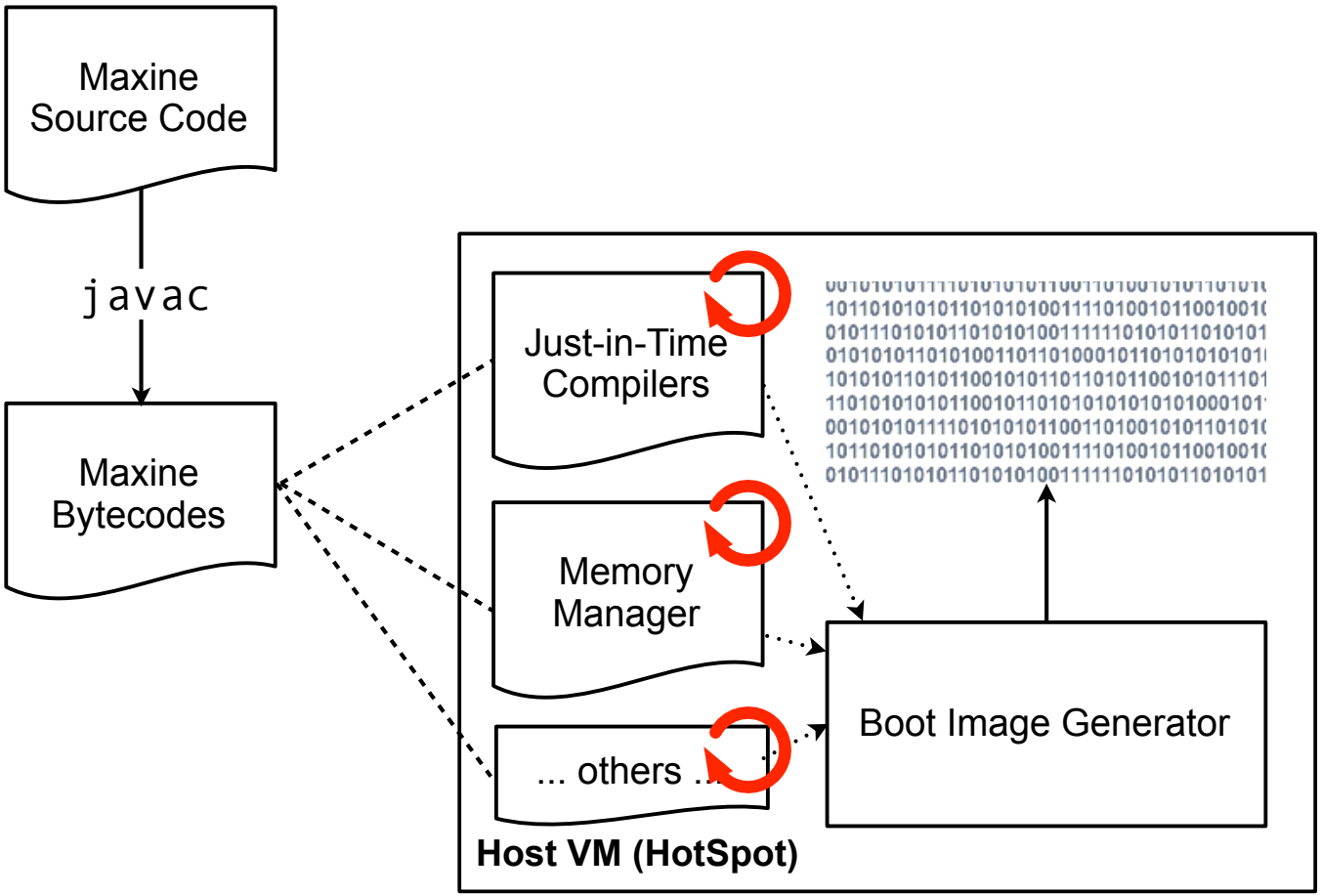

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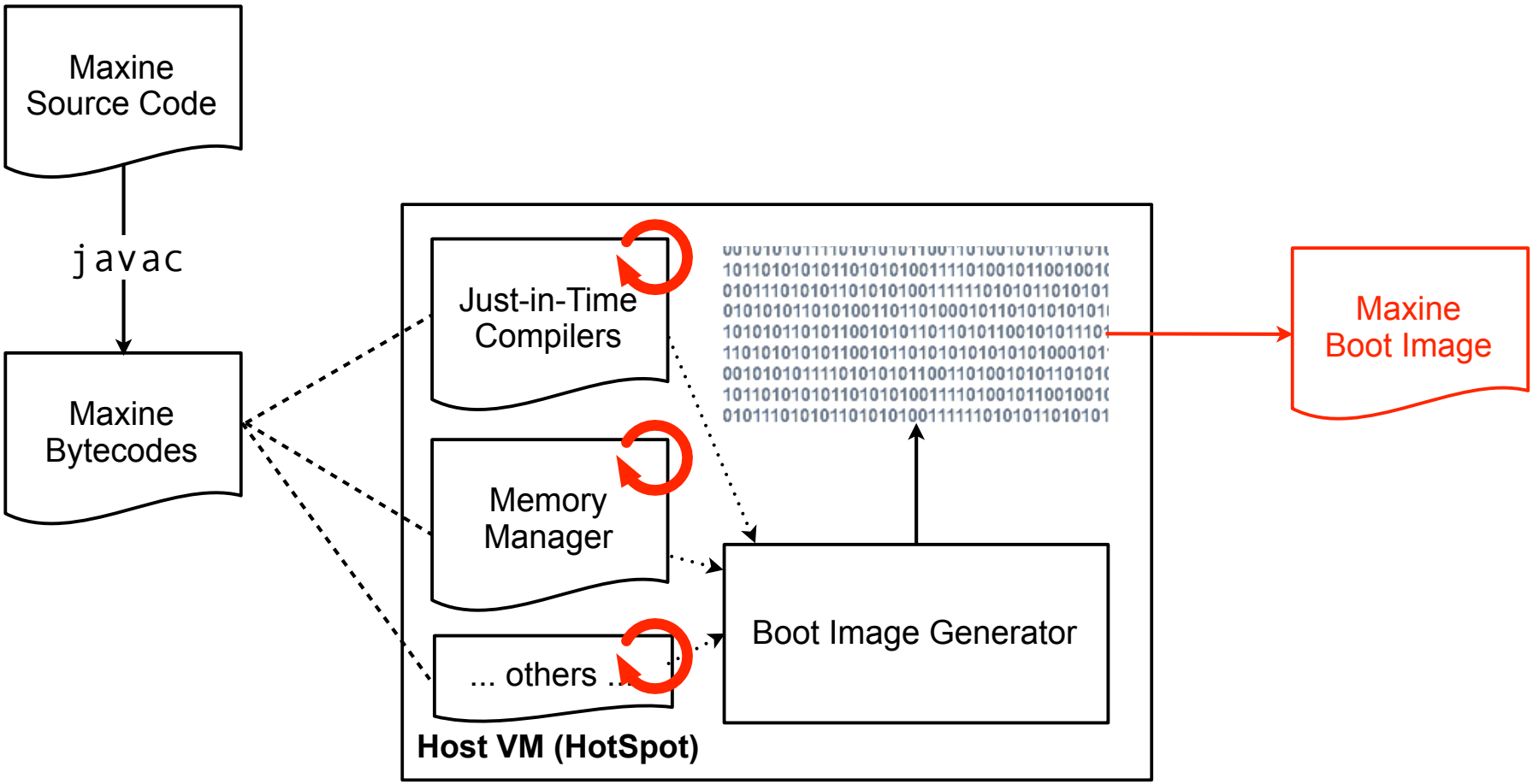

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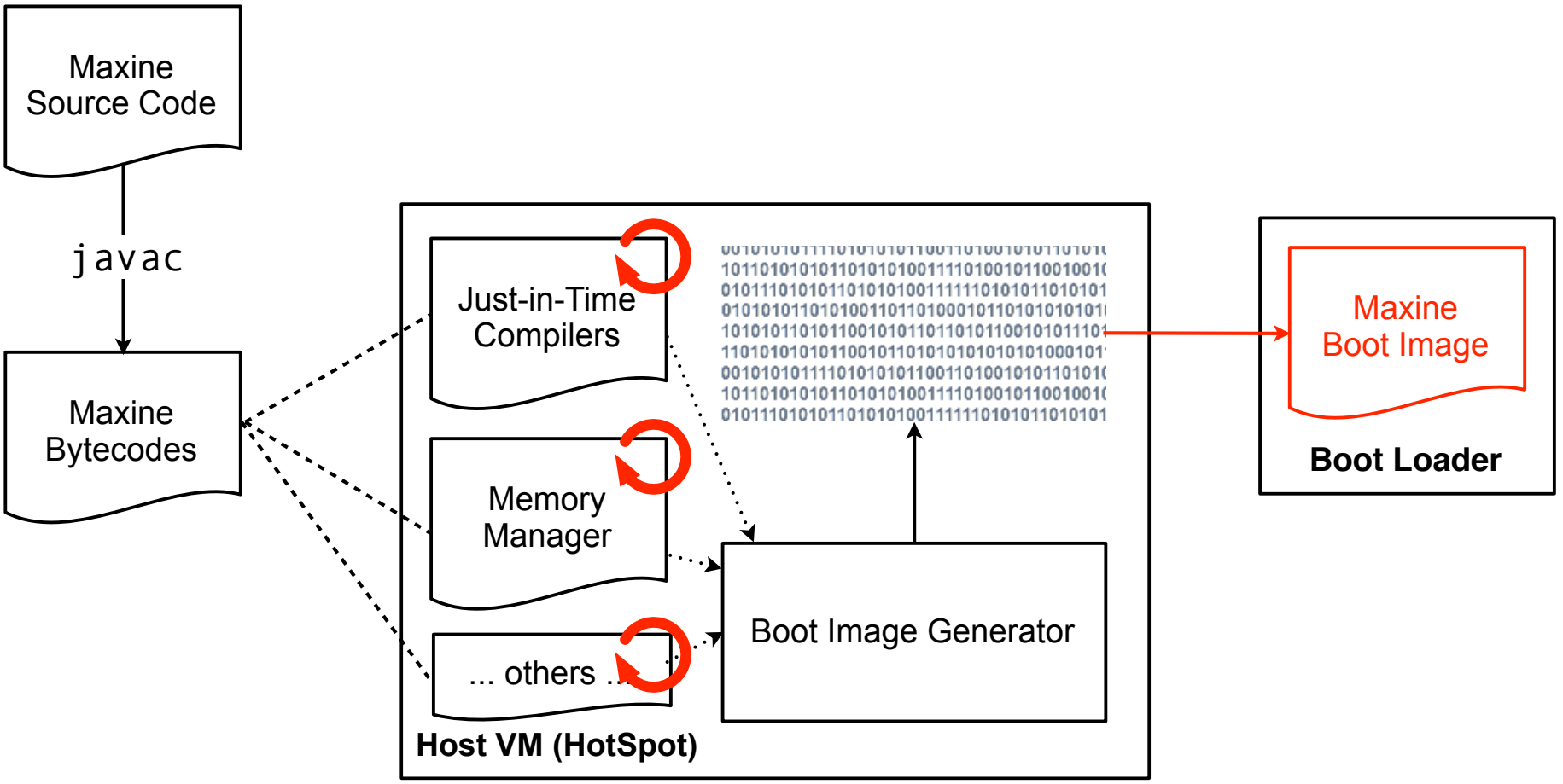
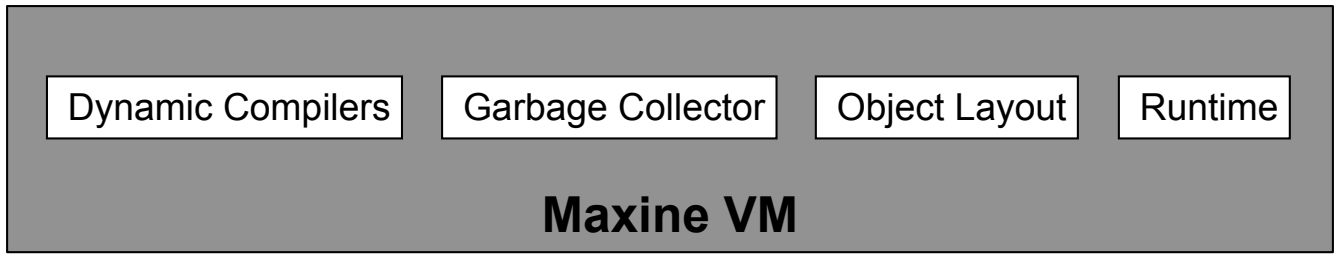


Maxine Scheme Abstractions



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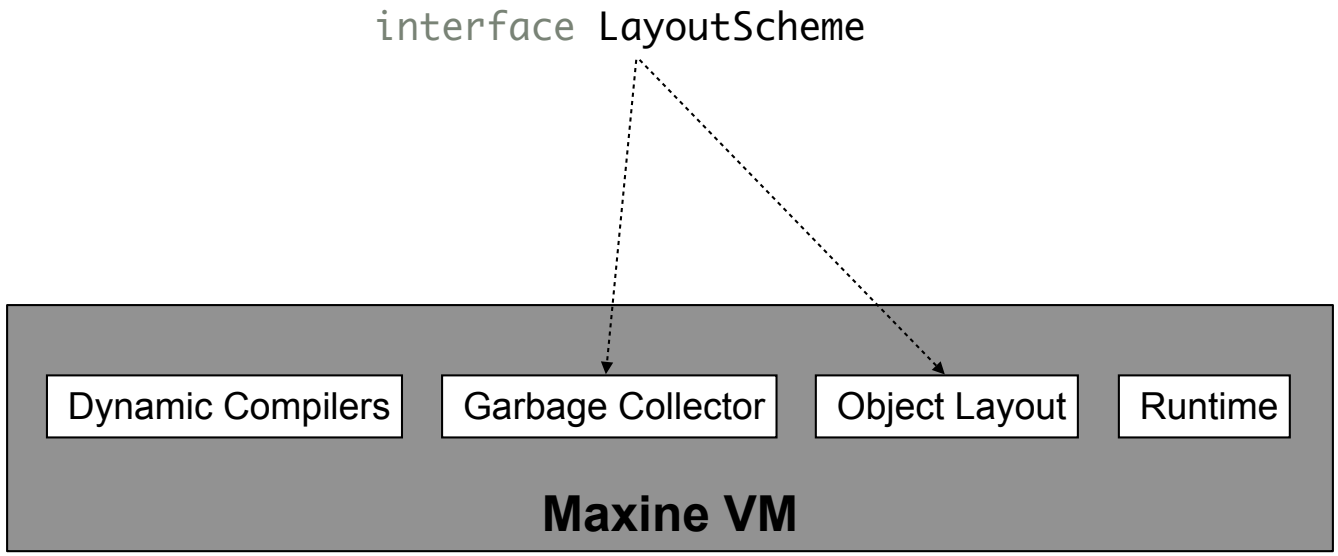

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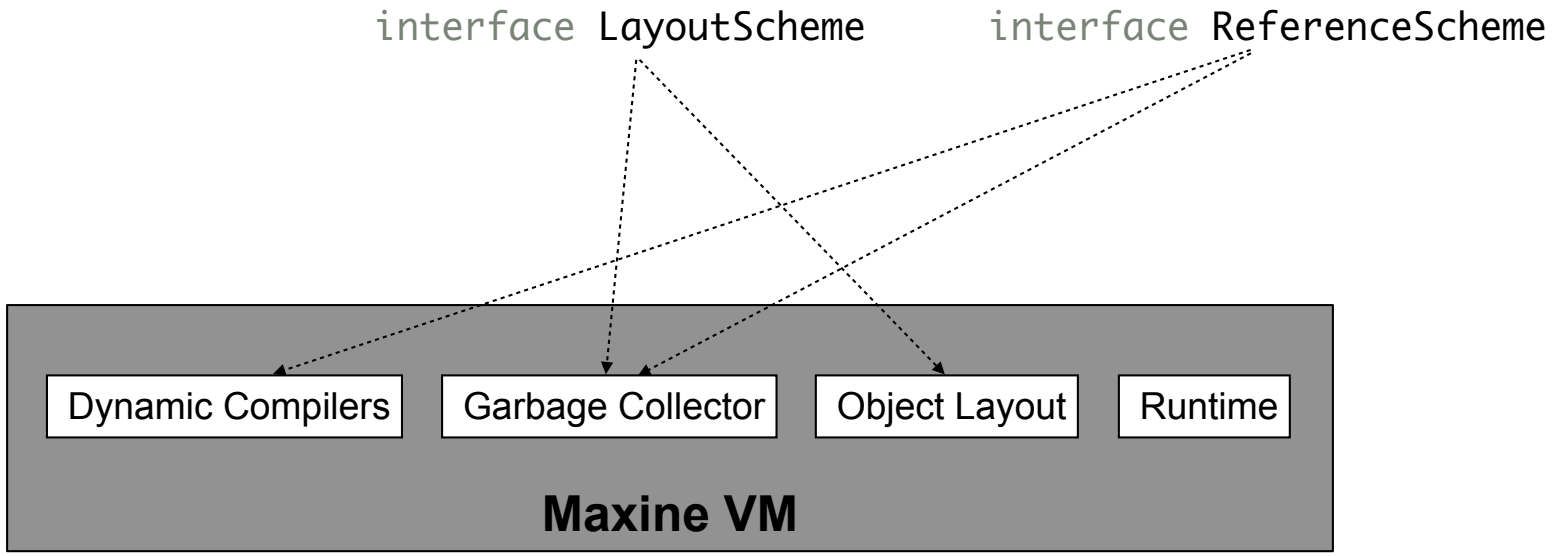

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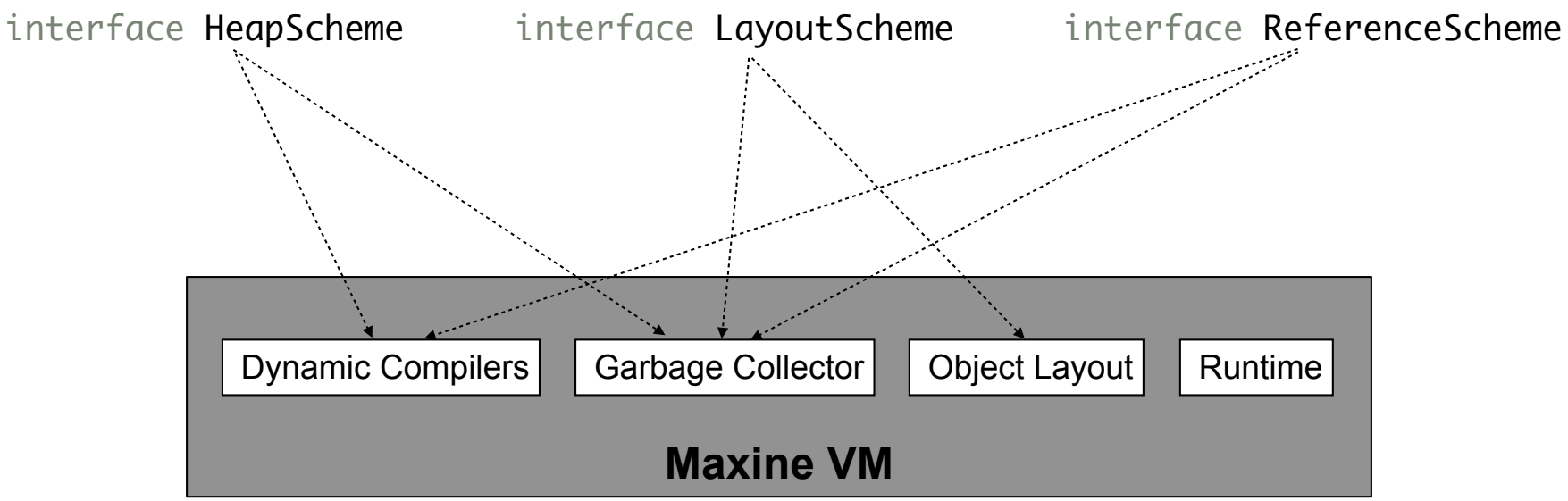

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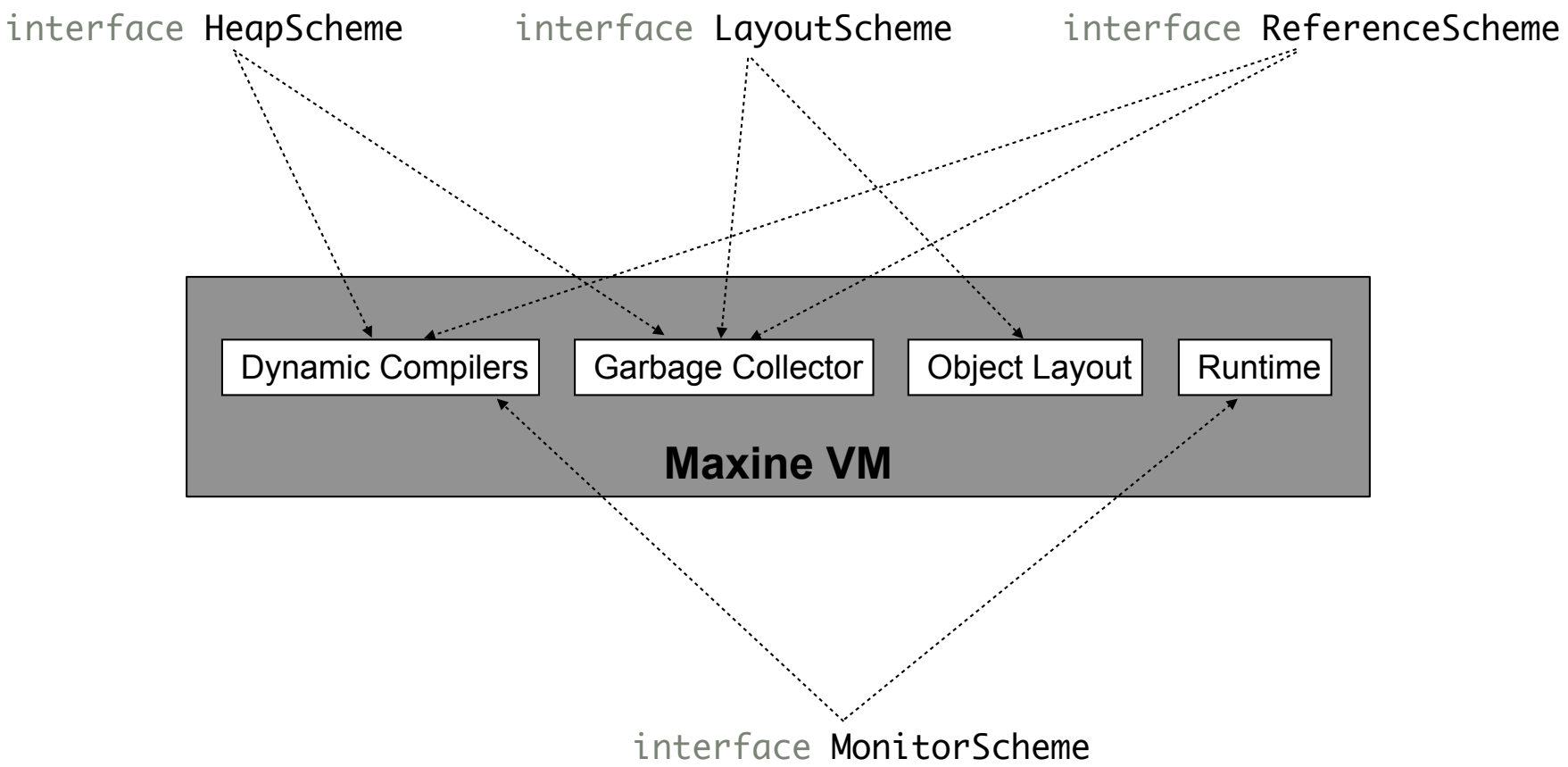

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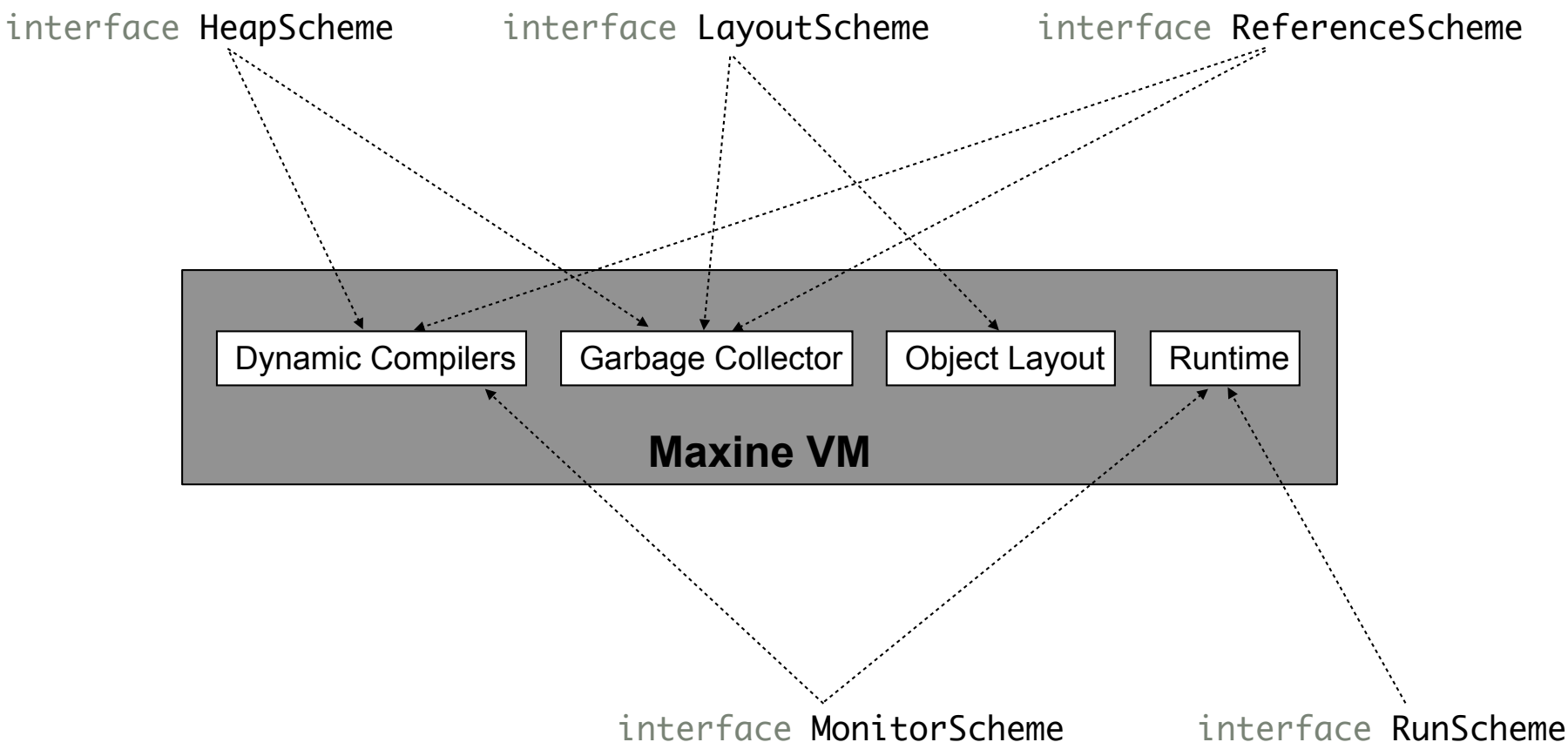

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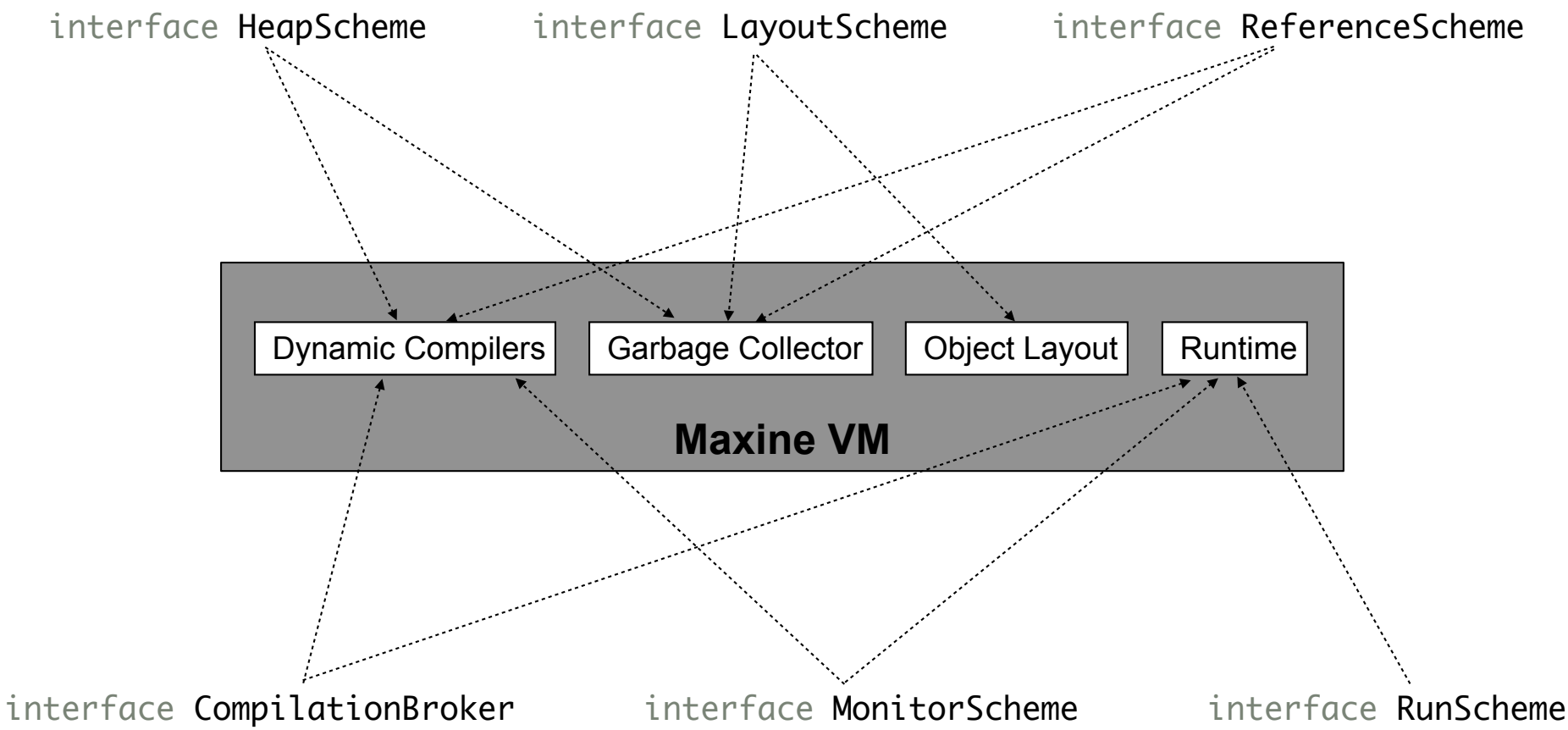

Example: ReferenceScheme

What you use in Maxine to access a field:

```
int x = Reference.fromJava(obj).readInt(24);
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field offset (in bytes) is computed by `LayoutScheme`; we assume a constant offset in this example

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Actual call chain after forced inlining via @INLINE or @FOLD:

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All fields are marked @CONSTANT, so the compiler knows the concrete scheme implementation used:

```
class DirectReferenceScheme implements ReferenceScheme {
    @INTRINSIC(UNSAFE_CAST)
    native Reference toReference(Object origin);
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Final machine code:

```
movl  [rax + 24], rbx
```

Baseline Compiler: T1X

job: assemble pre-generated bytecode templates

- written in Java
- compiled by optimising compiler at VM build time
- very small amount of glue assembly

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template code for integer array load (IALOAD)

```
@T1X_TEMPLATE(IALOAD)
static int iaload(@Slot(1) Object array, @Slot(0) int index) {
    ArrayAccess.checkIndex(array, index);
    return result = ArrayAccess.getInt(array, index);
}
```

```
@INLINE
static void checkIndex(Object array, int index) {
    int length = Layout.readArrayLength(Reference.fromJava(array));
    if (UnsignedMath.aboveOrEqual(index, length)) {
        throw Throw.arrayIndexOutOfBoundsException(array, index);
    }
}

@INLINE
static int getInt(Object array, int index) {
    return Layout.getInt(Reference.fromJava(array), index);
}
```

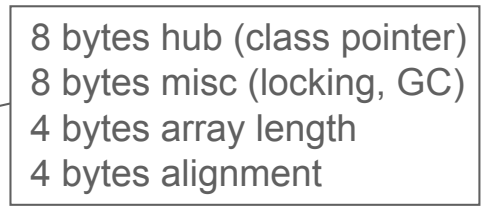
Baseline Compiler: T1X

instantiated template code for integer array load

```
    mov       rdi, [rsp + 16]
    mov       esi, [rsp]
-------------------------------------------
    mov       rax, rdi
    movsxd    rax, [rax + 16]
    cmp       esi, eax
    jb        L1
    call      Throw.indexOutOfBoundsException()
    nop
    mov       rdi, rax
    call      MaxRuntimeCalls.runtimeUnwindException
    nop
L1: movsxd    rsi, esi
    movsxd    rax, rdi[rsi * 4 + 24]
-------------------------------------------
    addq      rsp, 0x10
    mov       [rsp], eax
```

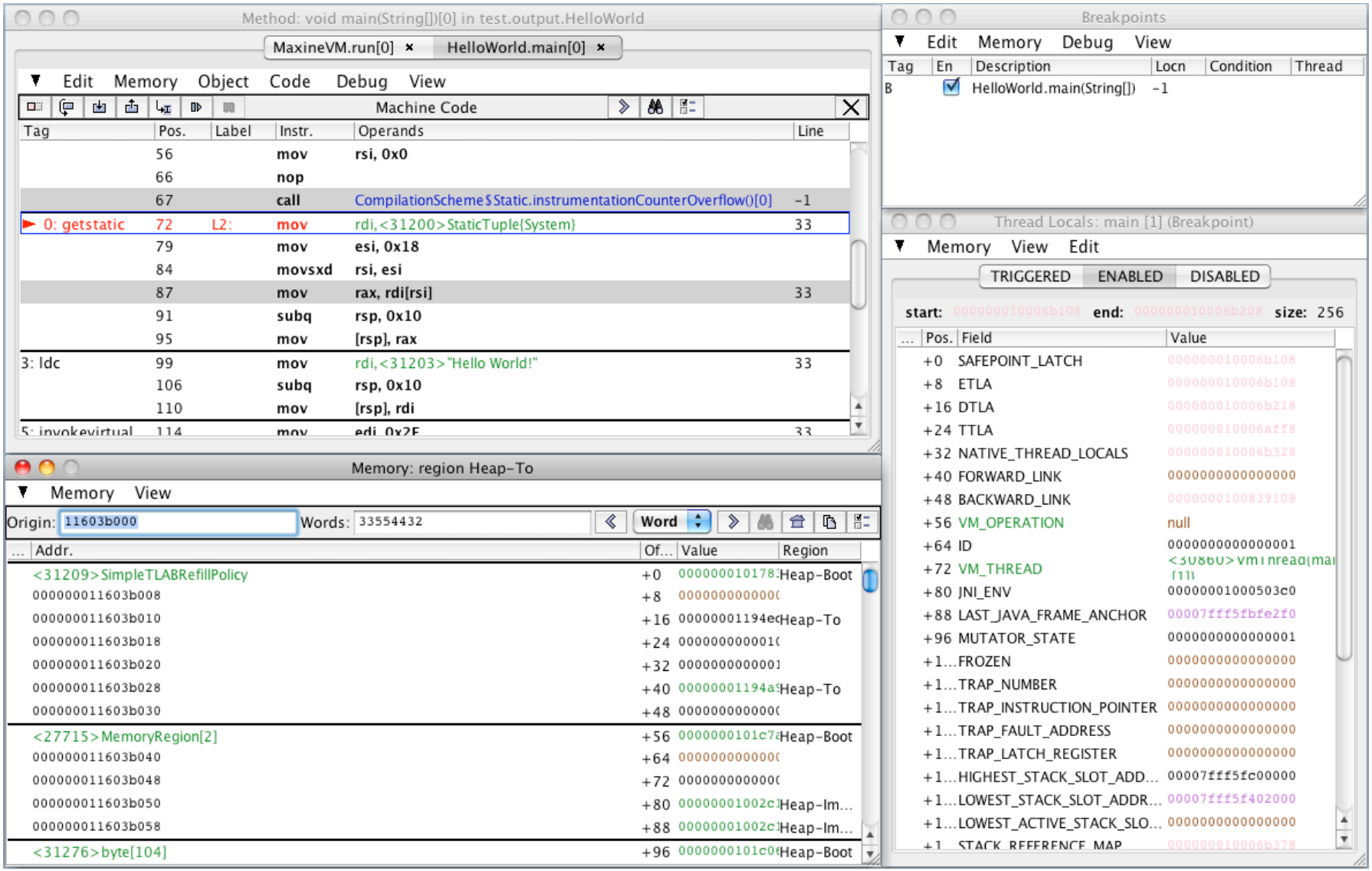
prologue
(loading of operand stack slots)

compiled template



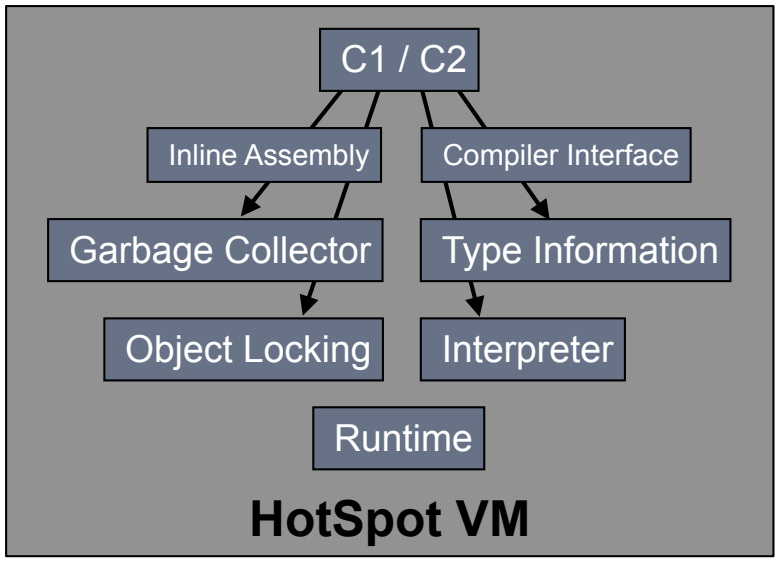
epilogue
(storing of operand stack slots)

Inspector

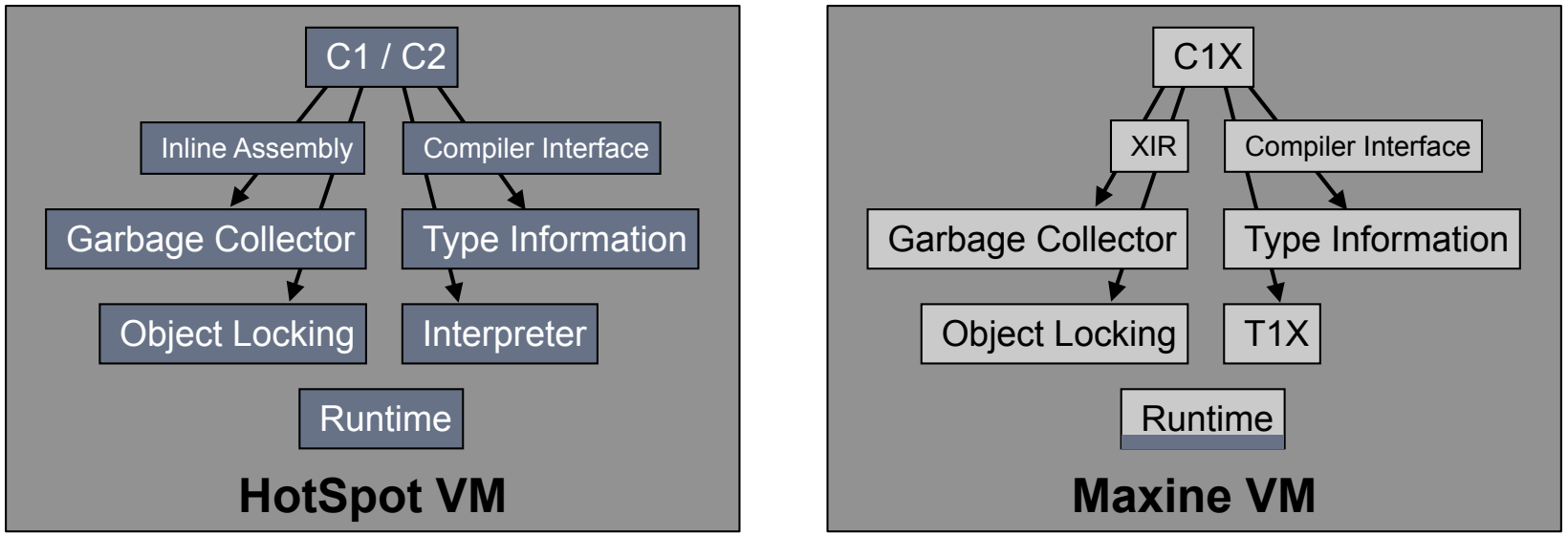

Method: void main(String[])[0] in test.output.HelloWorld
MaxineVM.run[0]
HelloWorld.main[0]
Edit Memory Object Code Debug View
Machine Code
Tag Pos. Label Instr. Operands Line
56 mov rsi, 0x0
66 nop
67 call CompilationScheme$Static.instrumentationCounterOverflow()[0] -1
0: getstatic 72 L2: mov rdi,<31200>StaticTuple{System} 33
79 mov esi, 0x18
84 movsxd rsi, esi
87 mov rax, rdi[rsi] 33
91 subq rsp, 0x10
95 mov [rsp], rax
3: ldc 99 mov rdi,<31203>"Hello World!" 33
106 subq rsp, 0x10
110 mov [rsp], rdi
Memory: region Heap-To
Memory View
Origin: 11603b000 Words: 33554432 Word
Addr. Of... Value Region
<31209>SimpleTLABRefillPolicy +0 Heap-Boot
000000011603b008 +8
000000011603b010 +16 Heap-To
000000011603b018 +24
000000011603b020 +32
000000011603b028 +40 Heap-To
000000011603b030 +48
<27715>MemoryRegion[2] +56 Heap-Boot
000000011603b040 +64
000000011603b048 +72
000000011603b050 +80 Heap-Im...
000000011603b058 +88 Heap-Im...
<31276>byte[104] +96 Heap-Boot
Breakpoints
Edit Memory Debug View
Tag En Description Locn Condition Thread
B HelloWorld.main(String[]) -1
Thread Locals: main [1] (Breakpoint)
Memory View Edit
TRIGGERED ENABLED DISABLED
start: 000000010006b108 end: 000000010006b208 size: 256
... Pos. Field Value
+0 SAFEPOINT_LATCH 000000010006b108
+8 ETLA 000000010006b108
+16 DTLA 000000010006b218
+24 TTLA 000000010006aff8
+32 NATIVE_THREAD_LOCALS 000000010006b328
+40 FORWARD_LINK 0000000000000000
+48 BACKWARD_LINK 0000000100839108
+56 VM_OPERATION null
+64 ID 0000000000000001
+72 VM_THREAD
+80 JNI_ENV 00000001000503c0
+88 LAST_JAVA_FRAME_ANCHOR 00007fff5fbfe2f0
+96 MUTATOR_STATE 0000000000000001
+1... FROZEN 0000000000000000
+1... TRAP_NUMBER 0000000000000000
+1... TRAP_INSTRUCTION_POINTER 0000000000000000
+1... TRAP_FAULT_ADDRESS 0000000000000000
+1... TRAP_LATCH_REGISTER 0000000000000000
+1... HIGHEST_STACK_SLOT_ADD... 00007fff5fc00000
+1... LOWEST_STACK_SLOT_ADDR... 00007fff5f402000
+1... LOWEST_ACTIVE_STACK_SLO... 0000000000000000

Optimising Compilers: C1X and Graal

C++



Optimising Compilers: C1X and Graal



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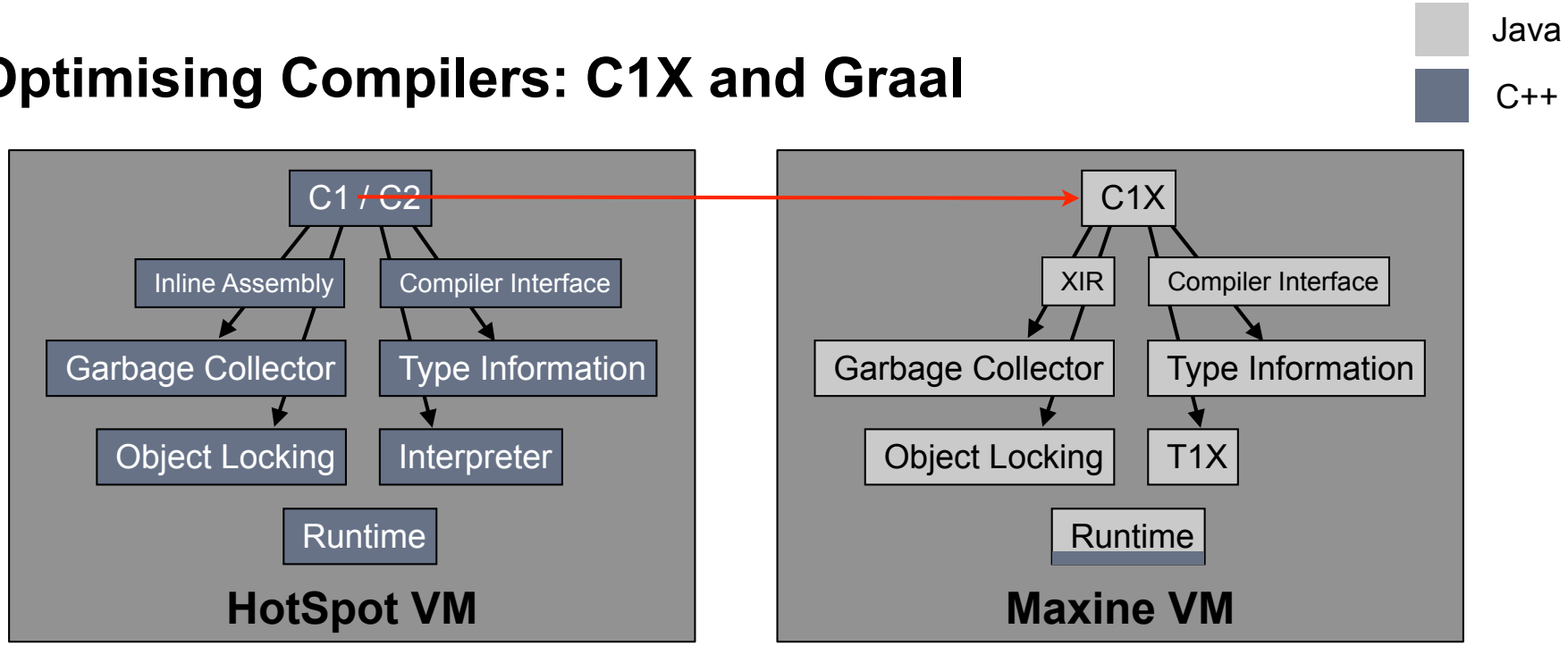
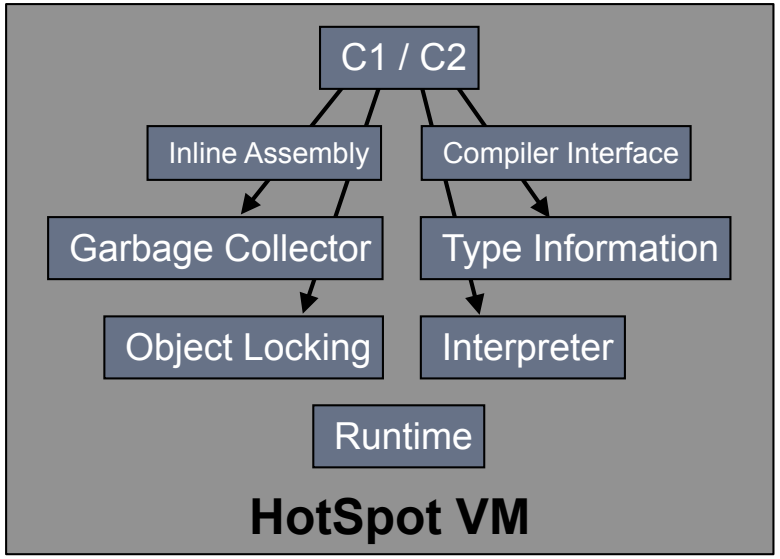
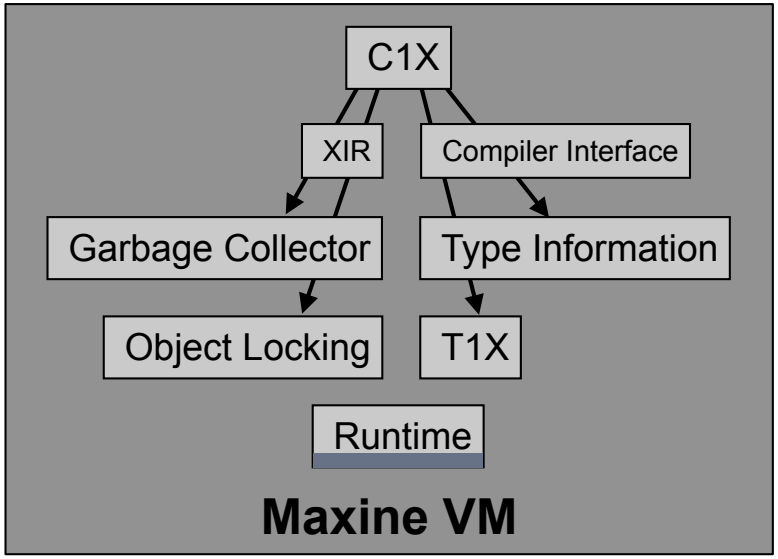
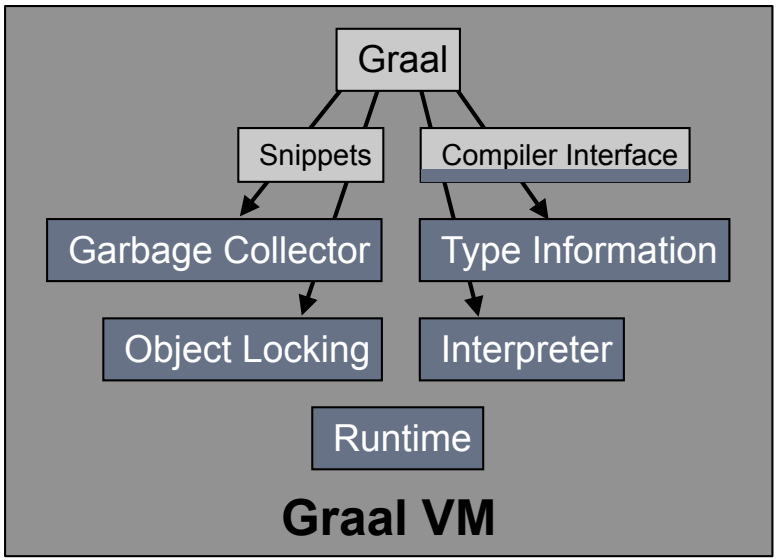


Optimising Compilers: C1X and Graal







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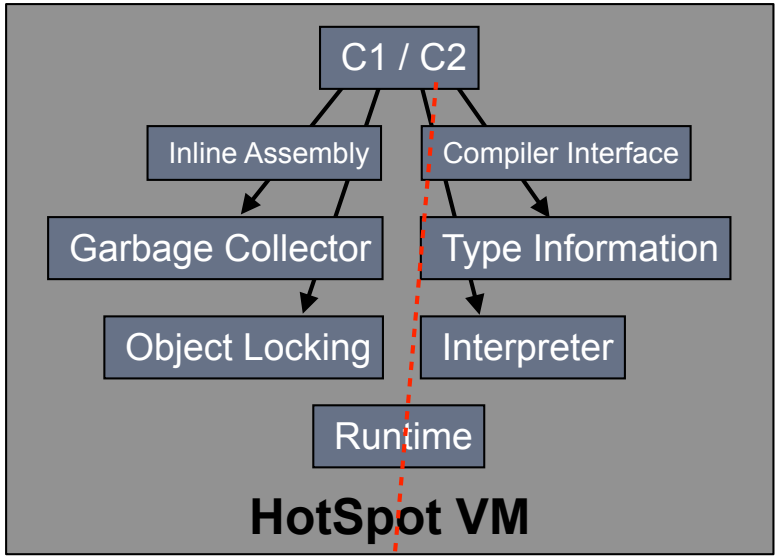
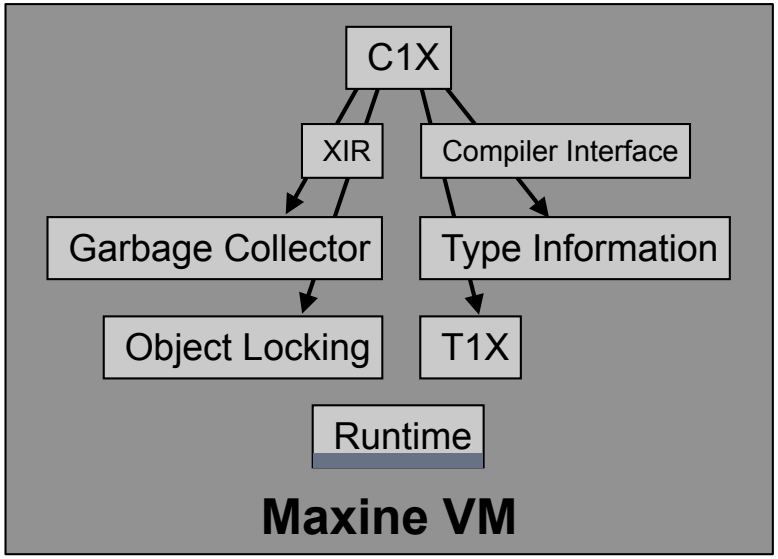
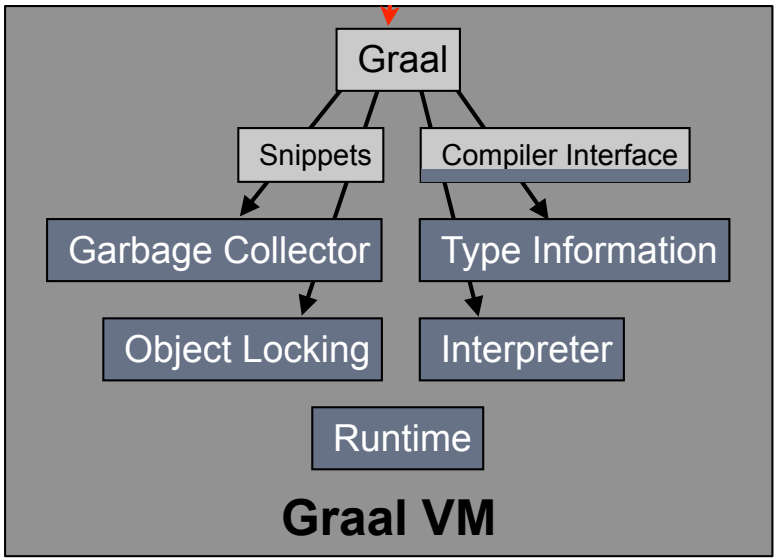
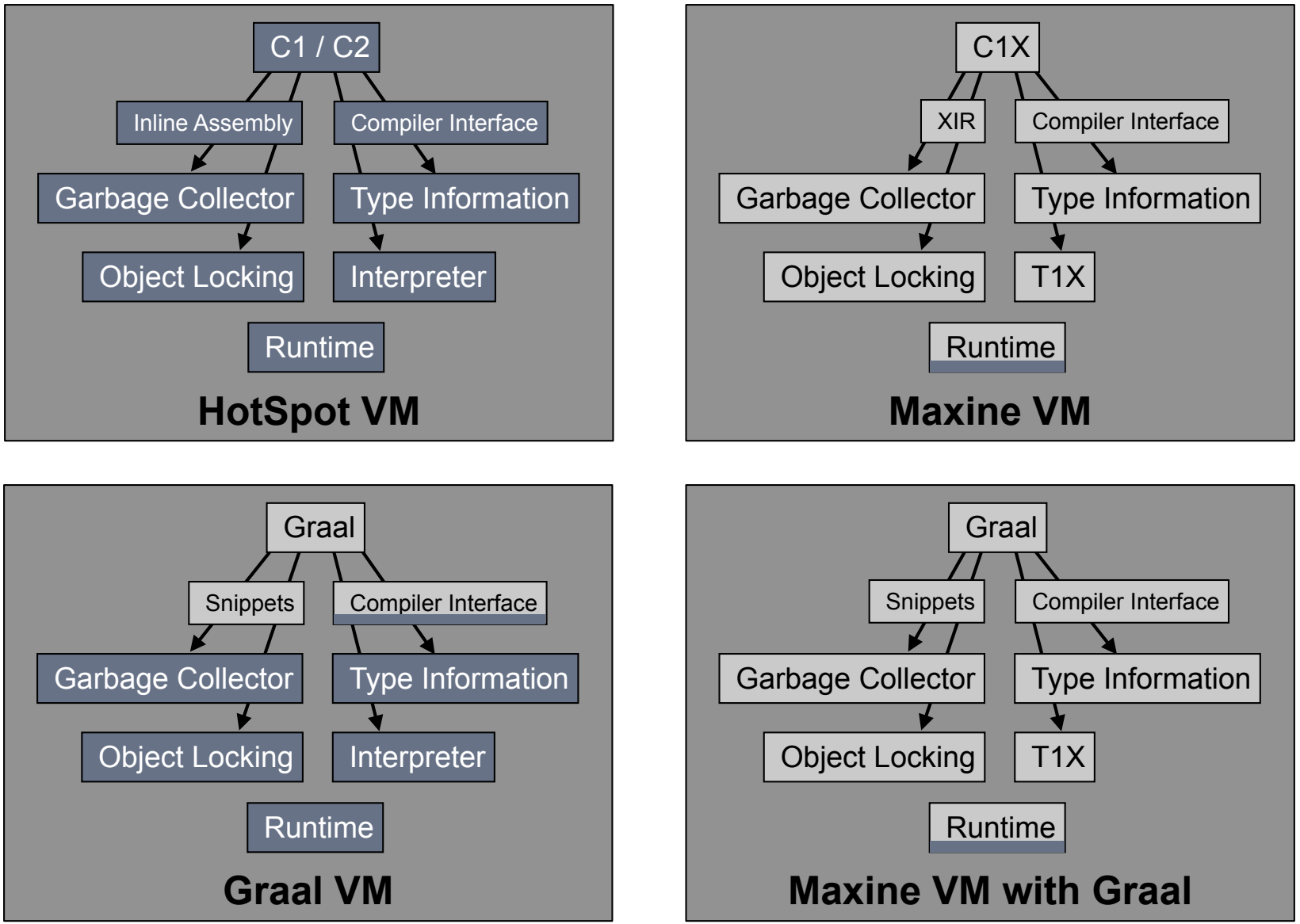


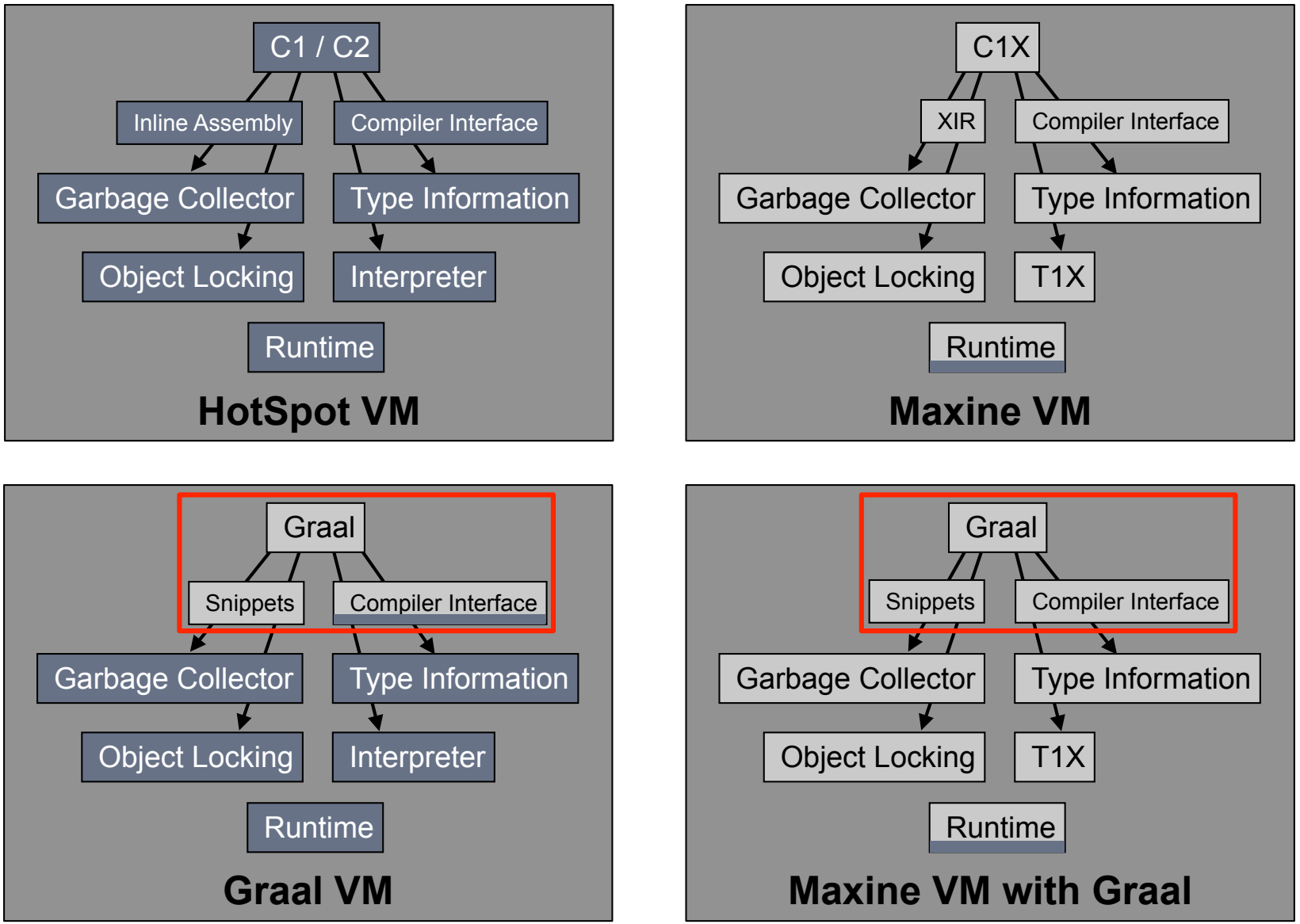




Optimising Compilers: C1X and Graal



Optimising Compilers: C1X and Graal



Graal

Vision Statement

Create an ***extensible***, ***modular***,
dynamic, *and* ***aggressive*** *compiler using*
object-oriented *and* ***reflective*** *Java programming,*
a ***graph-based***
and ***visualizable*** *intermediate representation,*
and Java ***snippets***.

-- Thomas Würthinger

Collaboration with Johannes-Kepler-Universität Linz, Austria

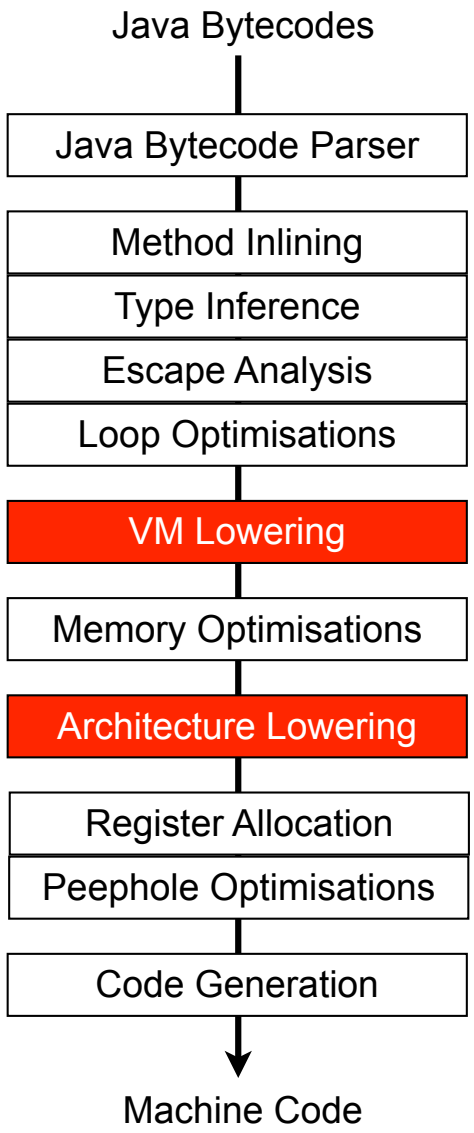
Lukas Stadler, Gilles Duboscq, Christian Häubl, Prof. Hanspeter Mössenböck

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

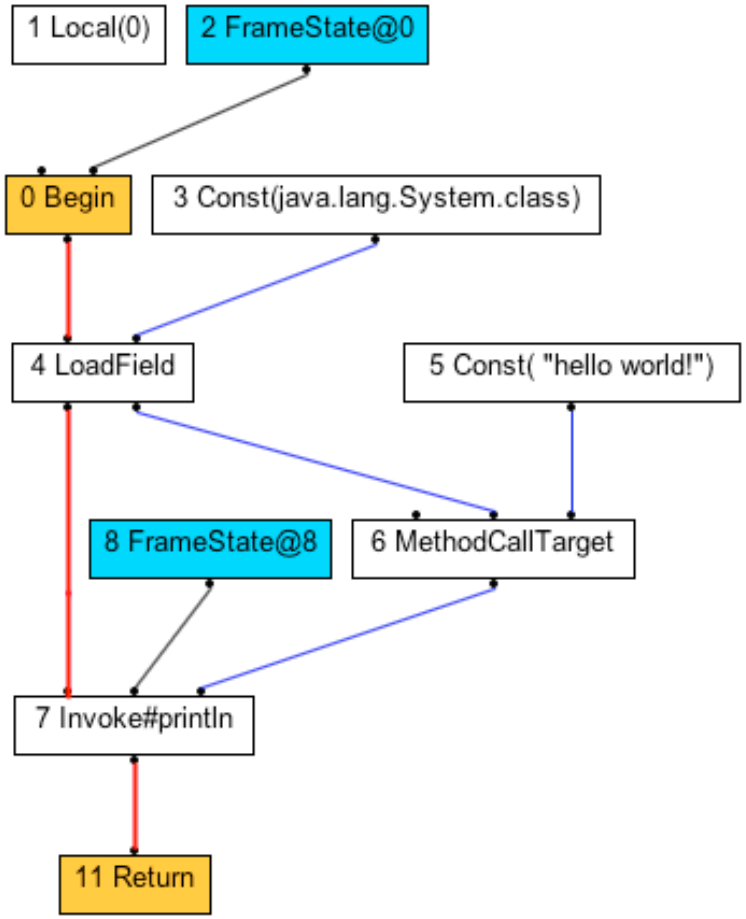
Source (GPLv2): http://hg.openjdk.java.net/graal/graal/

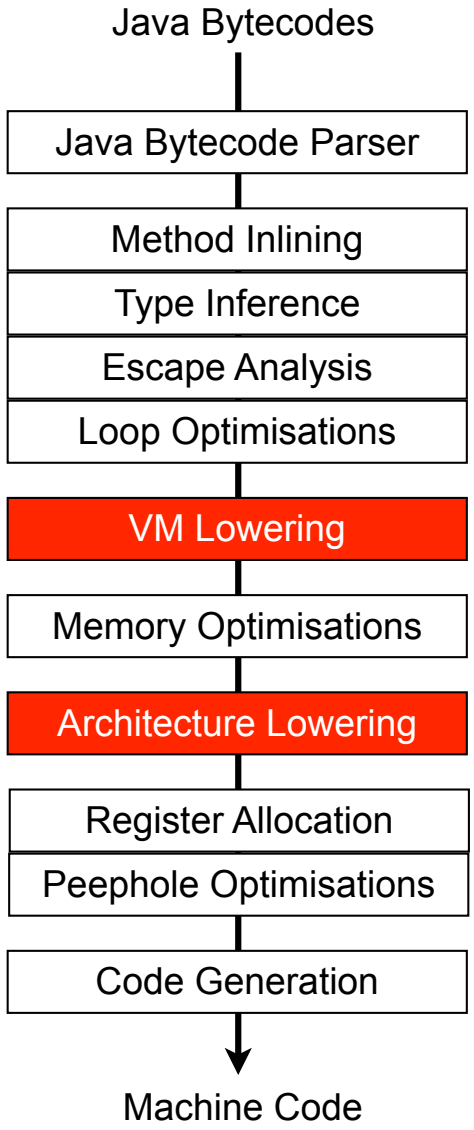
Mailing list: graal-dev@openjdk.java.net

Graal


Java Bytecodes
Java Bytecode Parser
Method Inlining
Type Inference
Escape Analysis
Loop Optimisations
VM Lowering
Memory Optimisations
Architecture Lowering
Register Allocation
Peephole Optimisations
Code Generation
Machine Code

Graal


1 Local(0)
2 FrameState@0
0 Begin
3 Const(java.lang.System.class)
4 LoadField
5 Const("hello world!")
8 FrameState@8
6 MethodCallTarget
7 Invoke#println
11 Return


Java Bytecodes
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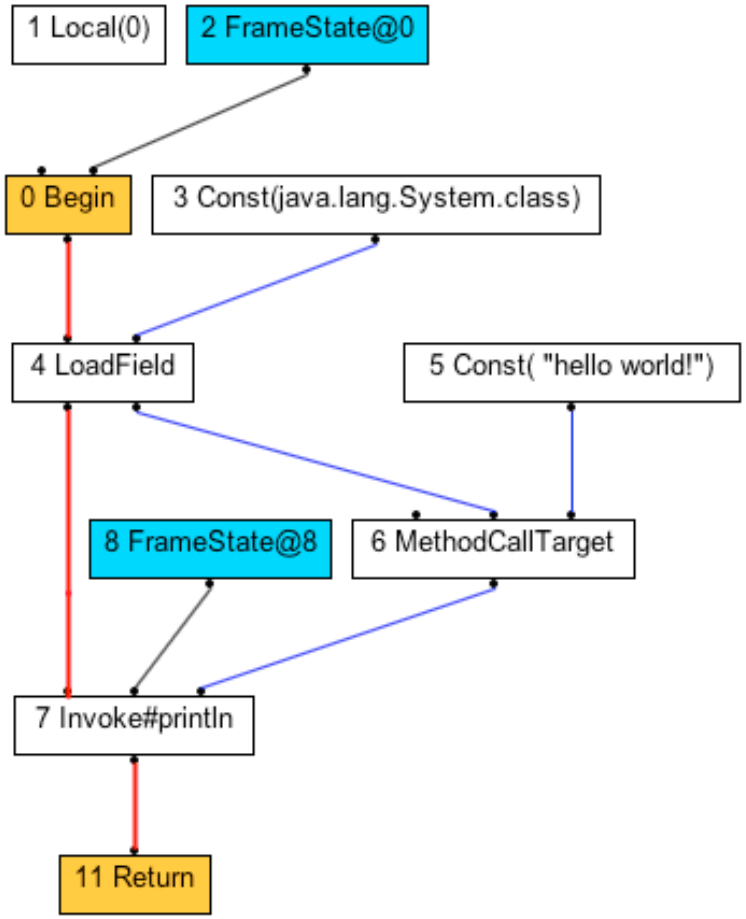
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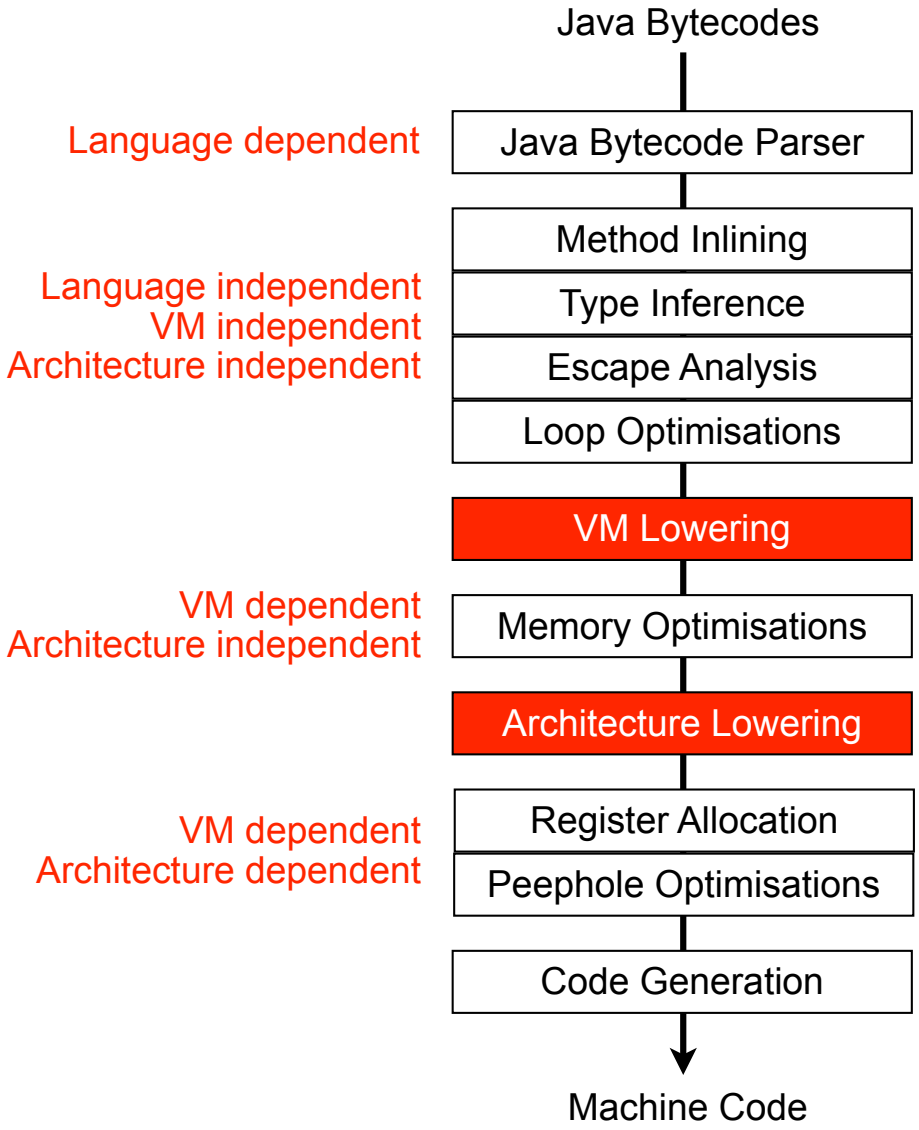
Java Bytecodes
Language dependent
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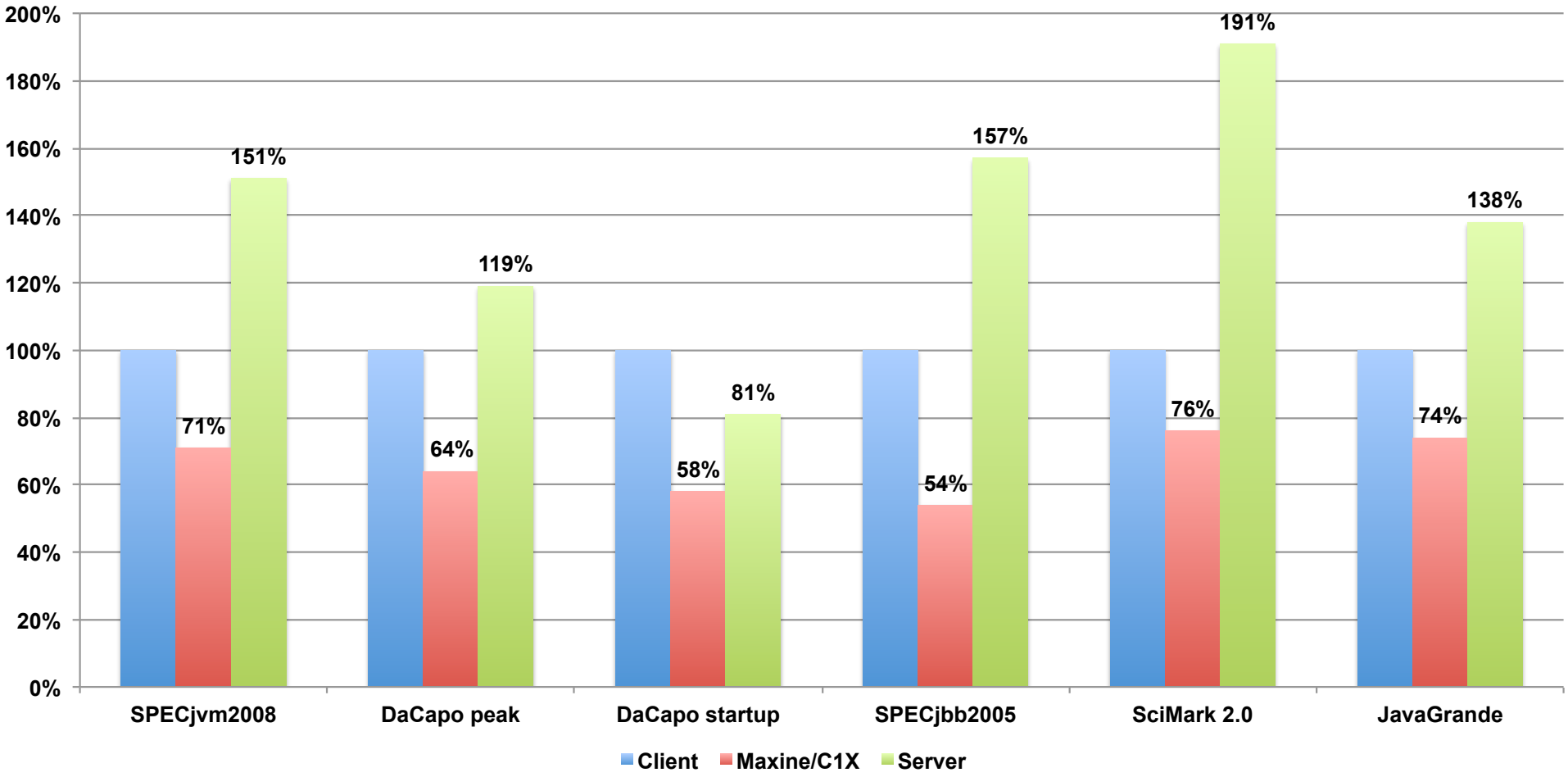
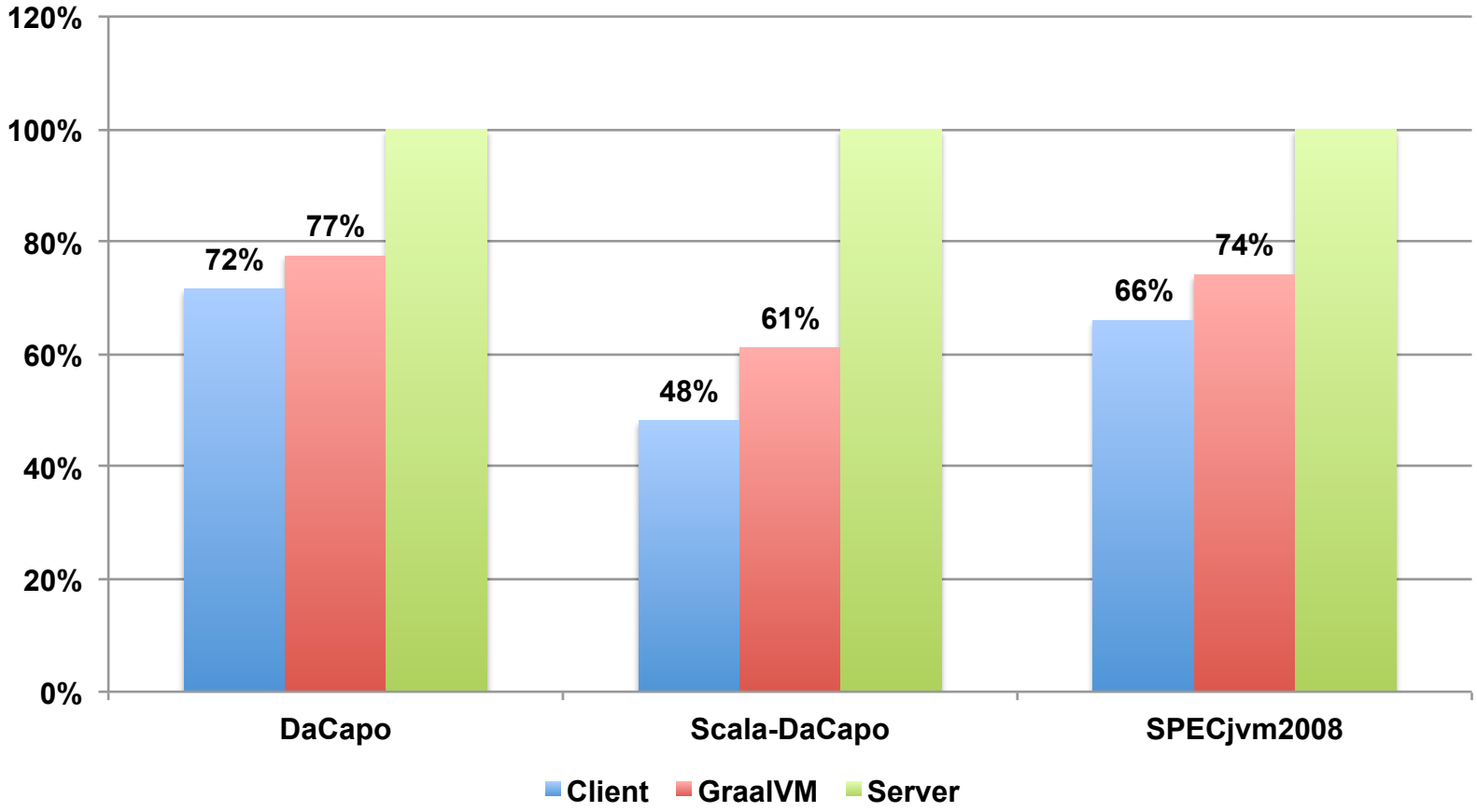
Architecture dependent
Register Allocation
Peephole Optimisations
Code Generation
Machine Code

Performance: Maxine/C1X



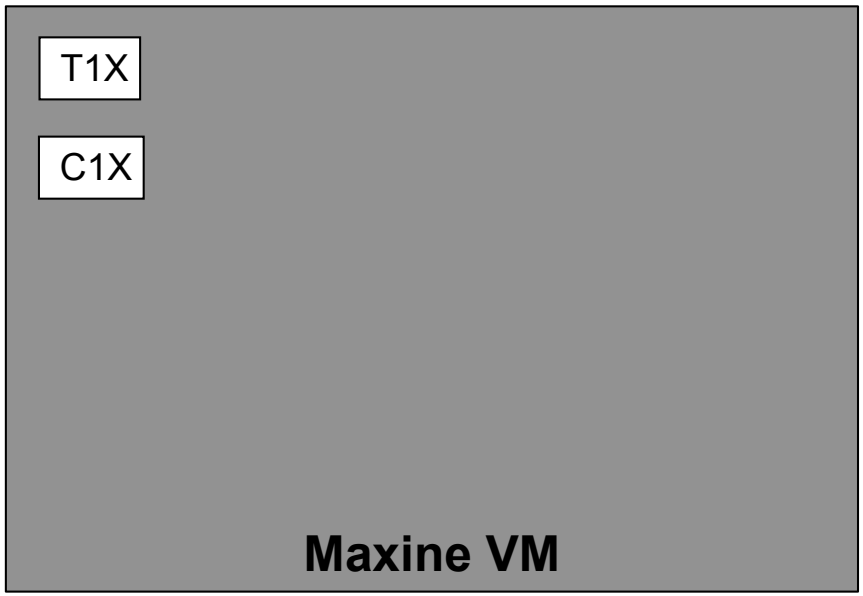
2-socket dual core AMD Opteron 2214, 2.2 GHz, 4 total cores
4 GByte main memory
Oracle Enterprise Linux, version 2.6.18-238.9.1.0.1.e15

Performance: GraalVM



Intel(R) Core(TM) i5-750 @ 2.67GHz (4 cores)
8 GByte main memory
Ubuntu Linux 11.10, kernel 3.0.0-12

Maxine: Code Cache Management



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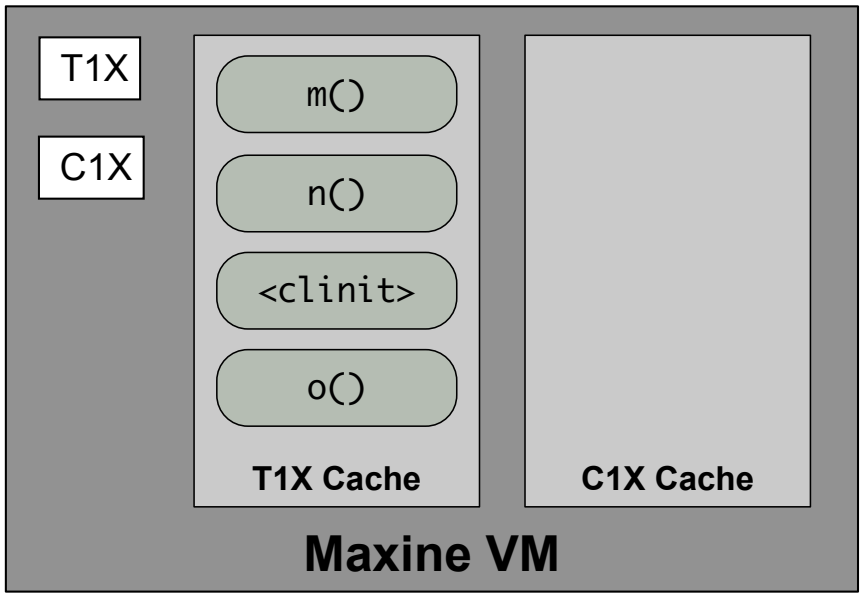
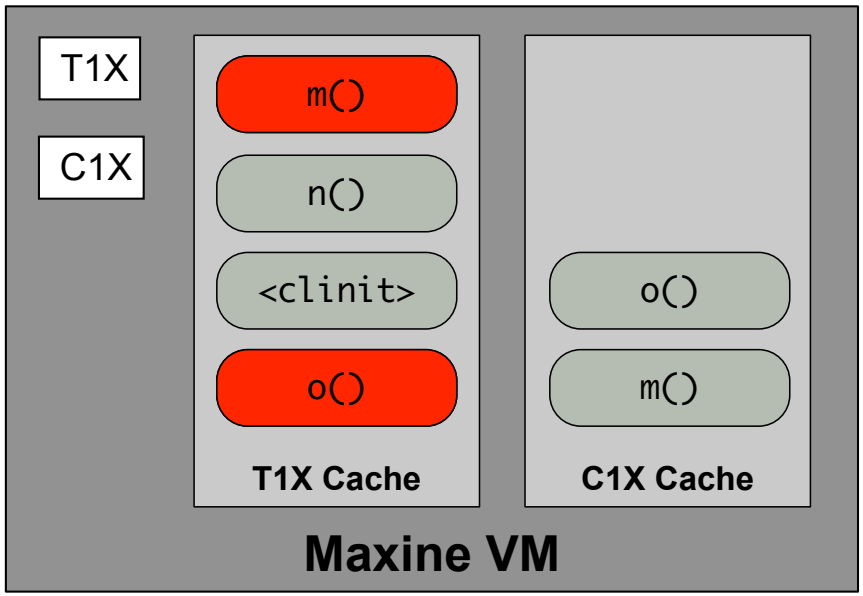


Maxine: Code Cache Management



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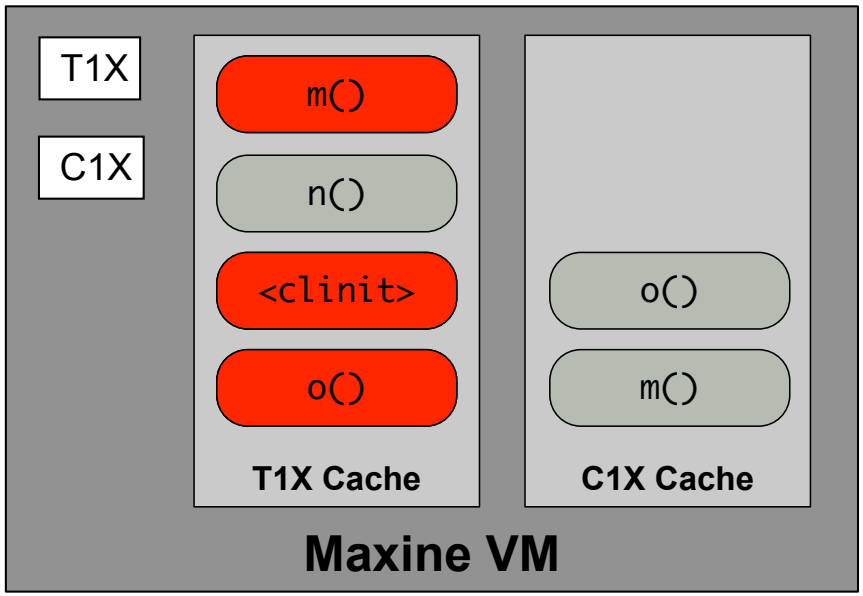

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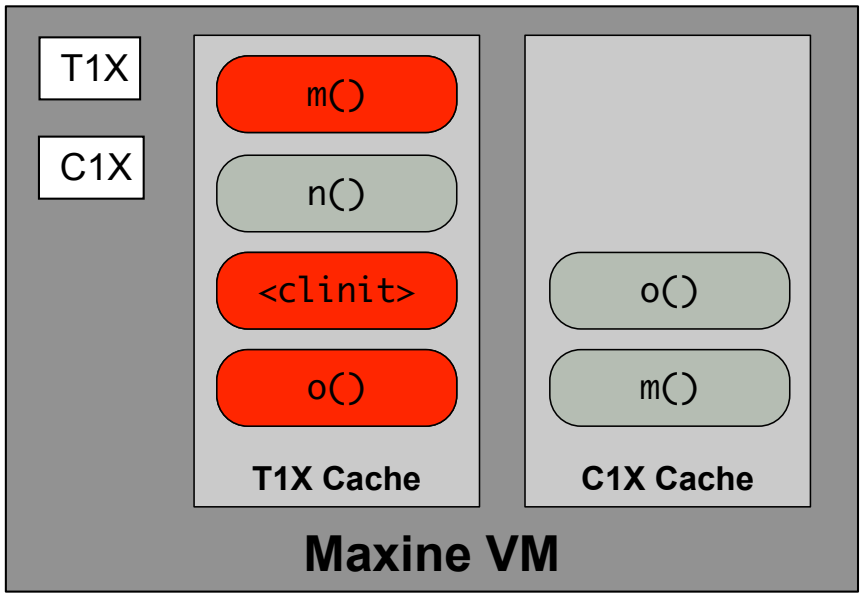
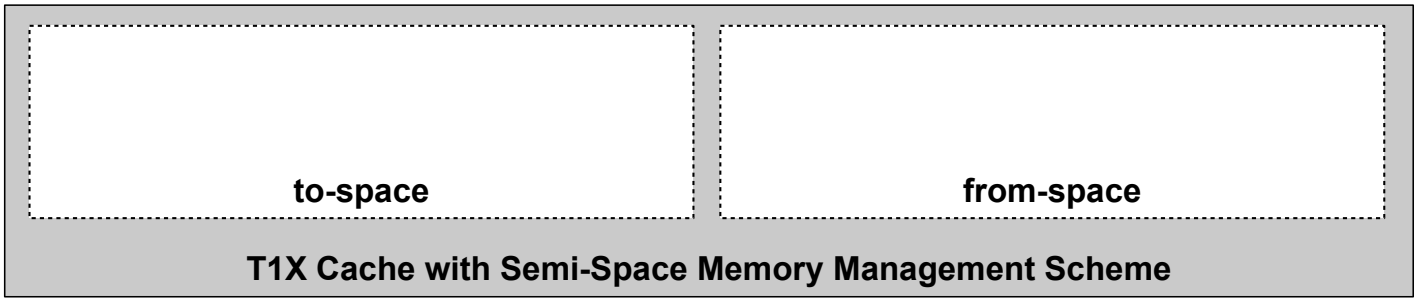
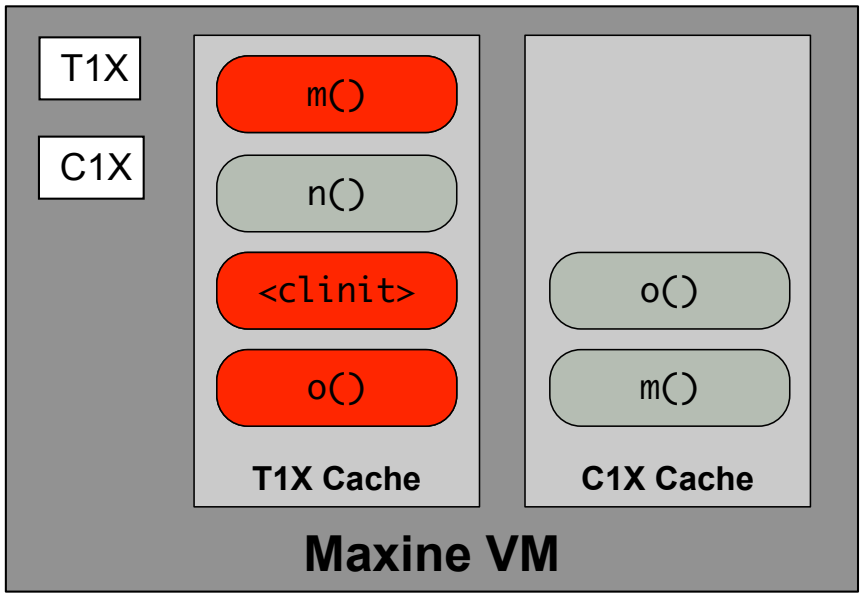
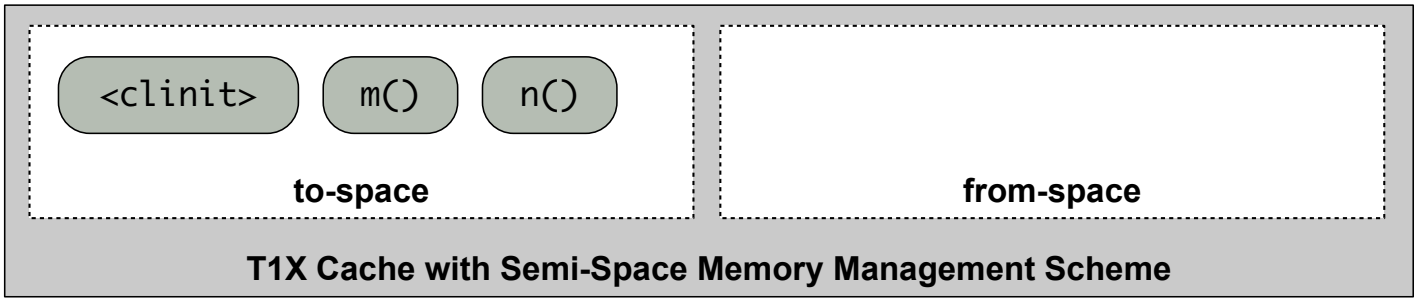




Maxine: Code Cache Management





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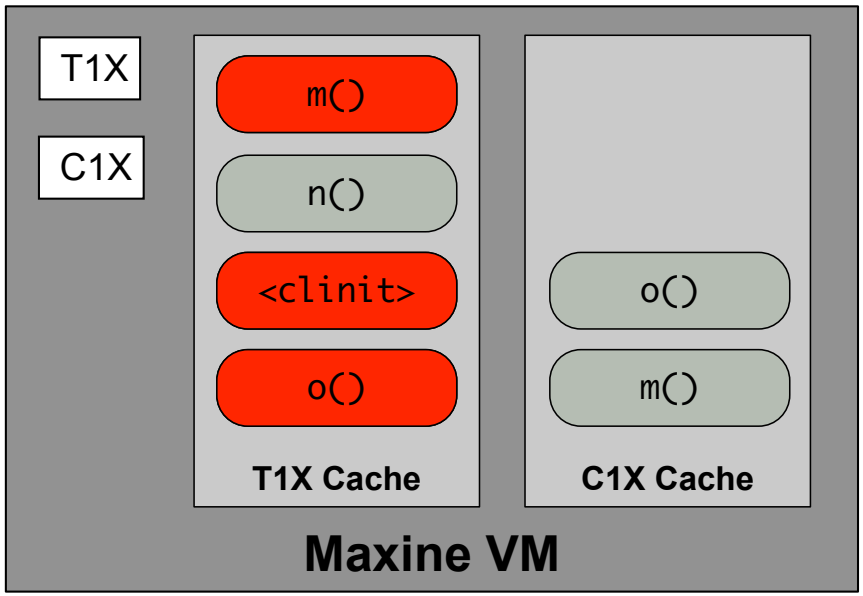

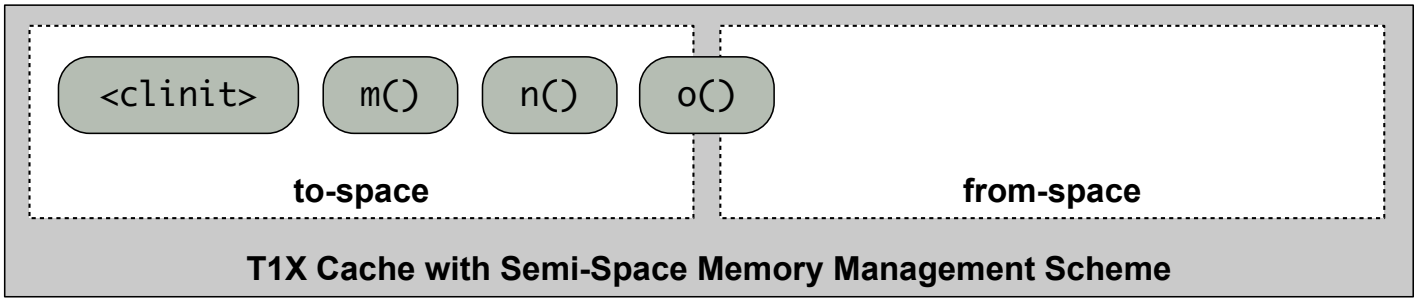

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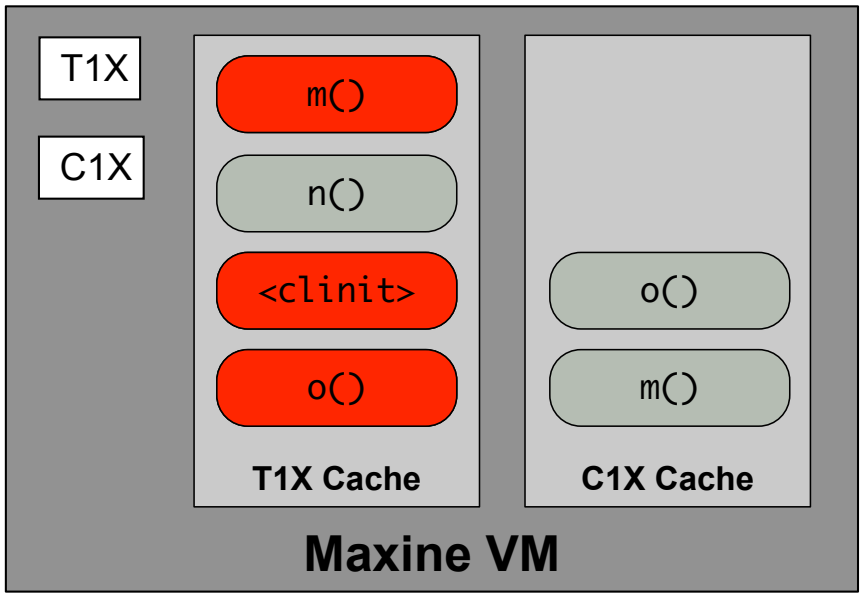

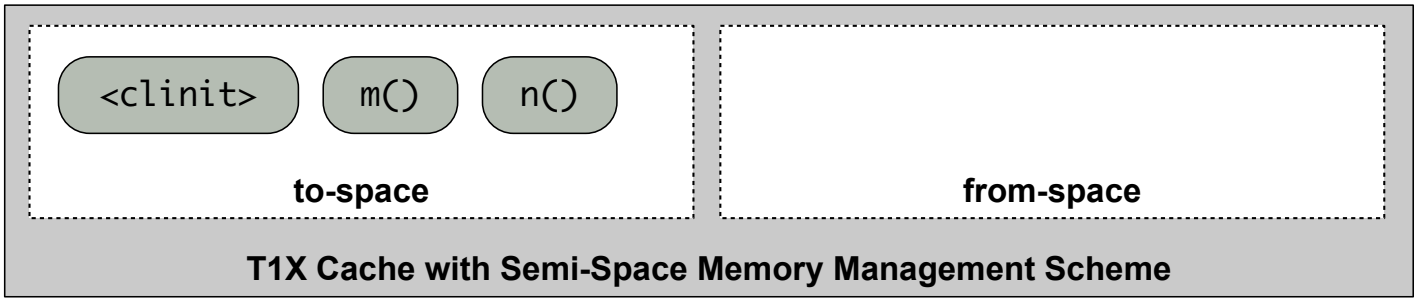

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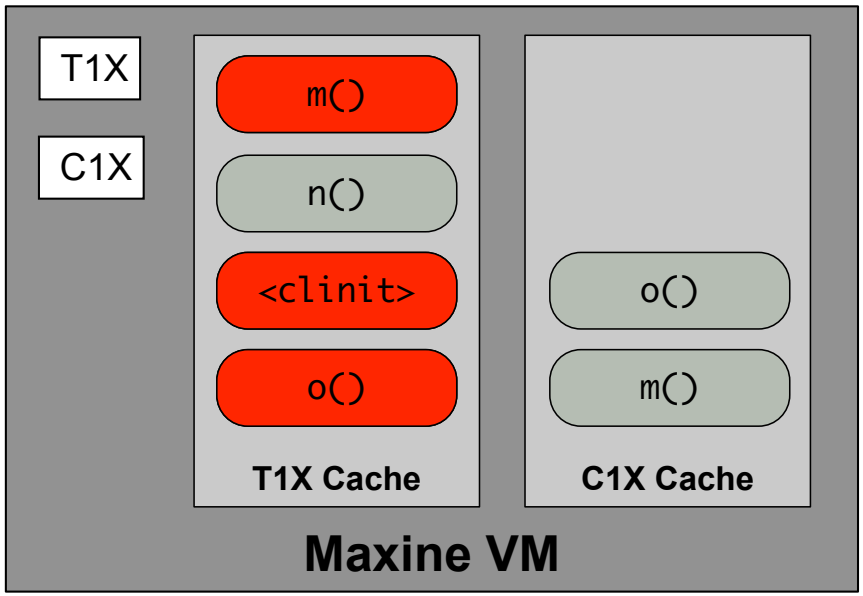

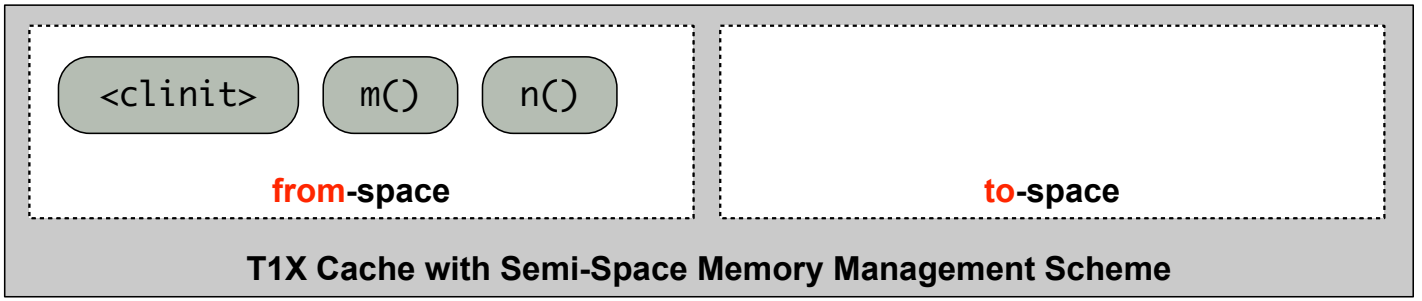

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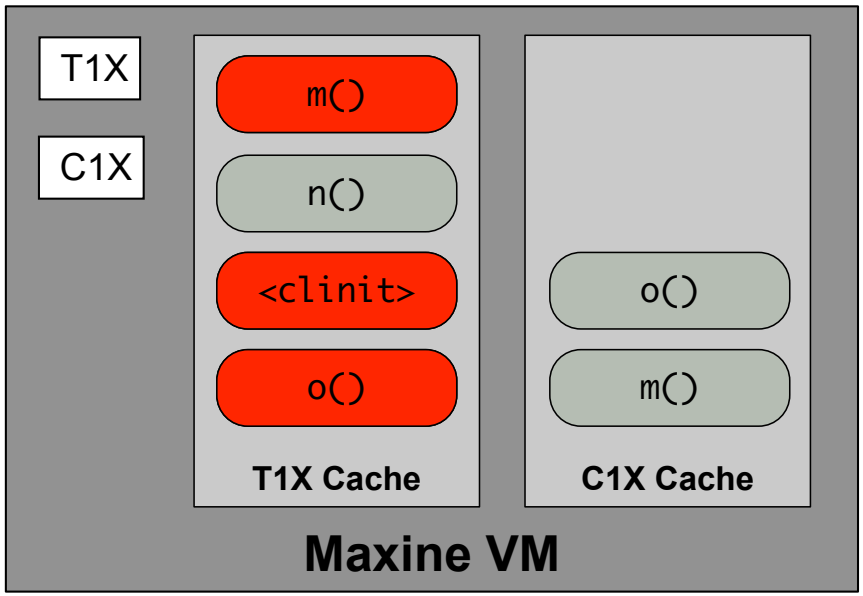

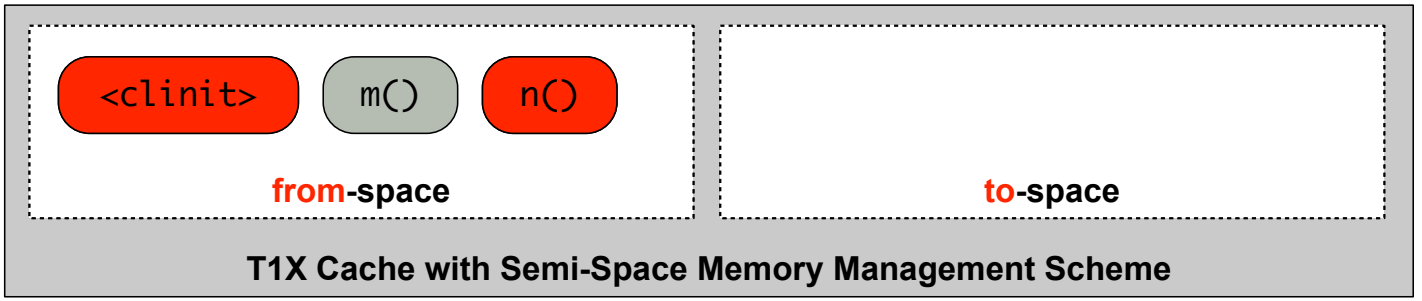

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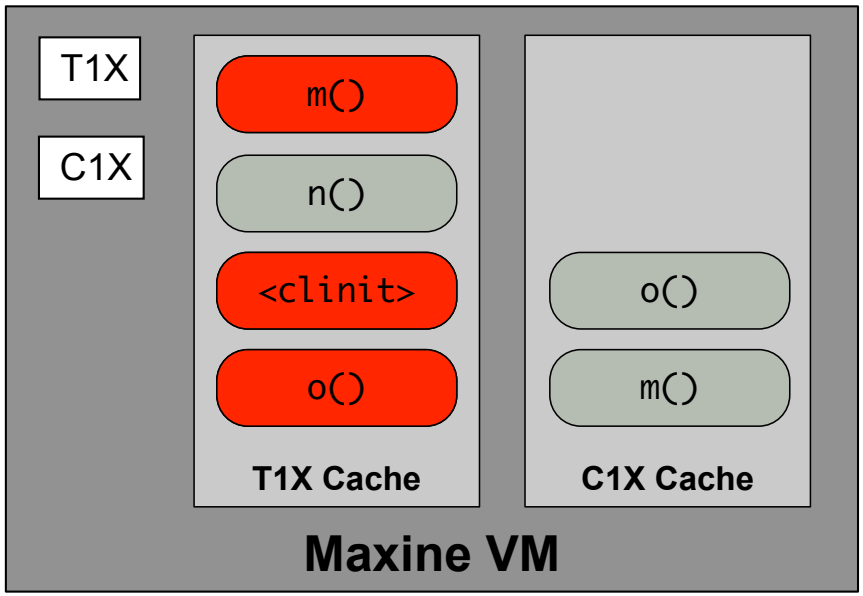

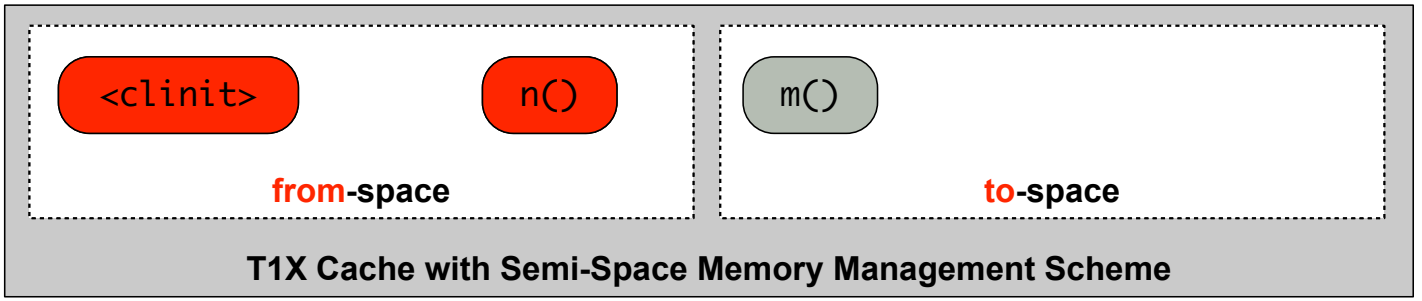

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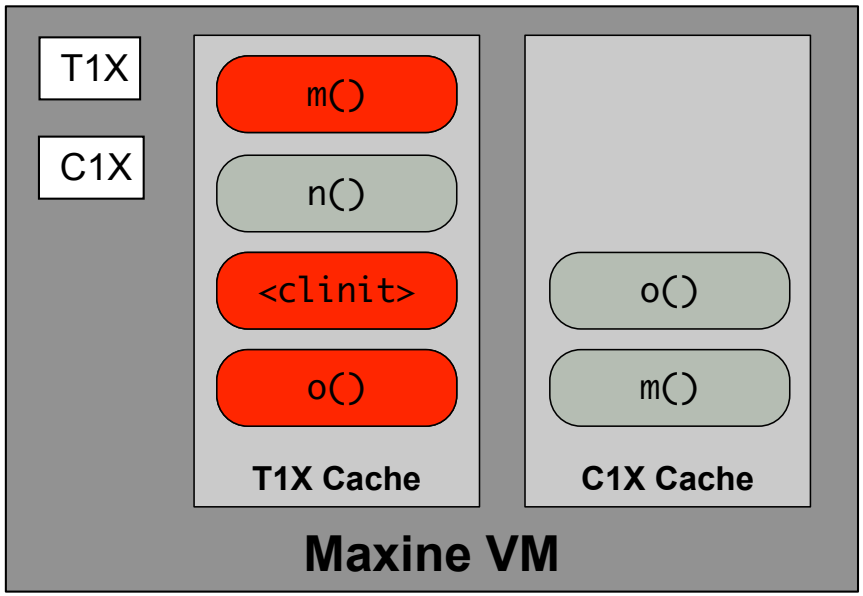
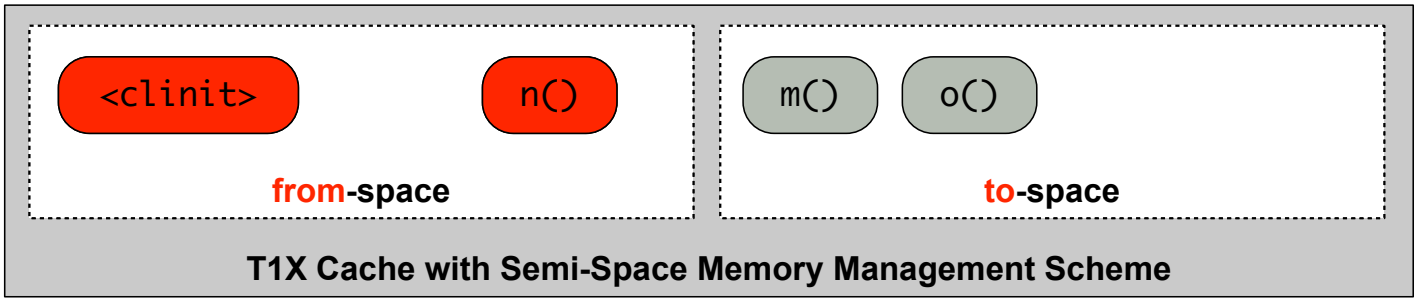


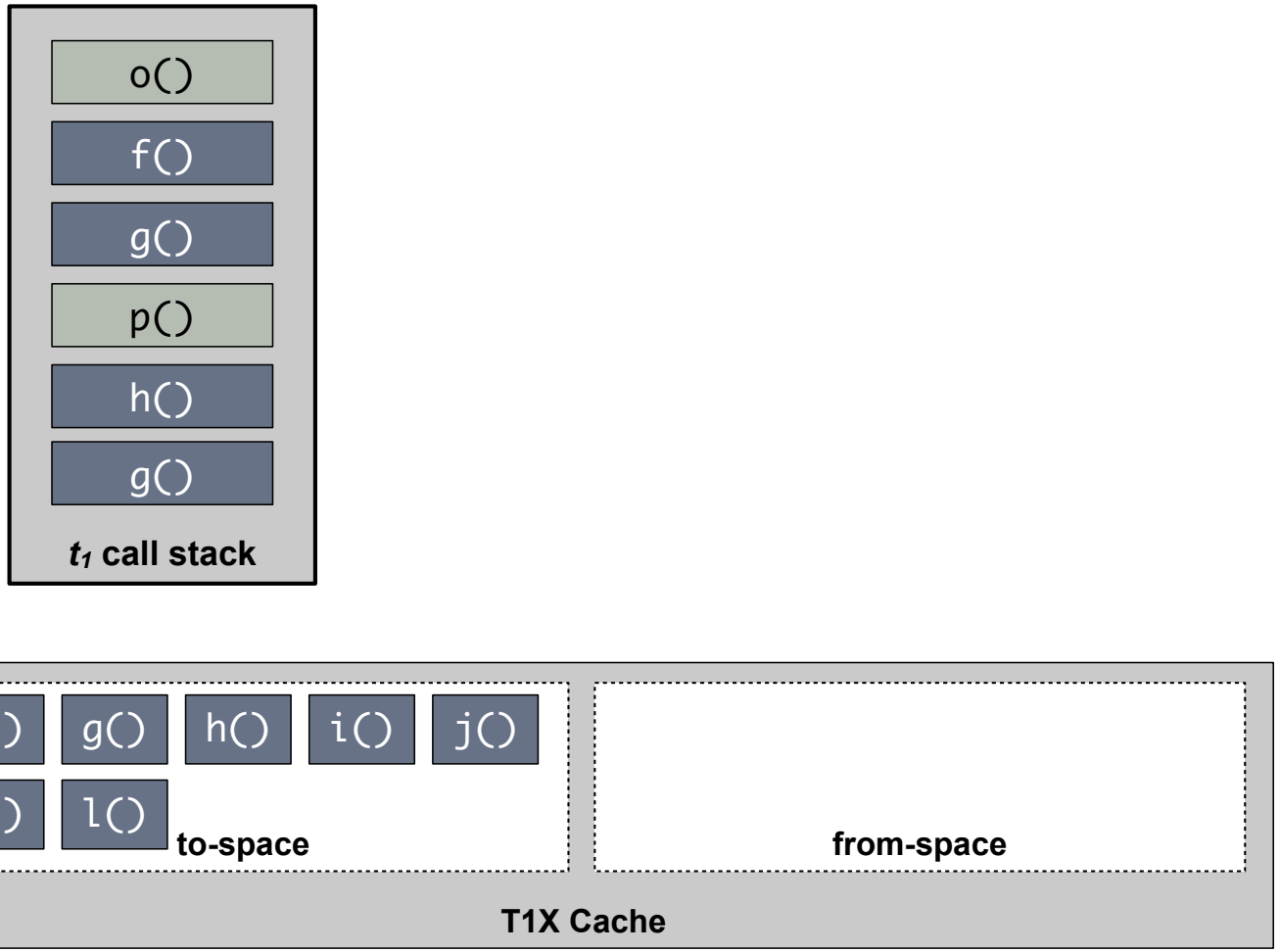


Code Cache Management: Which Methods are Live?

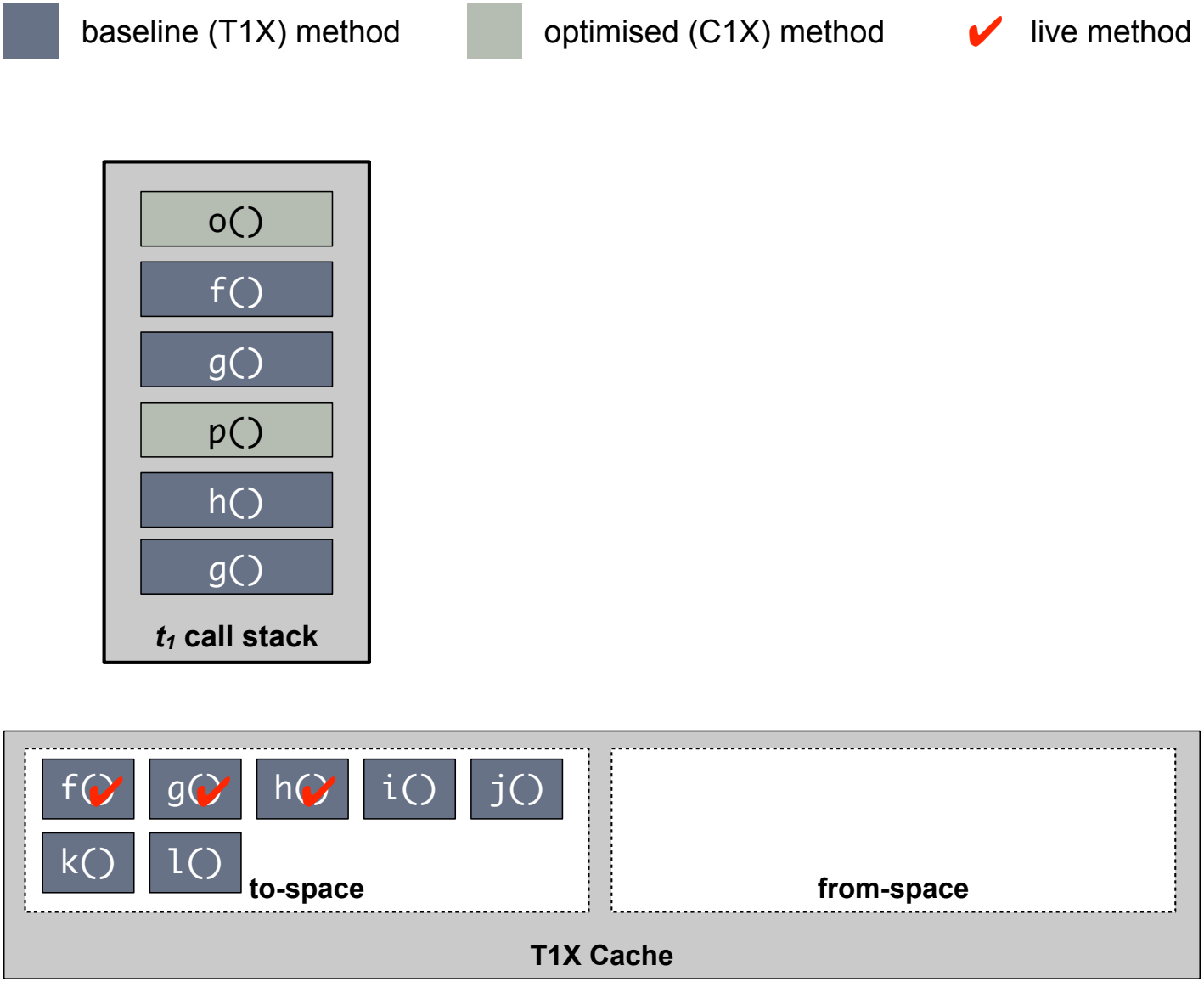
baseline (T1X) method

optimised (C1X) method

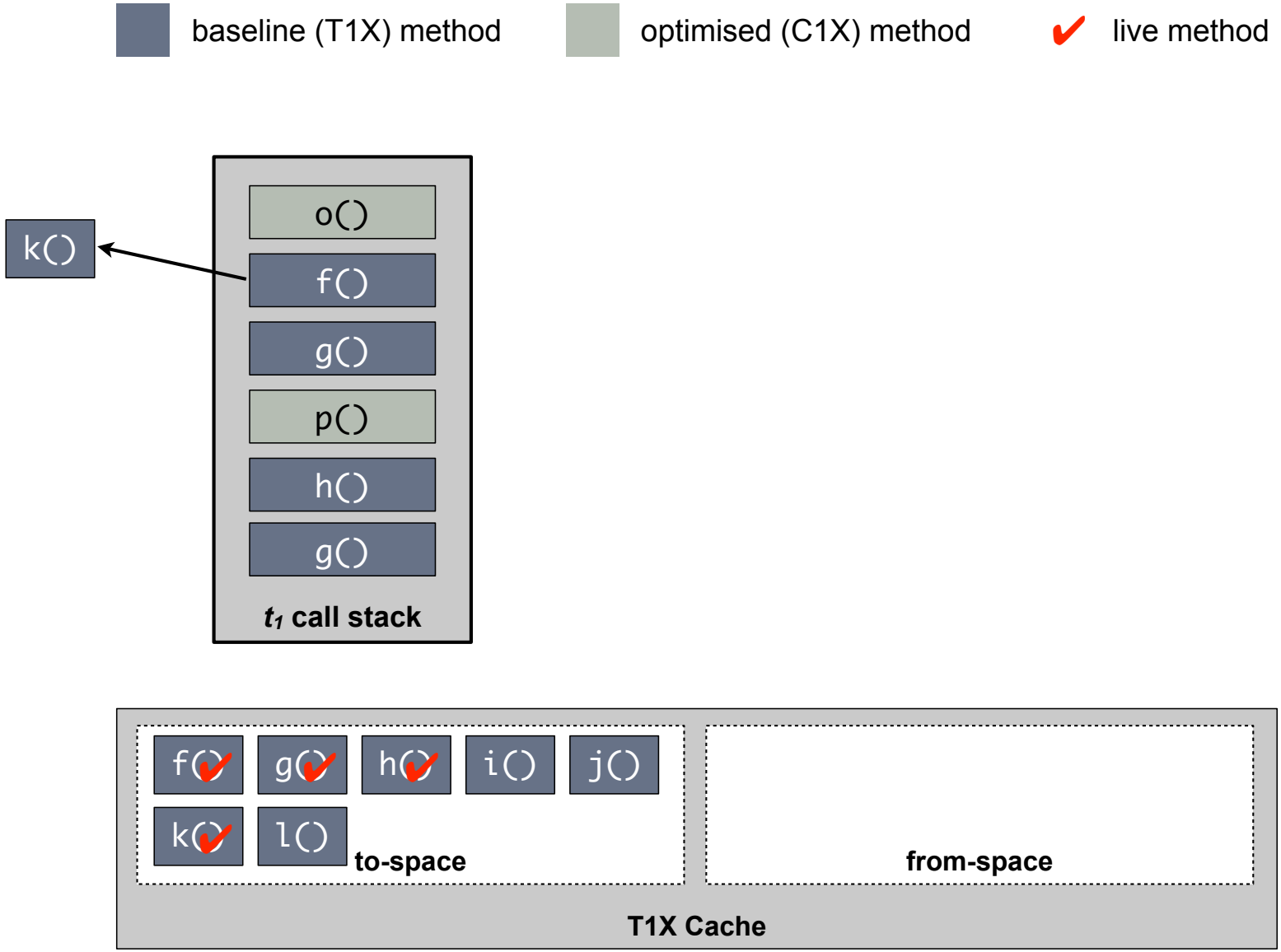
✔ live method



Code Cache Management: Which Methods are Live?



Code Cache Management: Which Methods are Live?



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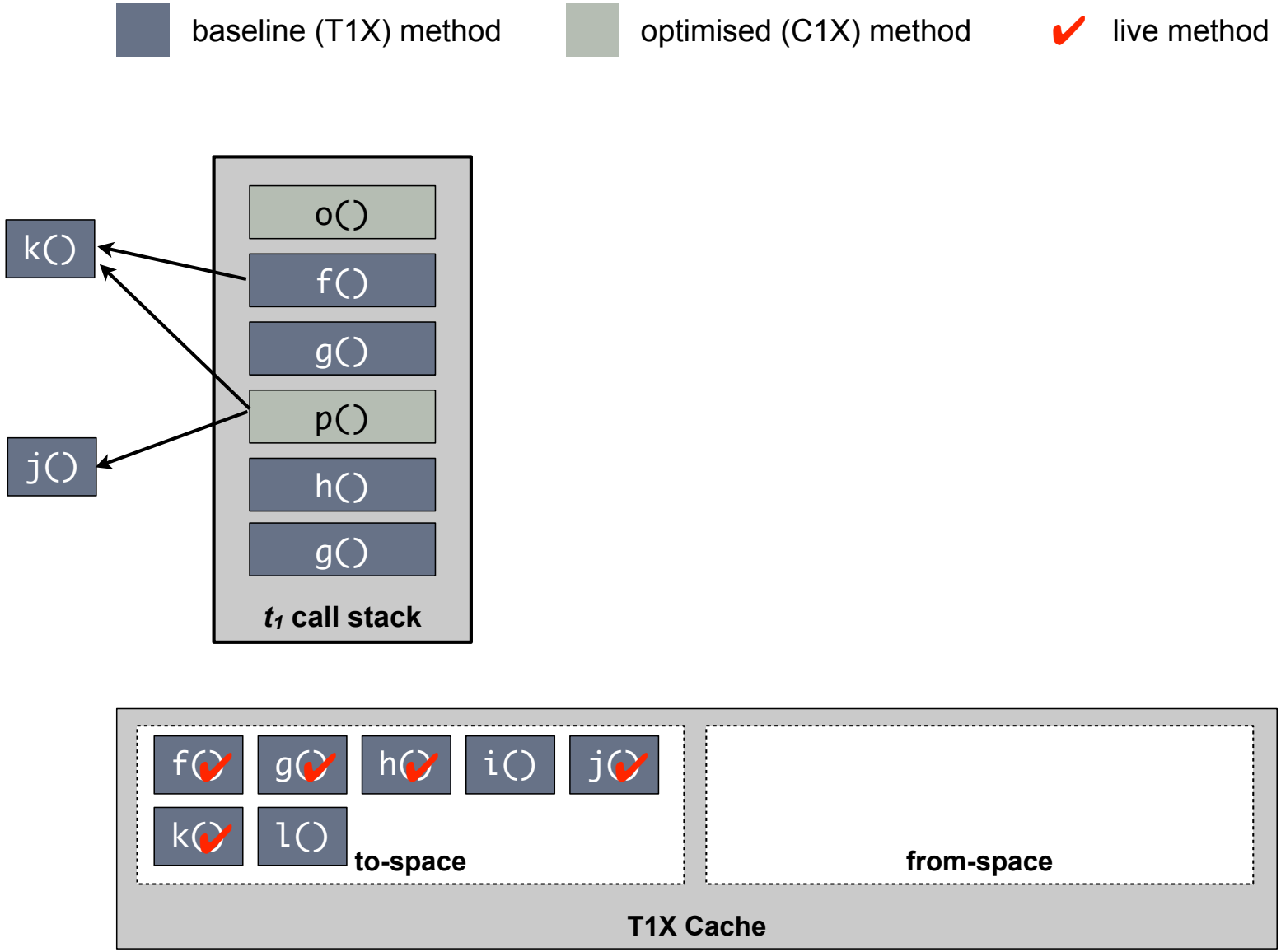

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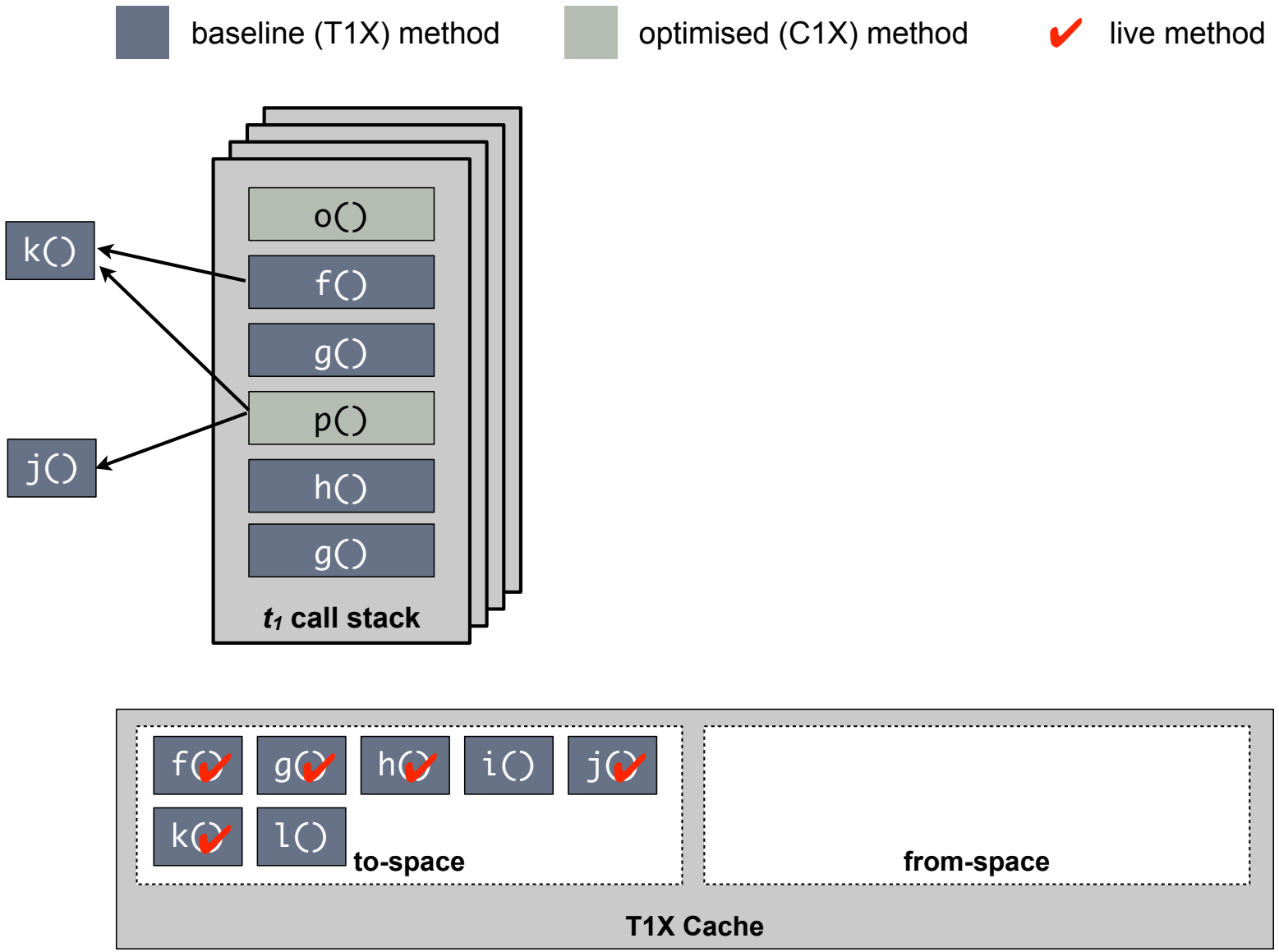
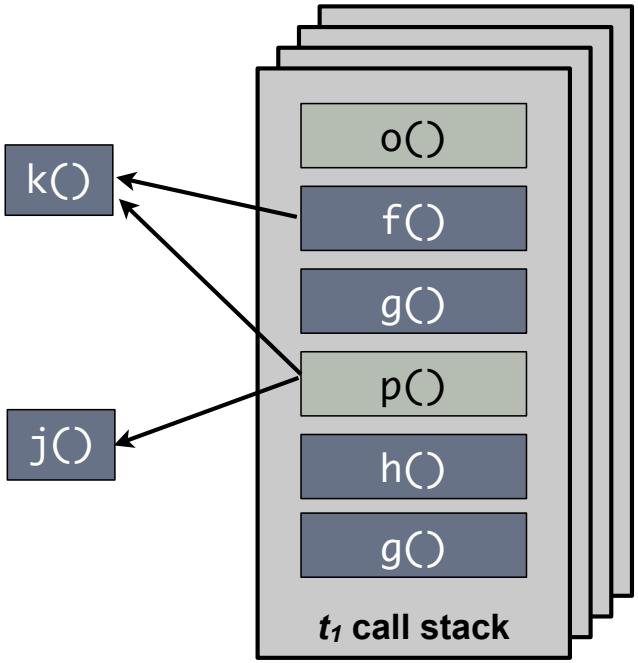


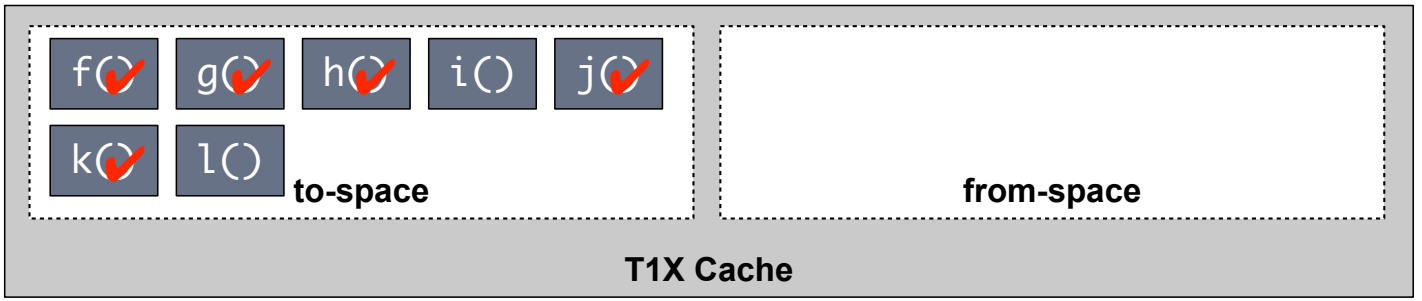
Code Cache Management: Which Methods are Live?

baseline (T1X) method optimised (C1X) method ✔ live method

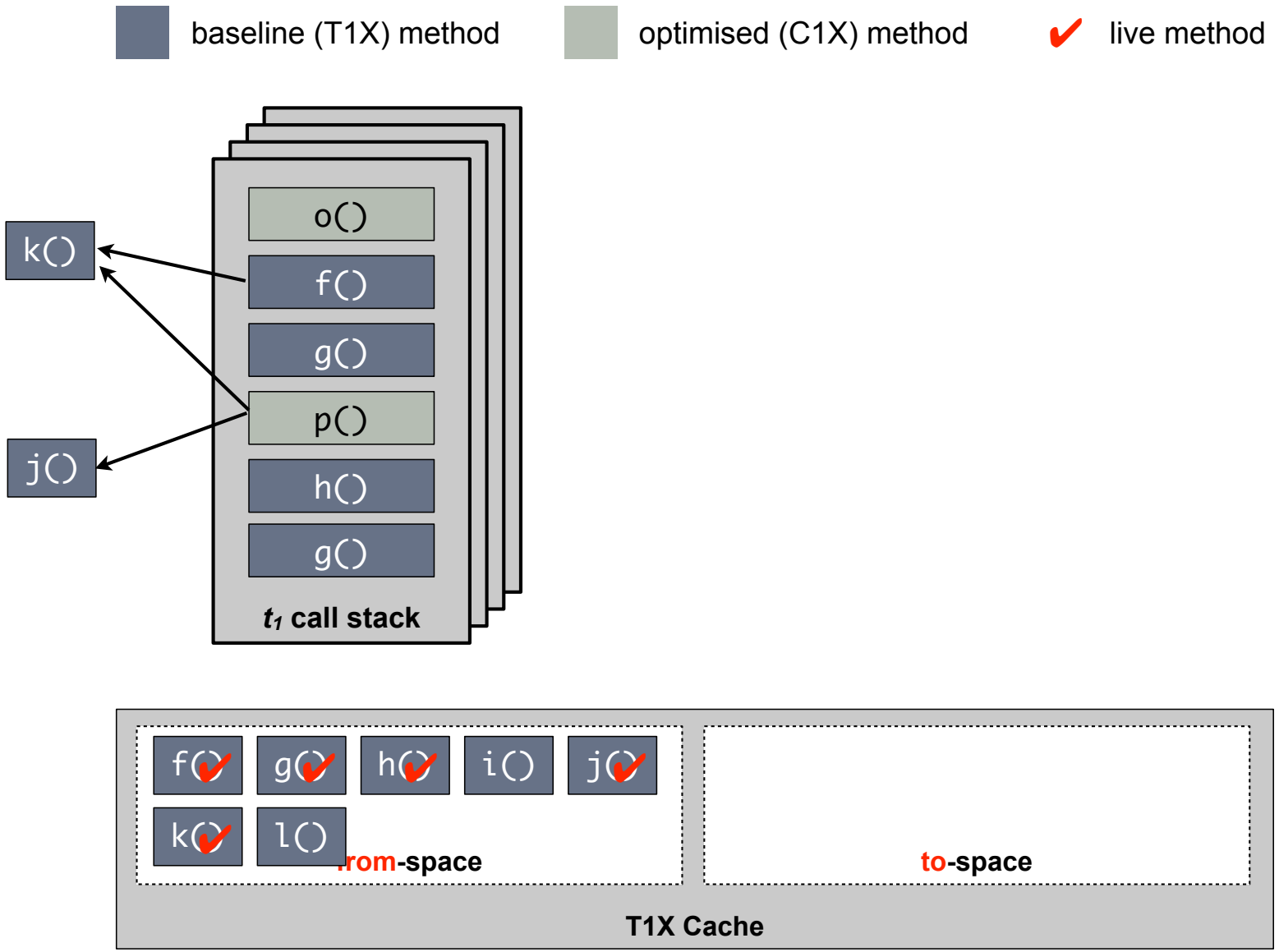


live methods
- methods on stack
- direct callees of on-stack methods

others to protect from eviction
- freshly compiled, not yet installed
- invocation counter within optimisation threshold
- existing type profile

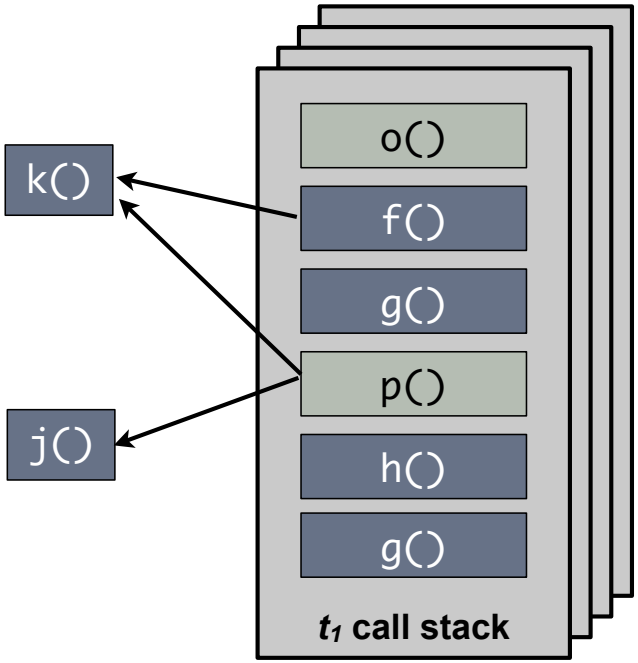


Code Cache Management: Eviction



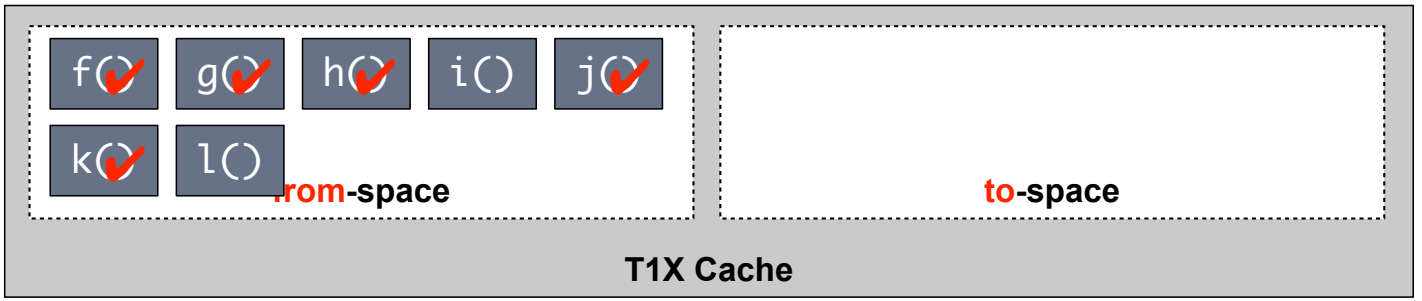
Code Cache Management: Eviction

baseline (T1X) method optimised (C1X) method ✔ live method



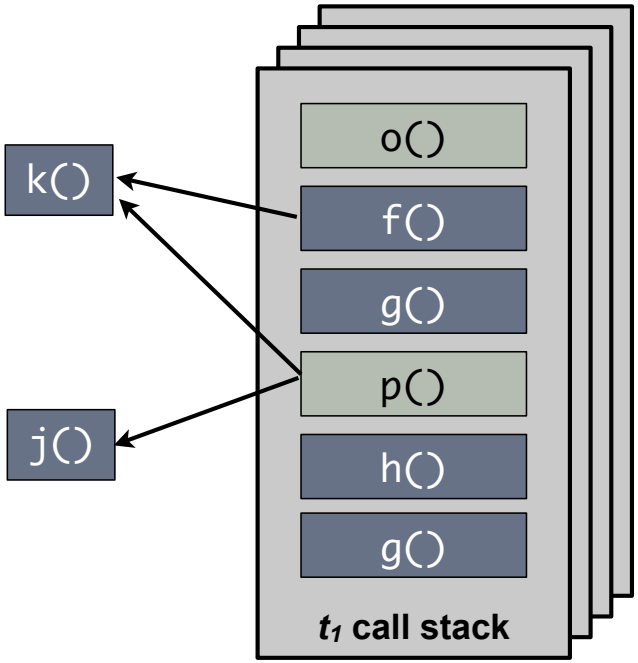
course of action

1. invalidate unmarked methods
   (and vtable entries, direct calls)



Code Cache Management: Eviction

baseline (T1X) method optimised (C1X) method ✔ live method



course of action

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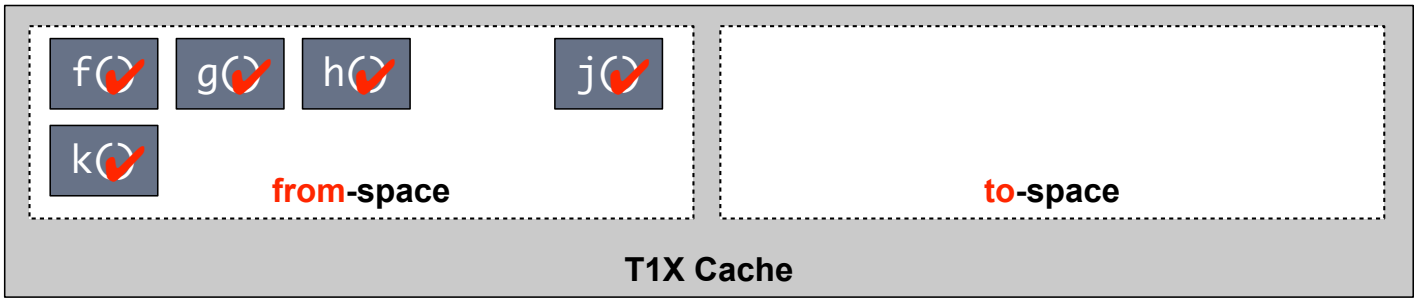
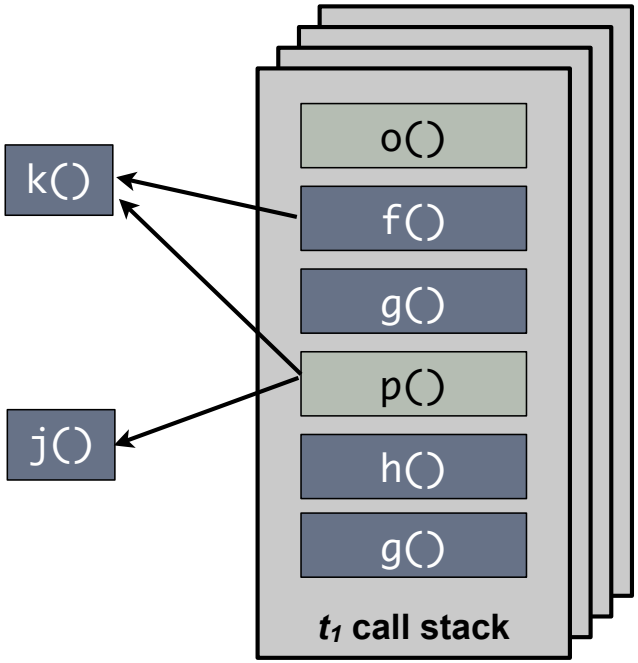


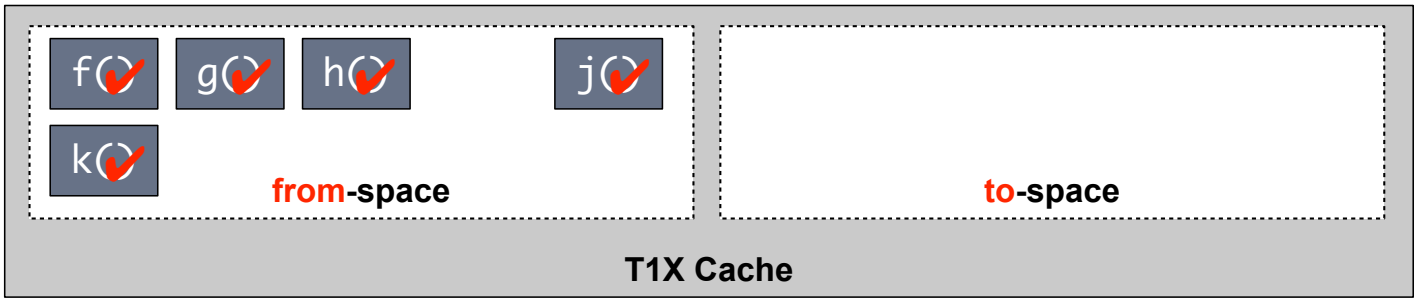
Code Cache Management: Eviction

baseline (T1X) method optimised (C1X) method ✔ live method



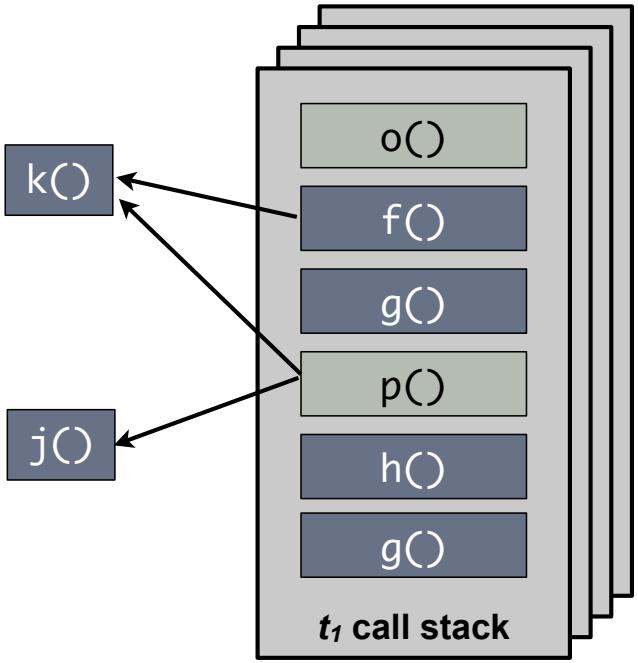
course of action

1. invalidate unmarked methods
   (and vtable entries, direct calls)
2. move marked methods
   (update vtable entries, direct calls)



Code Cache Management: Eviction

baseline (T1X) method optimised (C1X) method ✔ live method



course of action

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2. move marked methods
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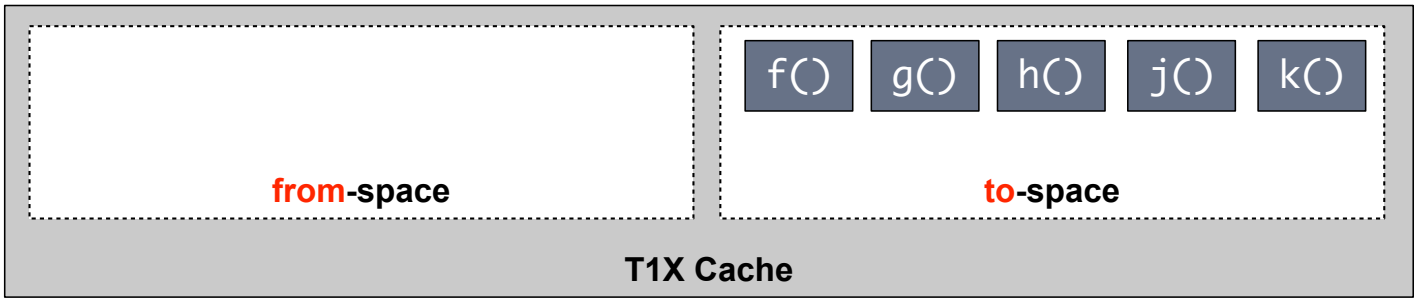

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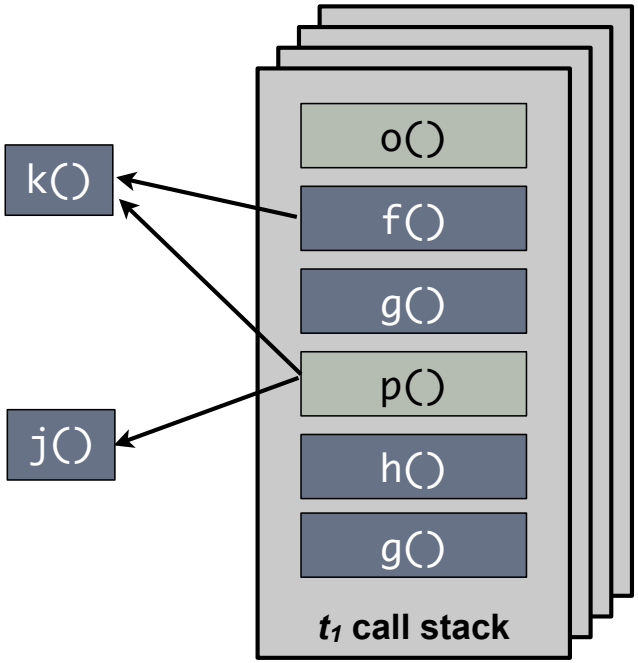

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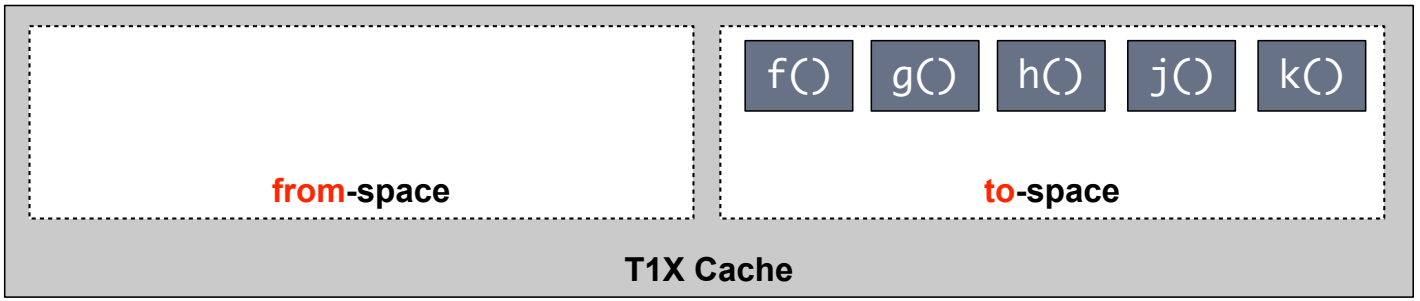

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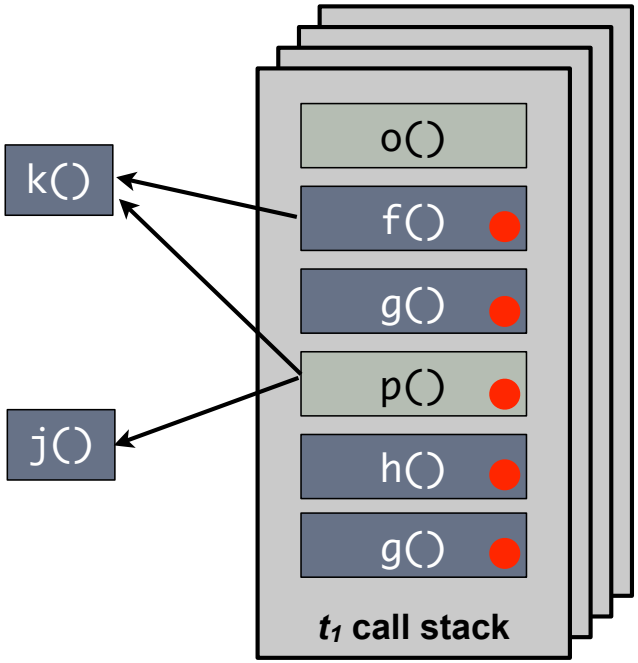

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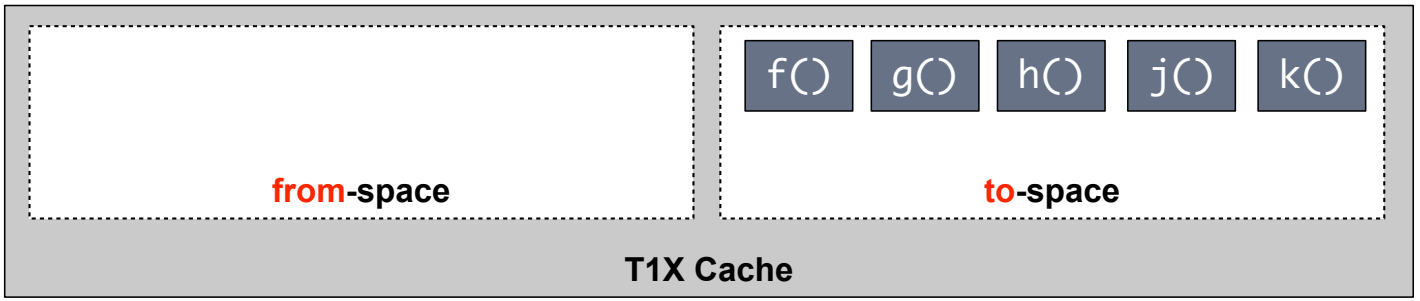

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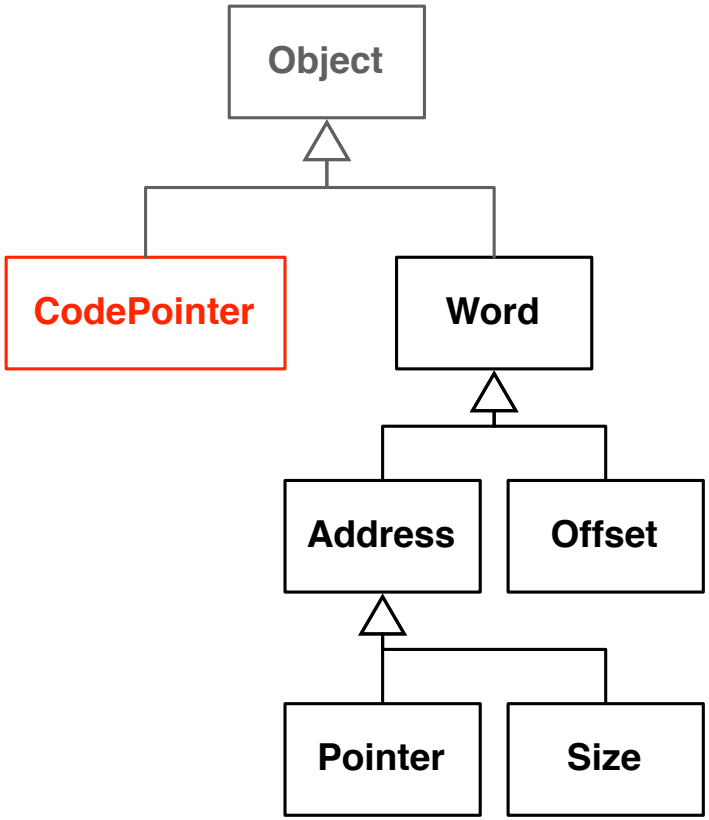
local variables	✗	These might have to be relocated—how to determine which `Address` is a code pointer?
member variables	✗	

Tagged Code Pointers



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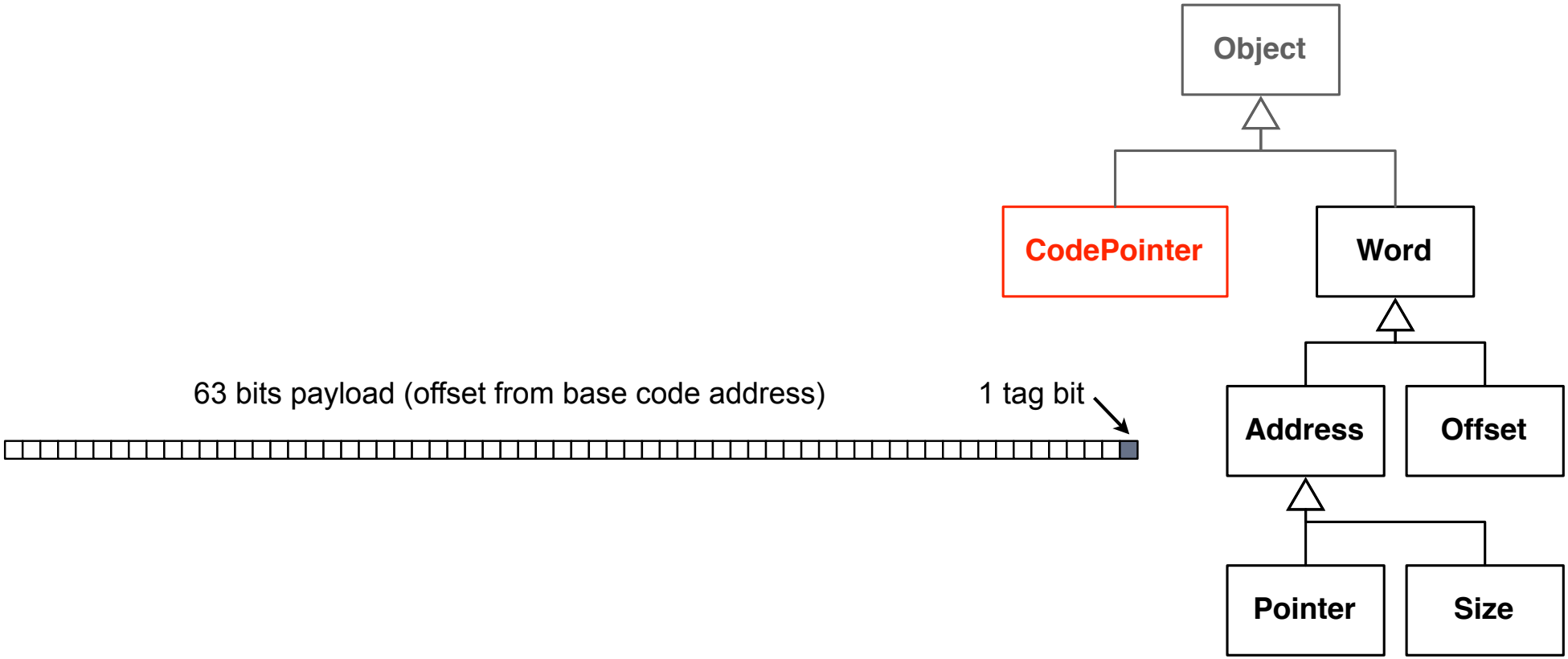

Tagged Code Pointers

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class CodePointer {
  ...
  @INLINE
  public static CodePointer from(long value) {
    if (isHosted()) {
      return new CodePointer(tag(value));
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    return UnsafeCast.asCodePointer(tag(value));
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  ...
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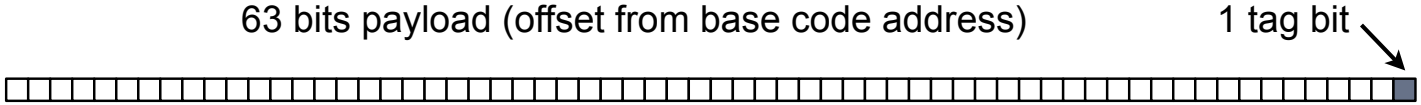

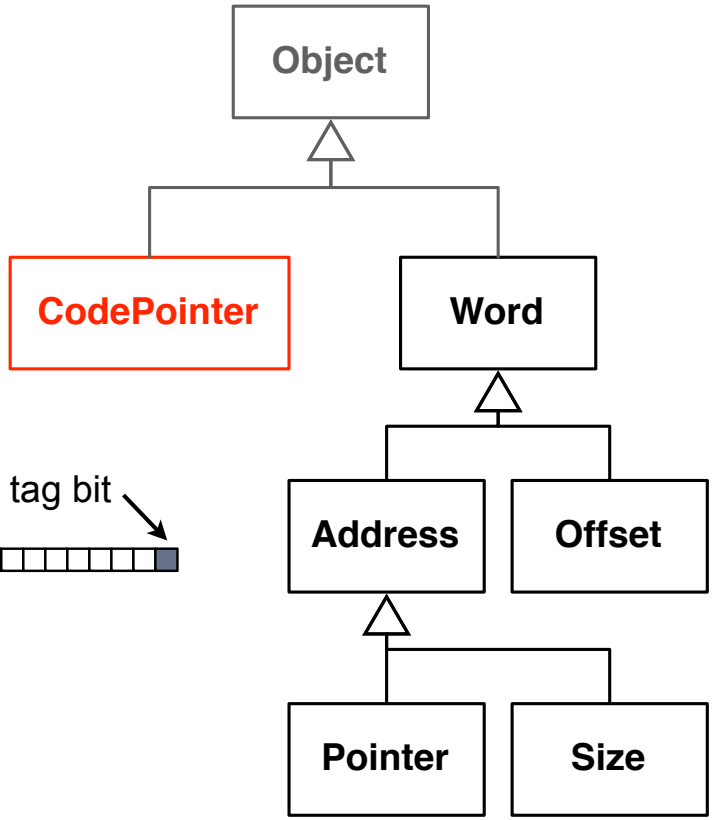

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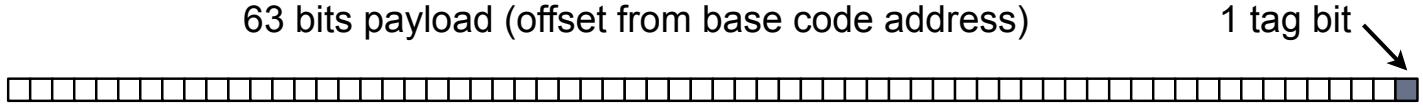

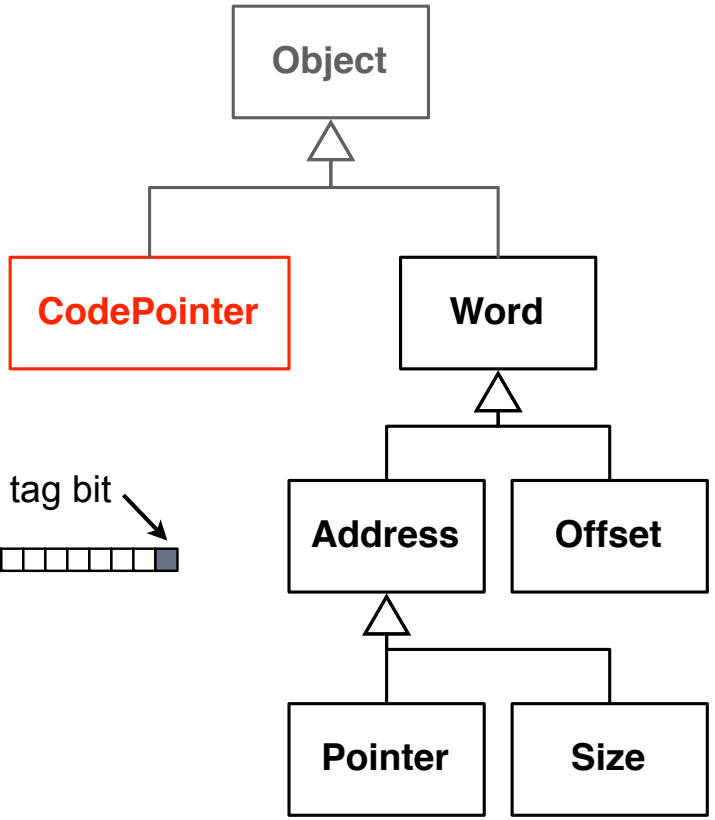


```
@INTRINSIC(UNSAFE_CAST)
public static CodePointer asCodePointer(long value) {
  return CodePointer.from(value);
}
```

Stack Reference Maps and Tagged Code Pointers

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static void m(int i, MyClass o) {
  int j = 2 * i;
  o.f(i);
}

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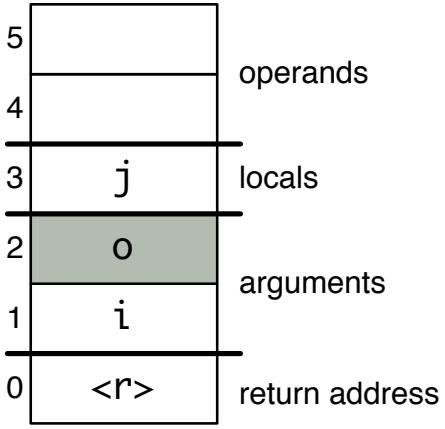
idealised stack frame layout



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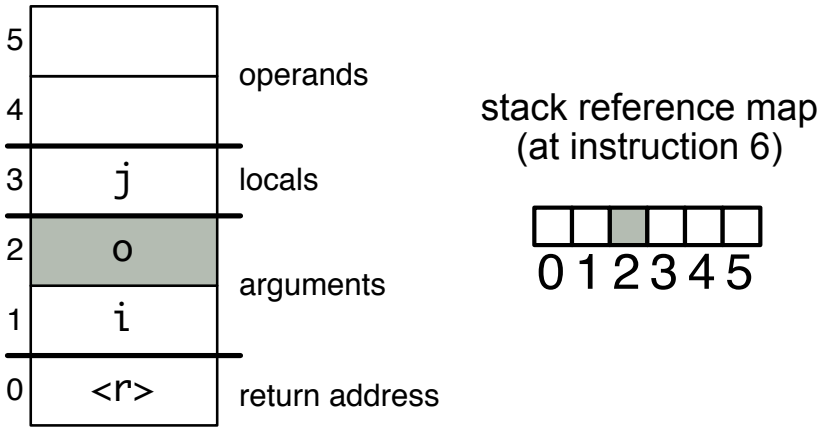

stack reference map
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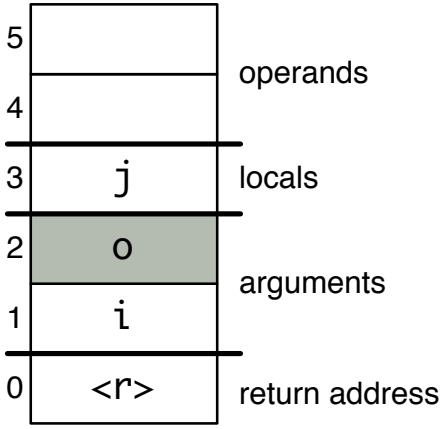

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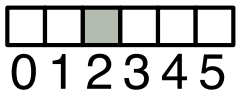


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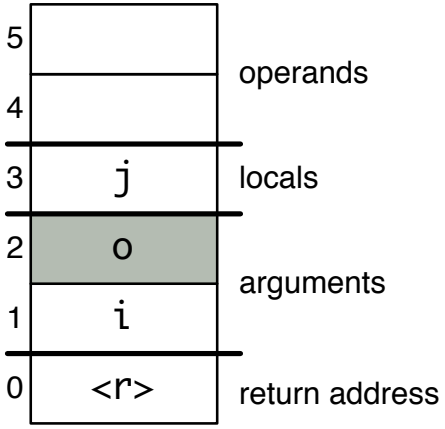

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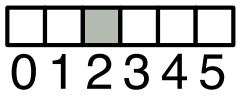


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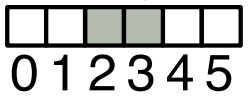

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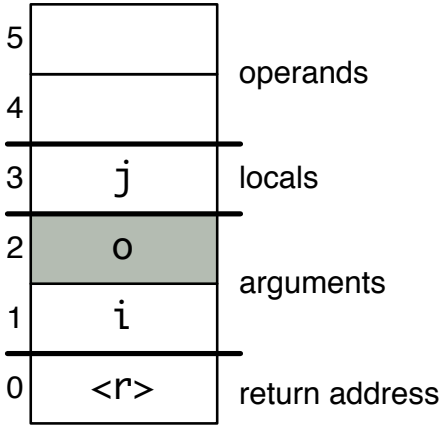

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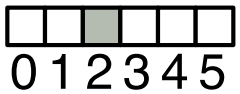


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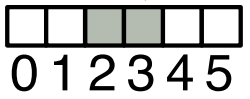

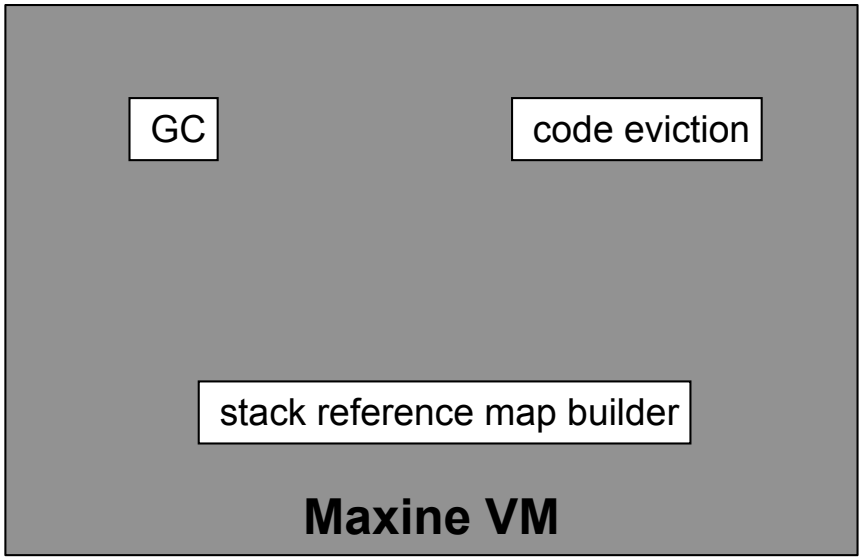

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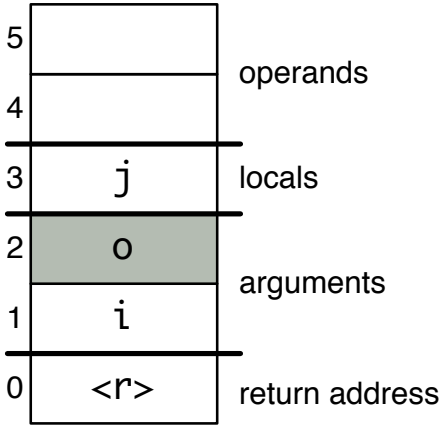

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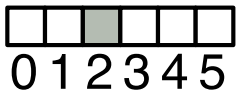


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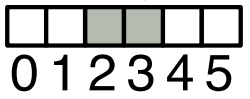

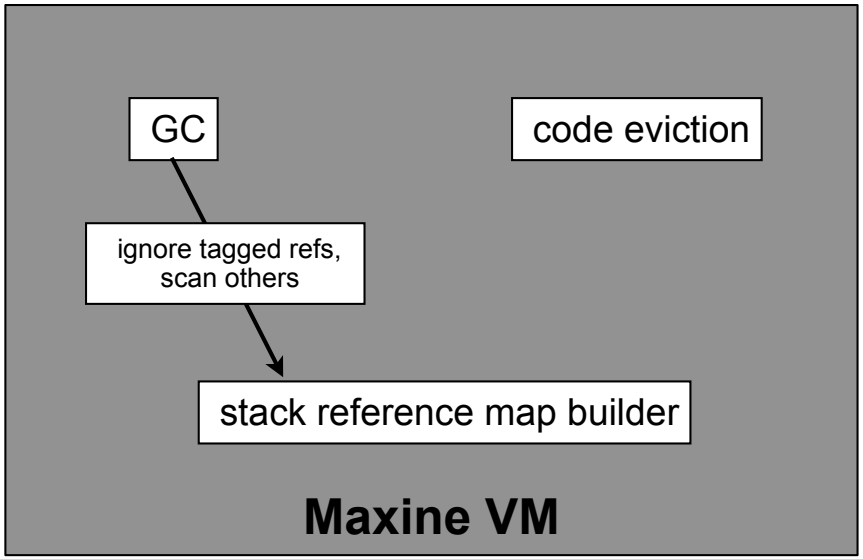

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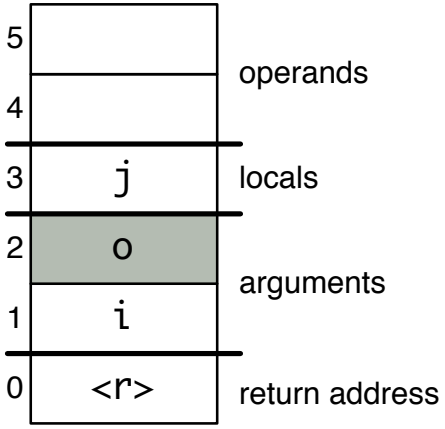

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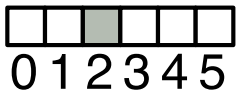


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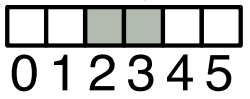

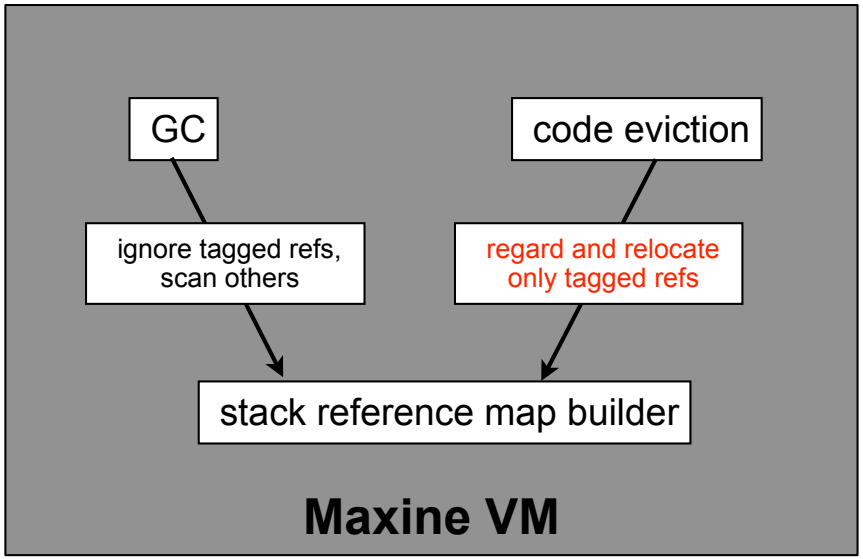

Thank you for your attention.

Acknowledgements: these slides are joint work of the VM research group.

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