The Java HotSpot VM
Under the Hood

Tobias Hartmann
Zoltán Majó

HotSpot Compiler Team
Oracle Corporation

About us

- **Tobias Hartmann**
  - MSc ETH Zurich, Switzerland
  - Lives in Rheinfelden, Germany
- **Zoltán Majó**
  - PhD ETH Zurich, Switzerland
  - Grew up in Cluj, Romania
- **Both of us: @Oracle since 2014**
  - Compiler team for the Java HotSpot Virtual Machine

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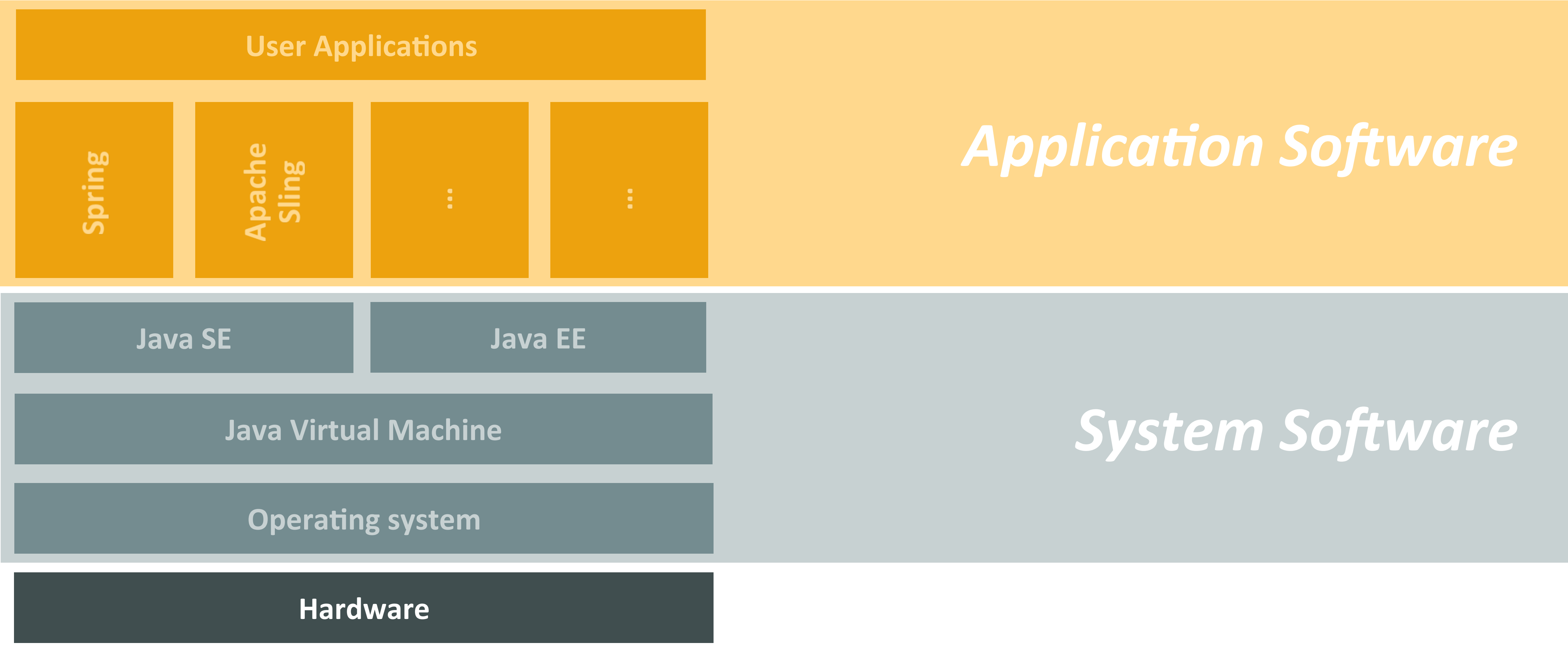
A typical computing platform



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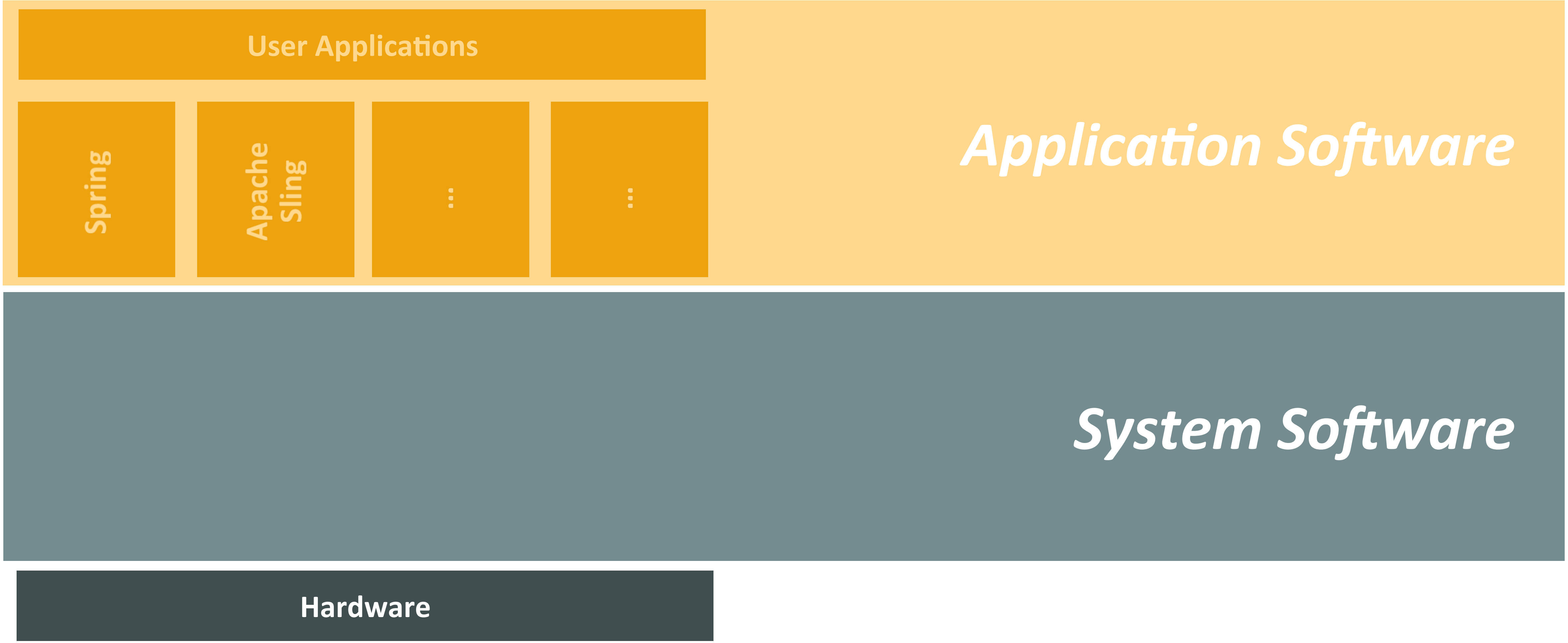

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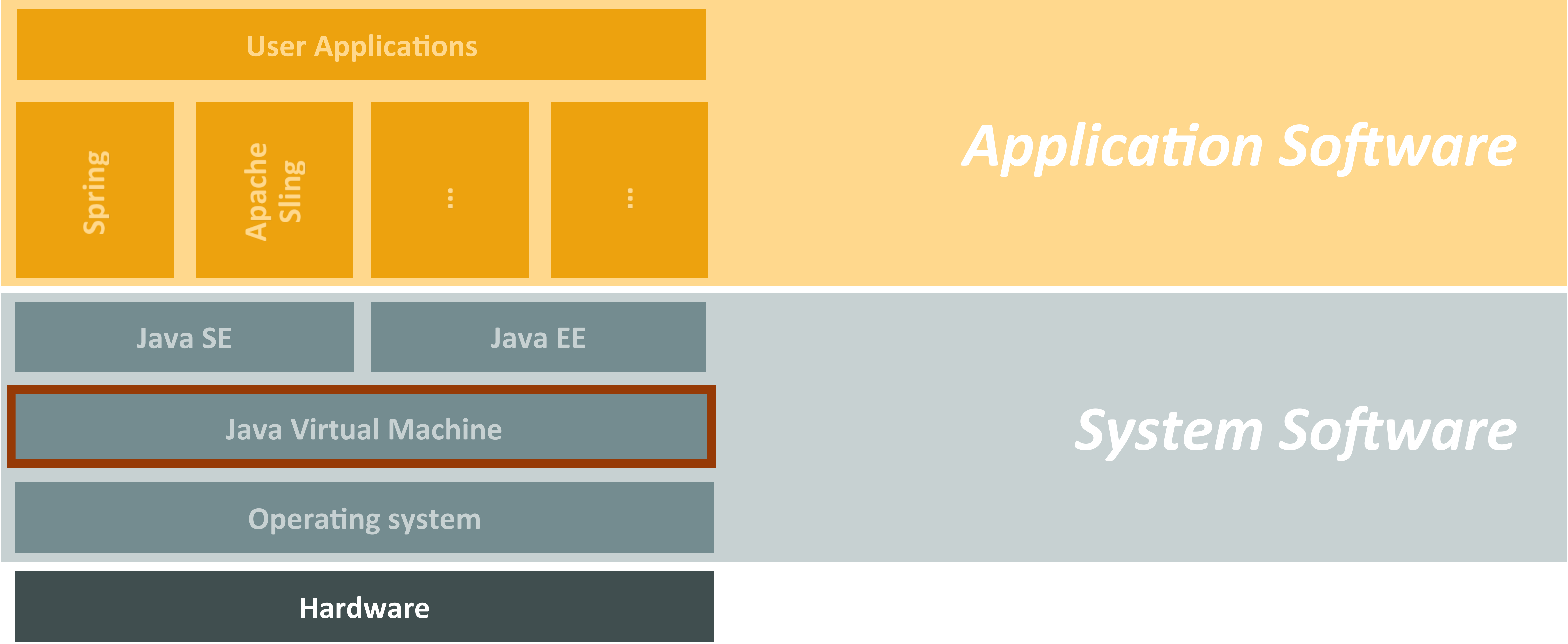
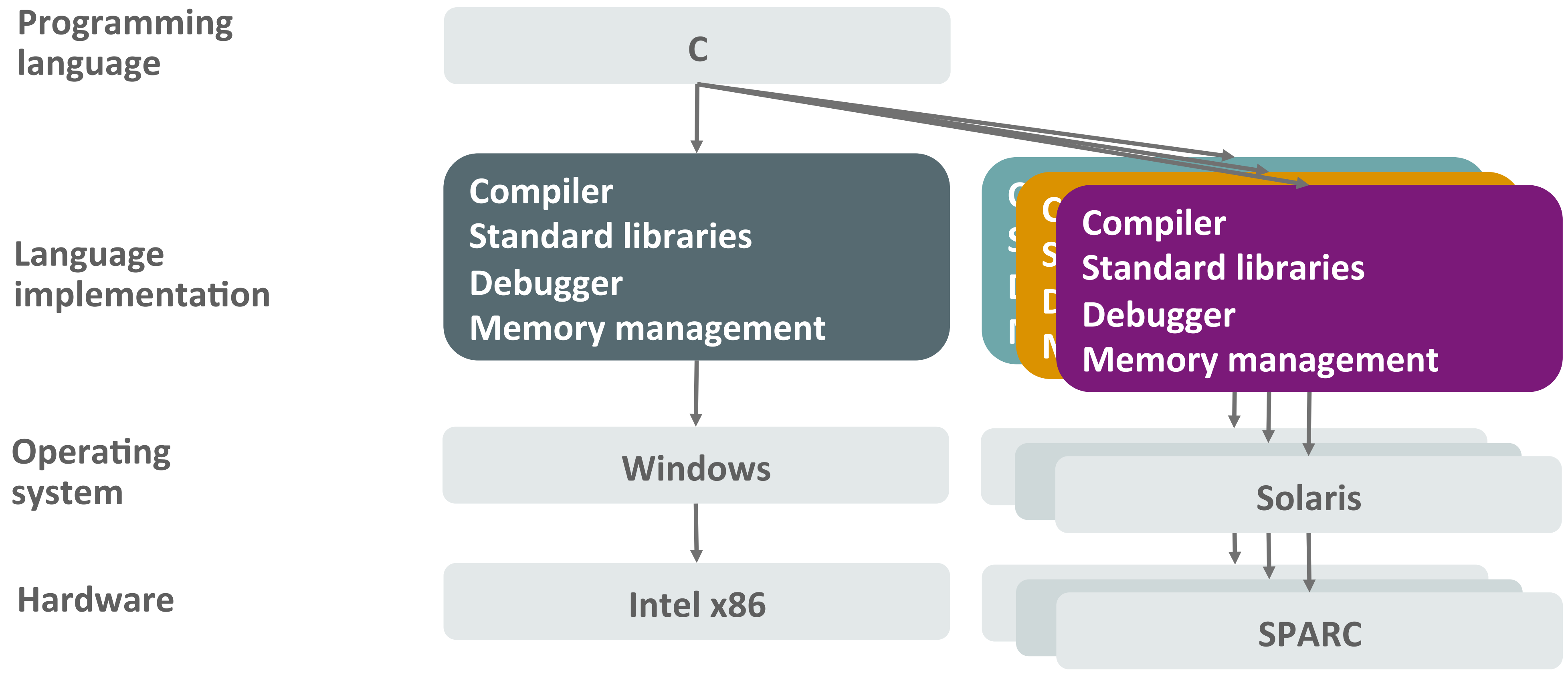


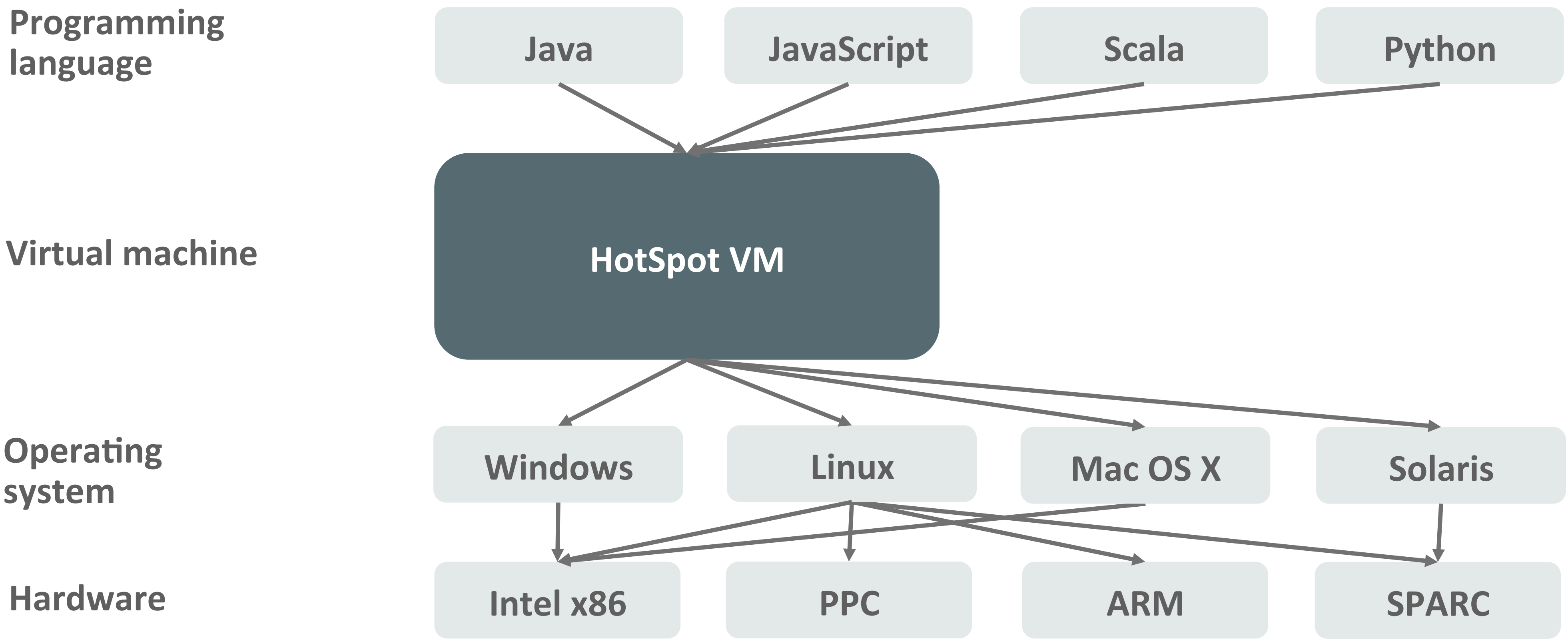
Outline

- **Why virtual machines?**
- **The Java HotSpot VM**
  - Just-in-time compilation
  - Optimistic compiler optimizations
  - Tiered compilation
  - Recent projects: Segmented Code Cache, Compact Strings
  - Future: AOT, JVMCI
- **Conclusions**

Programming language implementation



(Language) virtual machine



The VM: An application developer's view

Java source code

```
int i = 0;
do {
    i++;
} while (i < f());
```

compile

Bytecodes

```
 0: iconst_0
 1: istore_1
 2: iinc
 5: iload_1
 6: invokestatic f
 9: if_icmplt 2
12: return
```

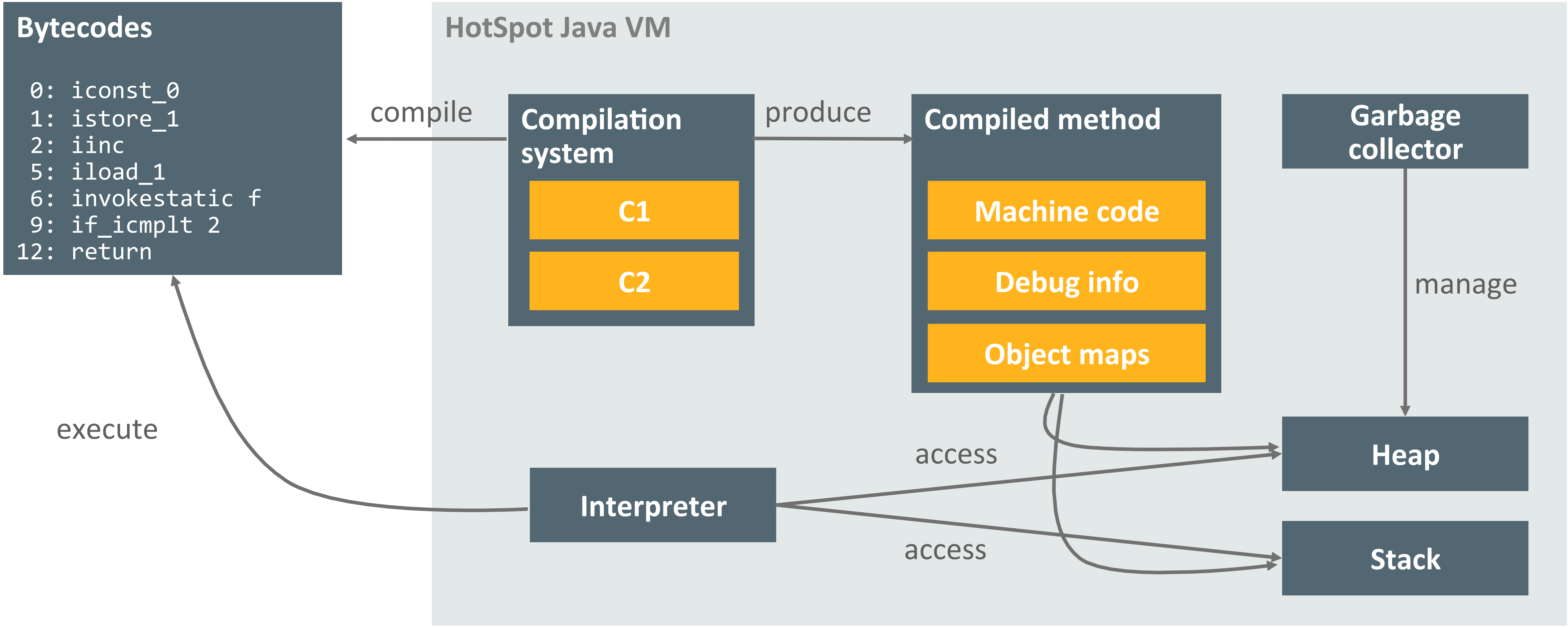
execute

HotSpot Java VM

- Ahead-of-time
- Using `javac`

- Instructions for an abstract machine
- Stack-based machine (no registers)

The VM: A VM engineer's view



Major components of HotSpot

- **Runtime**
  - Interpreter
  - Thread management
  - Synchronization
  - Class loading
- **Heap management**
  - Garbage collectors
- **Compilation system**

Interpretation vs. compilation in HotSpot

- **Template-based interpreter**
  - Generated at VM startup (before program execution)
  - Maps a well-defined machine code sequence to every bytecode instruction

Bytecodes

```
 0: iconst_0
 1: istore_1
 2: iinc
 5: iload_1
 6: invokestatic f
 9: if_icmplt 2
12: return
```

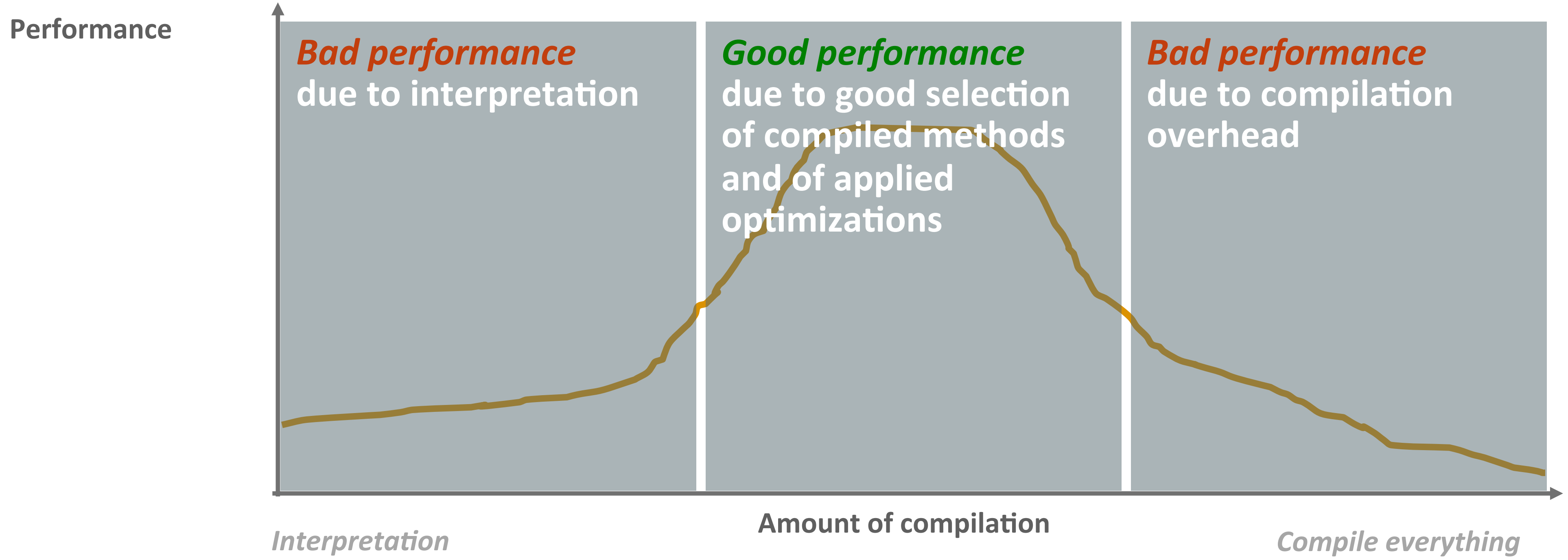
Machine code

```
mov      -0x8(%r14), %eax      ← Load local variable 1
movzbl    0x1(%r13), %ebx   ┐
inc       %r13              │
mov       $0xff40,%r10      │  Dispatch next instruction
jmpq      *(%r10,%rbx,8)    ┘
```

  - Optimization: cache top-of-stack value in a register to reduce # of memory accesses
- **Compilation system**
  - Speedup relative to interpretation: ~100X
  - Two ***just-in-time compilers*** (C1, C2)
  - Aggressive optimistic optimizations

Ahead-of-time vs. just-in-time compilation

- AOT: *Before* program execution
- JIT: *During* program execution
- Tradeoff: *Resource usage vs. performance of generated code*

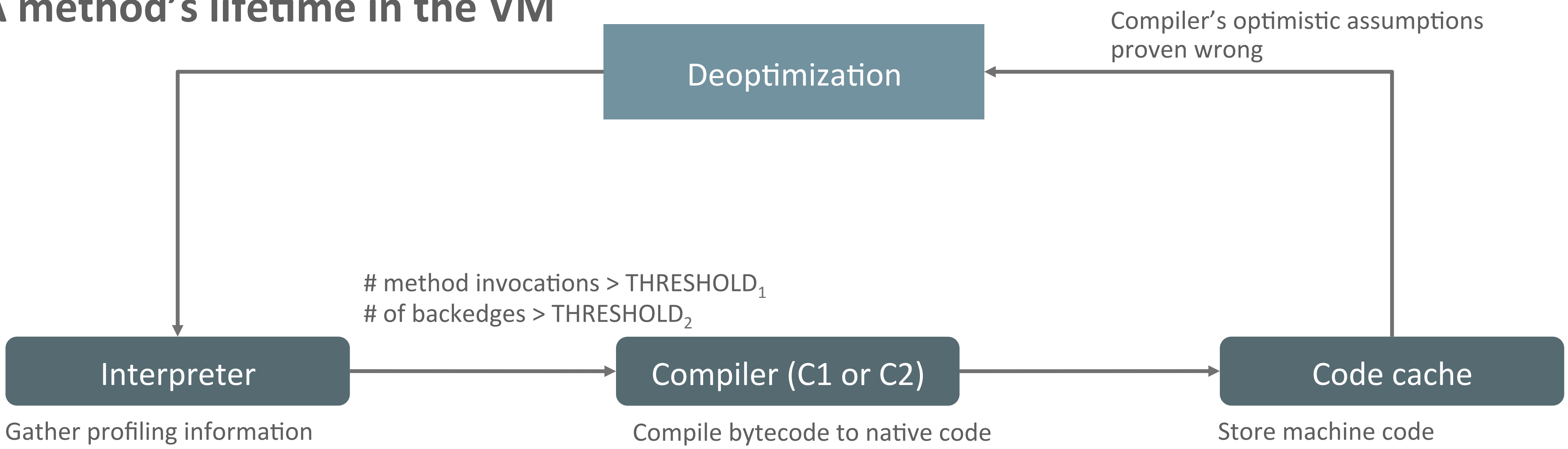


Balancing resource usage and performance

- **Getting to the “sweet spot”**
- **Carefully selecting**
  1. Methods to compile
  2. Applied compiler optimizations

1. Selecting method to compile

- ***Hot*** **methods (frequently executed methods)**
- **Profile method execution**
  - # of method invocations, # of backedges
- **A method's lifetime in the VM**



Virtual call inlining

Class hierarchy

```
class A {
  void bar() {
    S1;
  }
}
```

loaded

```
class B extends A {
  void bar() {
    S2;
  }
}
```

not loaded

Method to be compiled

```
void foo() {
  A a = create(); // return A or B
  a.bar();
}
```

Compiler: Inline call?

Yes.

Virtual call inlining

Class hierarchy

```
class A {
  void bar() {
    S1;
  }
}
```

loaded

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class B extends A {
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  }
}
```

not loaded

Method to be compiled

```
void foo() {
  A a = create(); // return A or B
  S1;
}
```

Compiler: Inline call?

Yes.

- **Benefits of inlining**
  - Virtual call avoided
  - Code locality
- **Optimistic assumption: only A is loaded**
  - Note dependence on class hierarchy
  - Deoptimize if hierarchy changes

Virtual call inlining

Class hierarchy

```
class A {
  void bar() {
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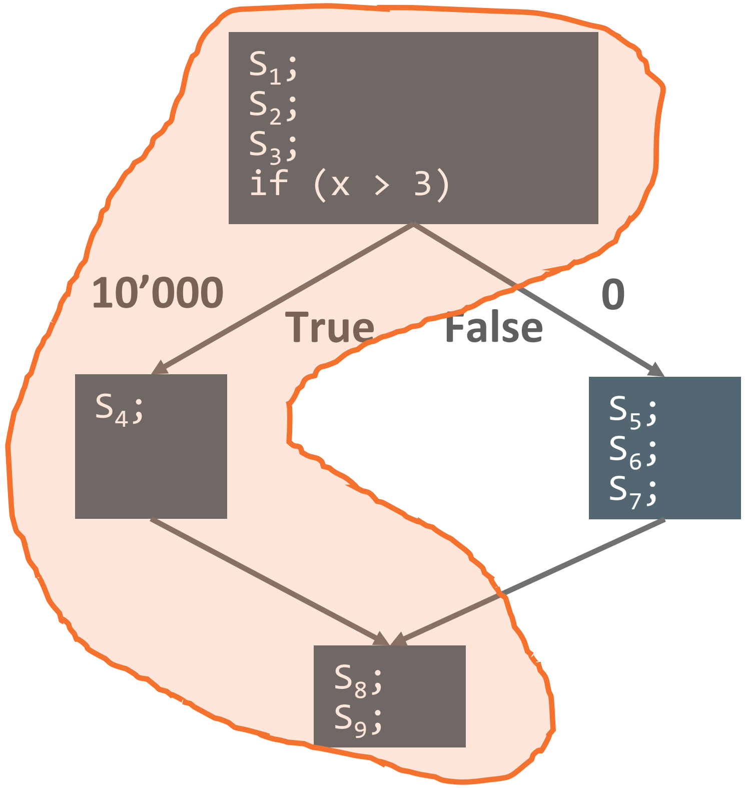
```

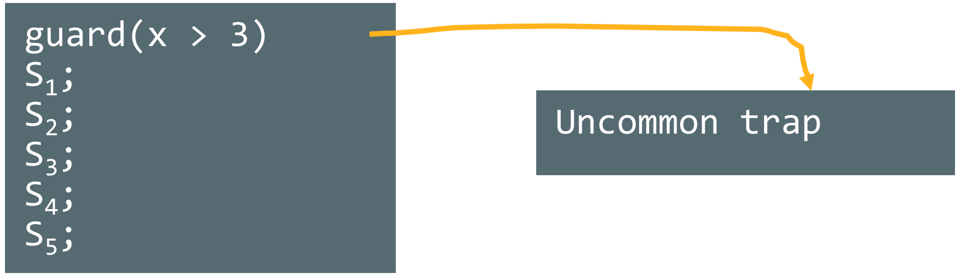
Compiler:
Inline call?
No.

Hot path compilation

Control flow graph



Generated code

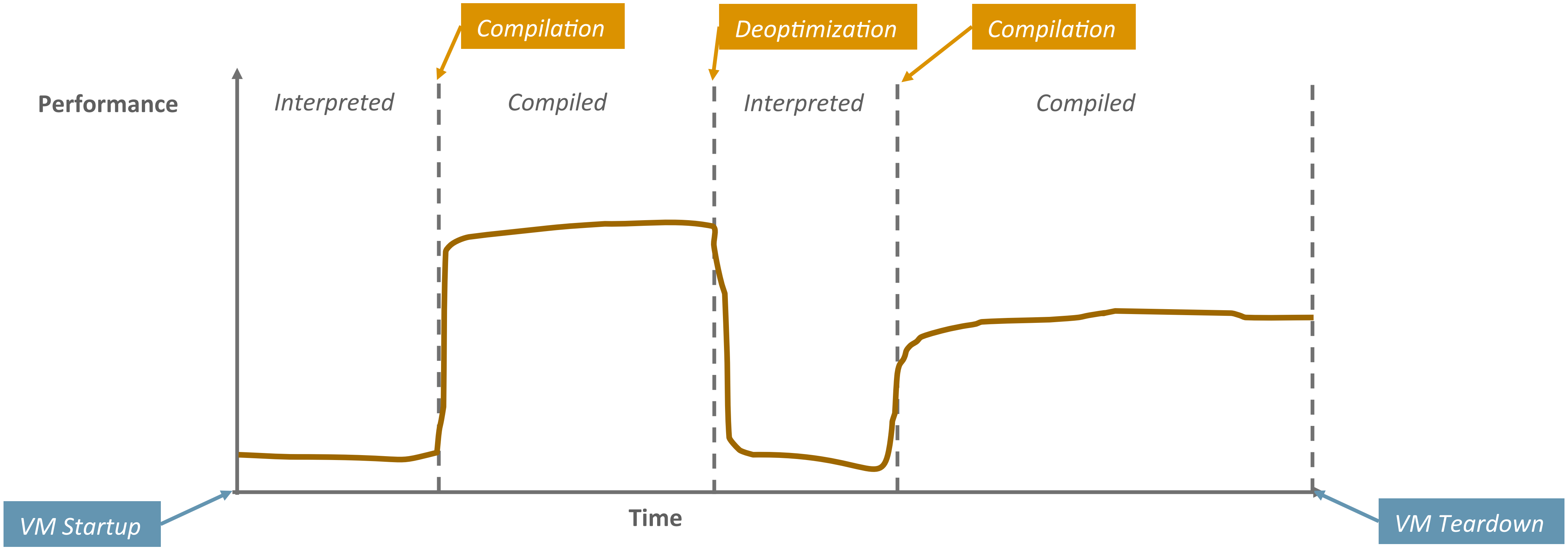


Deoptimization

- **Compiler's optimistic assumption proven wrong**
  - Assumptions about class hierarchy
  - Profile information does not match method behavior
- **Switch execution from compiled code to interpretation**
  - Reconstruct state of interpreter at runtime
  - Complex implementation
- **Compiled code**
  - Possibly thrown away
  - Possibly reprofiled and recompiled

Performance effect of deoptimization

- **Follow the variation of a single method's performance**



2. Selecting compiler optimizations

- **C1 compiler**
  - Limited set of optimizations
  - Fast compilation
  - Small footprint
- **C2 compiler**
  - Aggressive optimistic optimizations
  - High resource demands
  - High-performance code
- **Graal**
  - Experimental compiler
  - Not part of HotSpot

Client VM

Server VM

Tiered compilation (enabled since JDK 8)

Balancing resource usage and performance

1. **Selecting methods to compile**
   - "Hot" methods
   - Controlled by invocation and backedge threshold
2. **Choosing compiler optimizations**
   - C1: ***moderately optimizing*** and ***fast*** compiler
   - C2: ***highly optimizing*** and ***slow*** compiler
   - Limitation (before JDK 8): ***Single compiler*** in the VM (client or server)
   - Starting with JDK 8: ***Both compilers enabled*** at the same time (tiered compilation)

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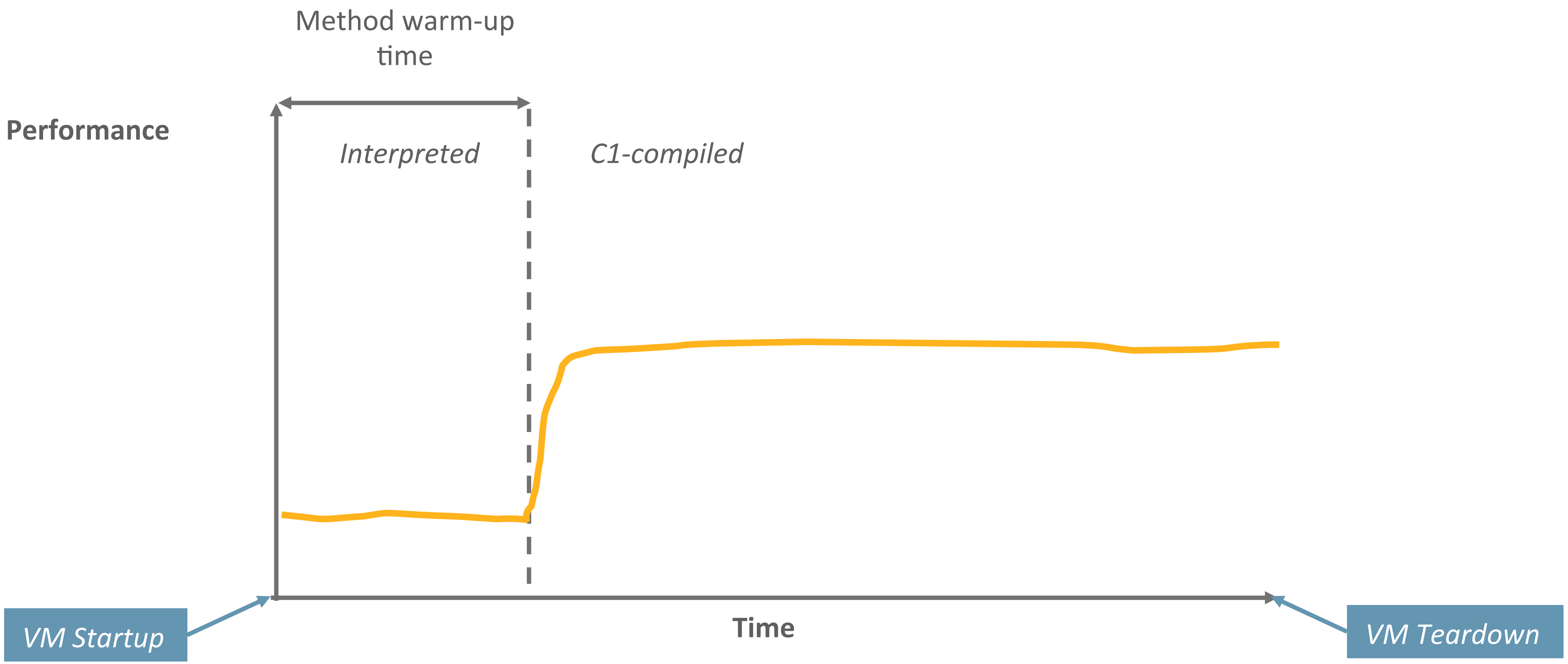
Tiered compilation

- **Combine the benefits of**
  - Interpreter: Fast startup
  - C1: Fast warmup
  - C2: High peak performance
  - Still within the sweet spot of resource usage/performance tradeoff

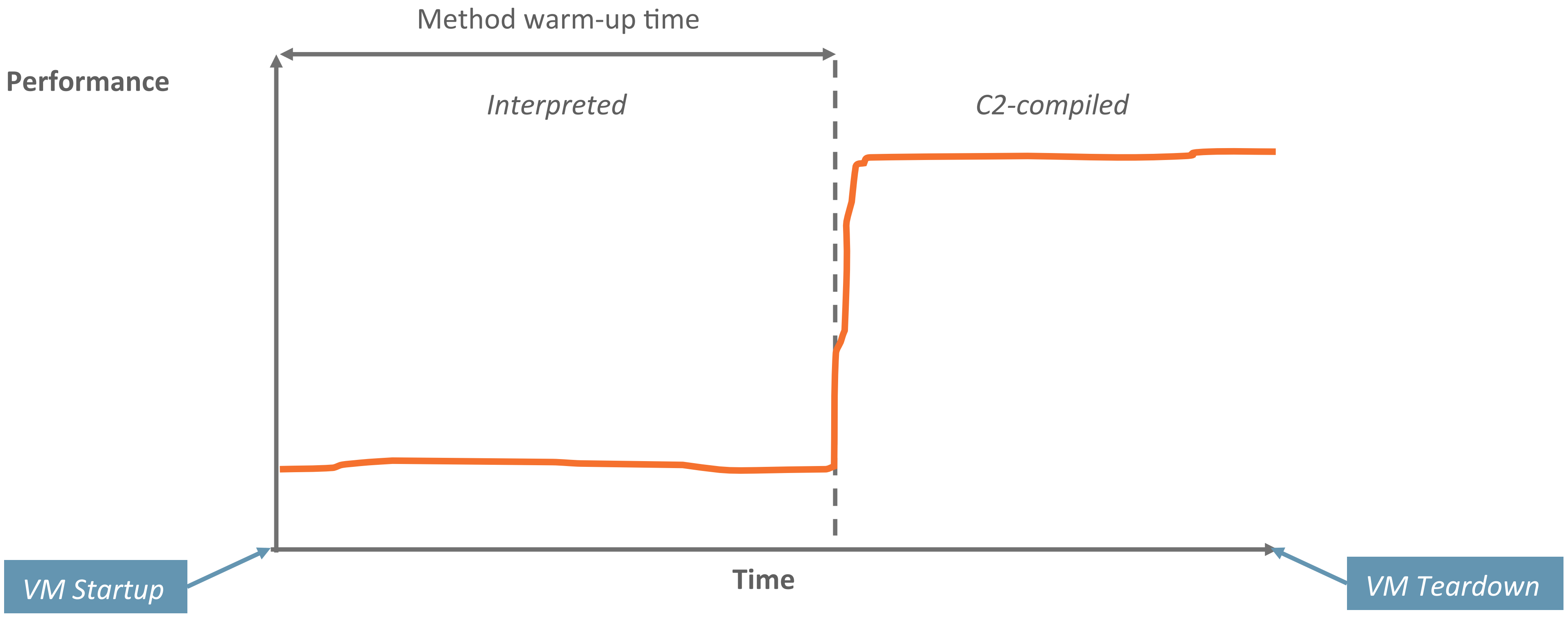
Benefits of tiered compilation (artist's concept)

Client VM (C1 only)



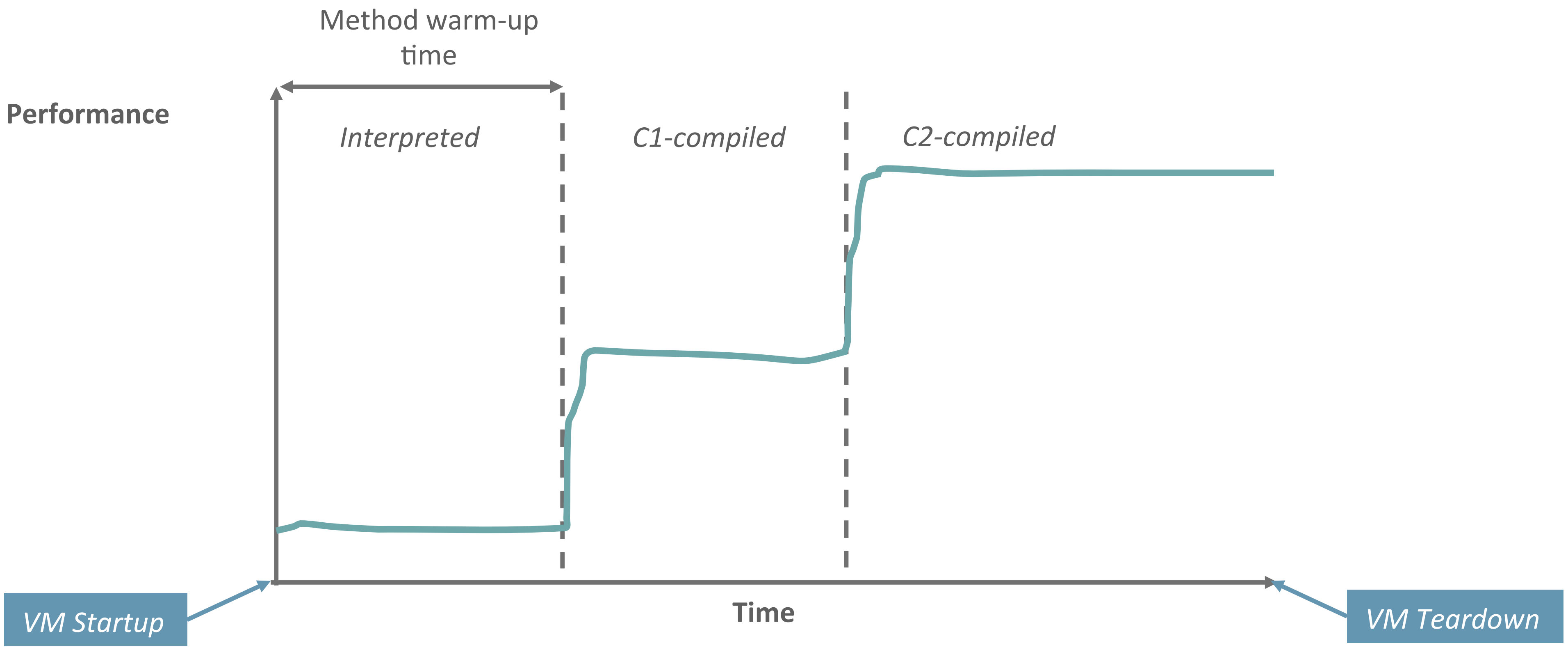
Benefits of tiered compilation (artist's concept)

Server VM (C2 only)



Benefits of tiered compilation (artist's concept)

Tiered compilation

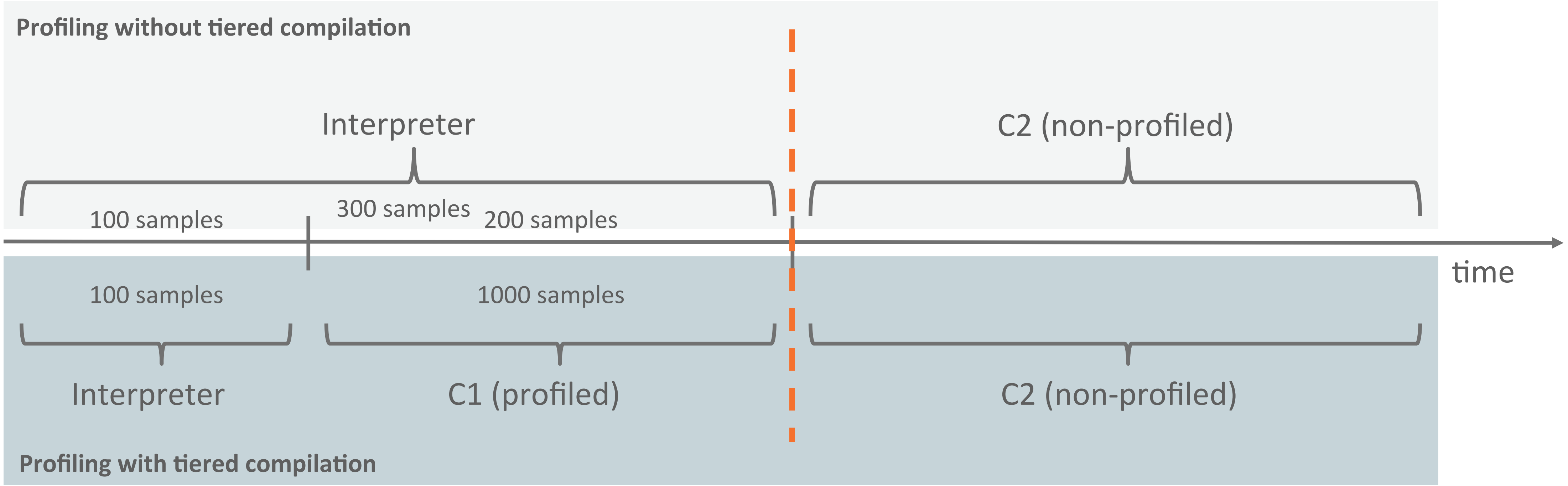


Tiered compilation

- **Combined benefits of interpreter, C1, and C2**
- **Additional benefits**
  - More accurate profiling information

More accurate profiling

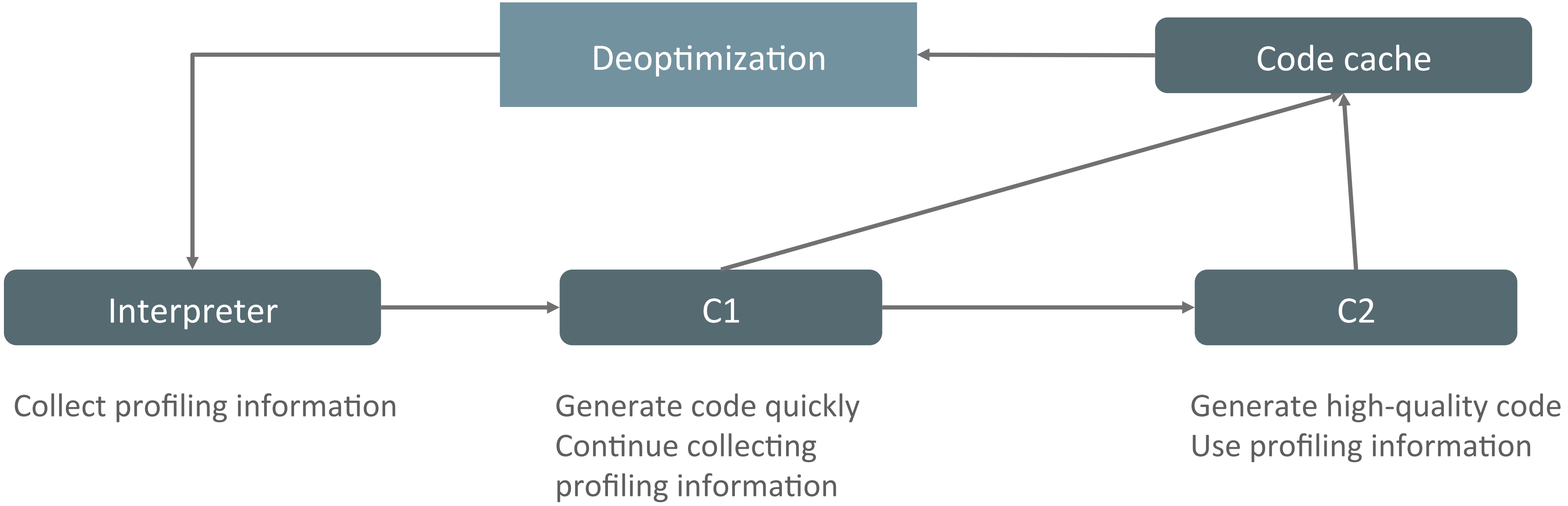
w/ tiered compilation: 1’100 samples gathered
w/o tiered compilation: 300 samples gathered



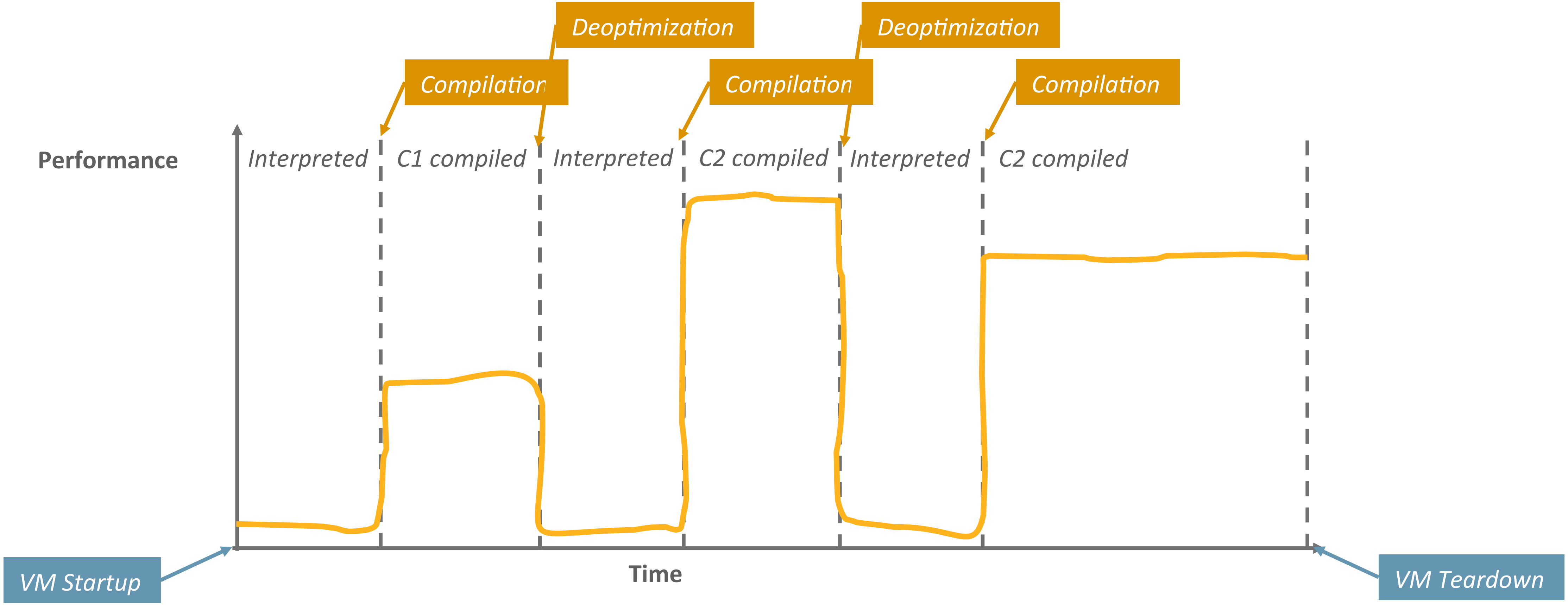
Tiered compilation

- **Combined benefits of interpreter, C1, and C2**
- **Additional benefits**
  - More accurate profiling information
- **Drawbacks**
  - Complex implementation
  - Careful tuning of compilation thresholds needed
  - More pressure on code cache – Tobias will tell you more about that

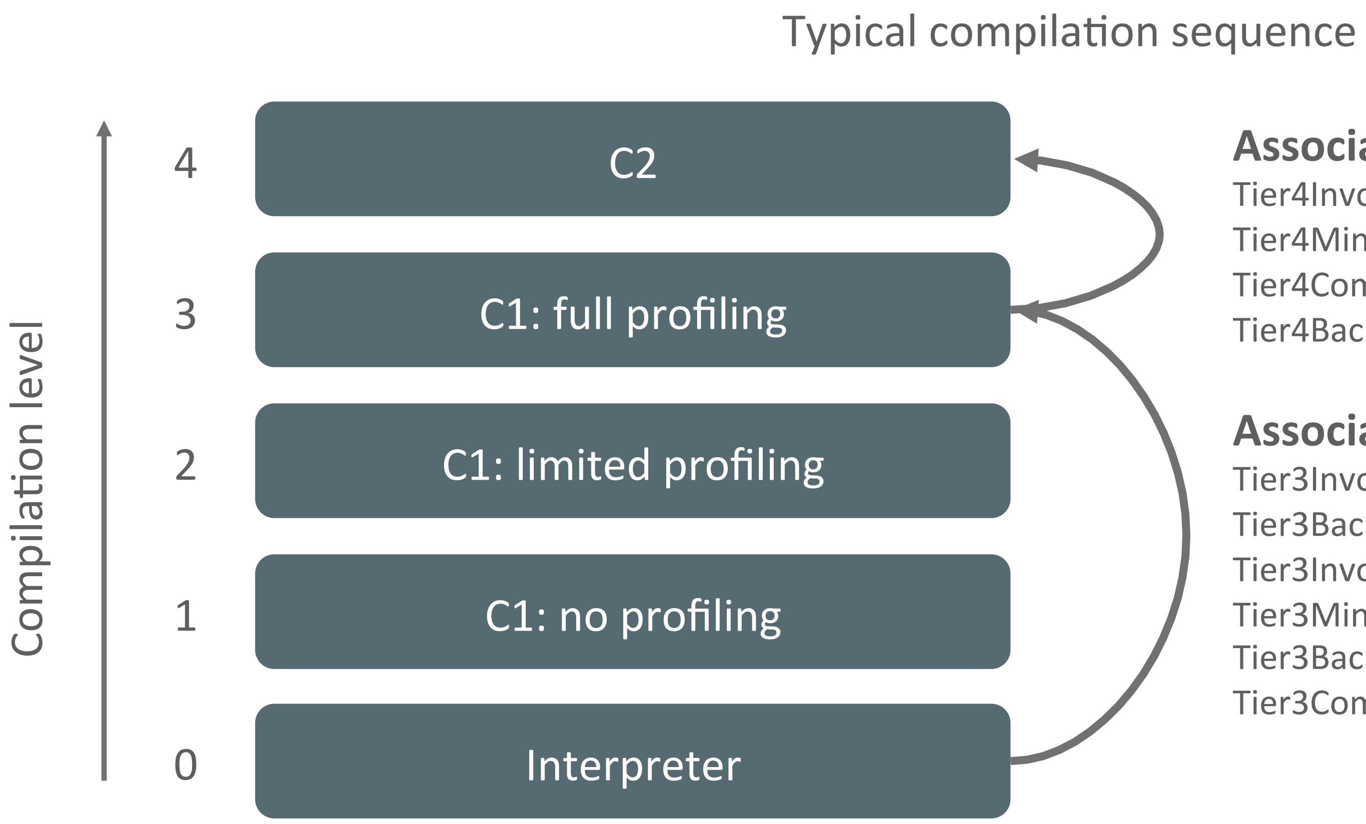
A method’s lifetime (w/ tiered compilation)



Performance of a single method (w/ tiered compilation)



Compilation levels (detailed view)



Associated thresholds:

Tier4InvocationThreshold
Tier4MinInvocationThreshold
Tier4CompileThreshold
Tier4BackEdgeThreshold

Associated thresholds:

Tier3InvokeNotifyFreqLog
Tier3BackedgeNotifyFreqLog
Tier3InvocationThreshold
Tier3MinInvocationThreshold
Tier3BackEdgeThreshold
Tier3CompileThreshold

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Part 1: Segmented Code Cache

Improving the layout of JIT generated code

Program Agenda

1. Background
2. Challenges
3. Design
4. Evaluation
5. Conclusion

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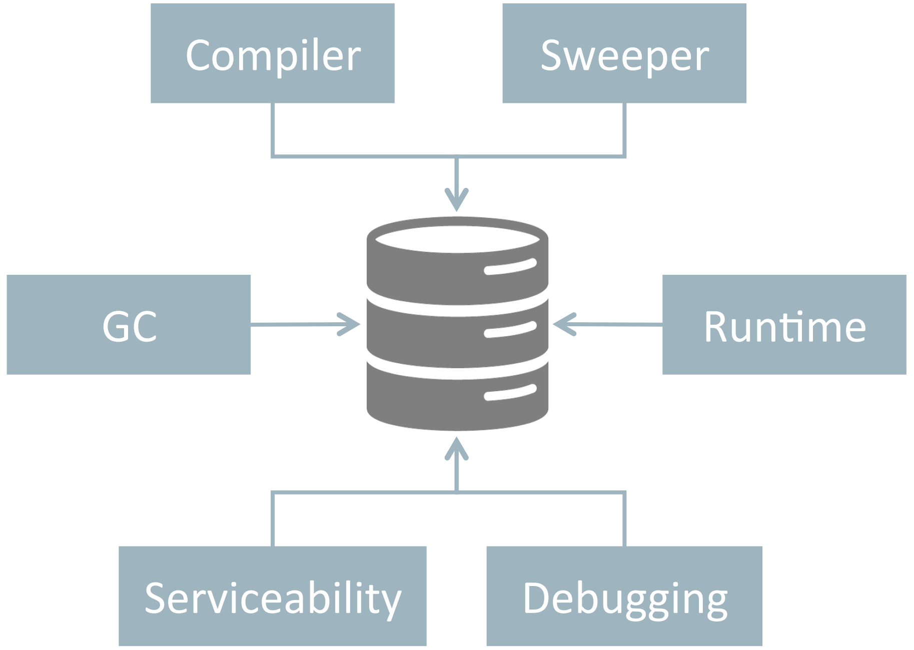
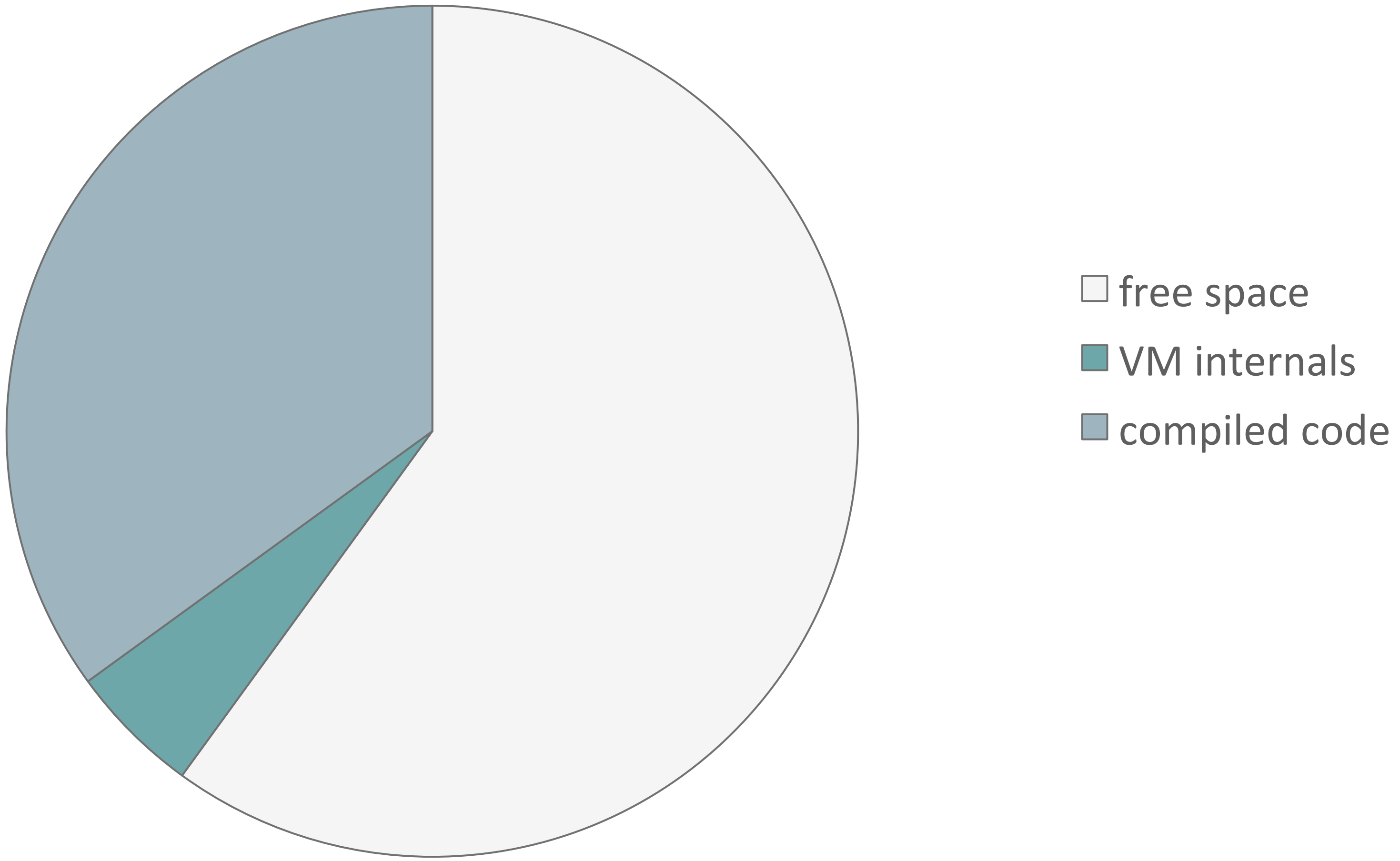
What is a code cache?

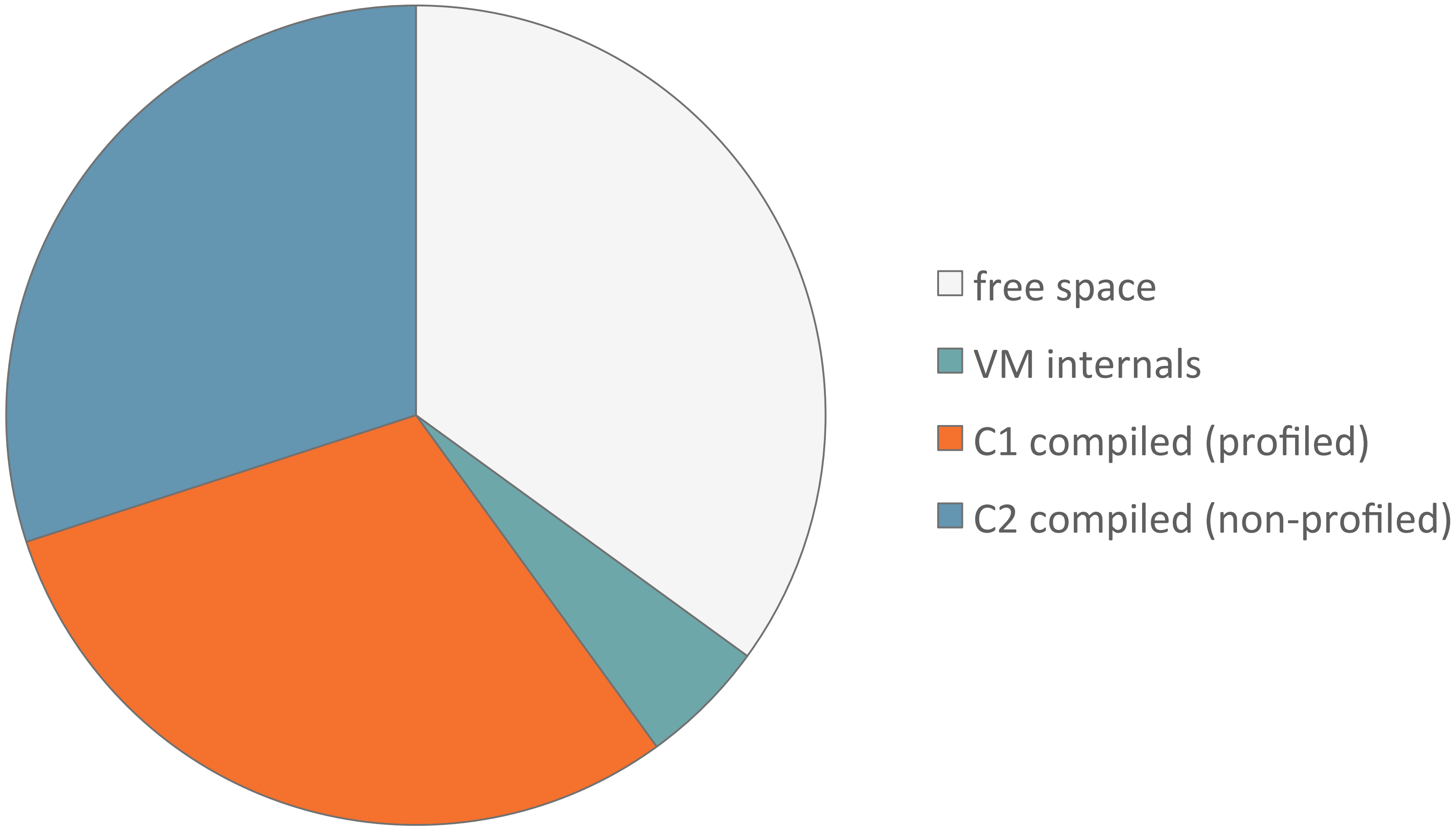
- **Stores code** generated by JIT compilers
- Continuous chunk of memory
  - **Fixed size** -XX:ReservedCodeCacheSize
  - Bump pointer allocation with free list
- Memory **managed by sweeper**
  - Cold methods are evicted
  - Hot methods remain
- Why should I care?
  - Essential for **performance**



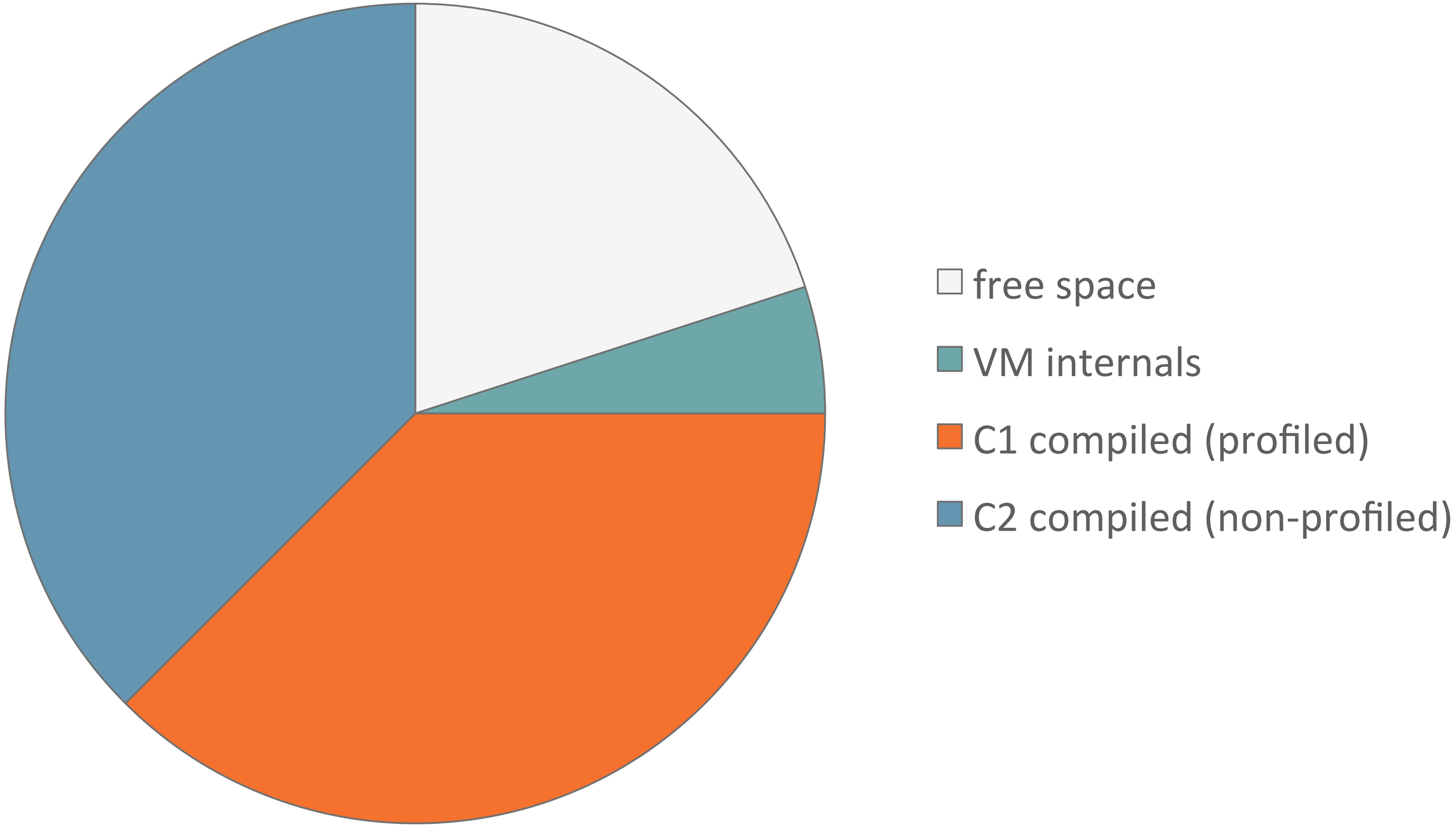
Code cache usage: JDK 6 and 7



Code cache usage: JDK 8 (Tiered Compilation)



Code cache usage: JDK 9



Program Agenda

1 Background

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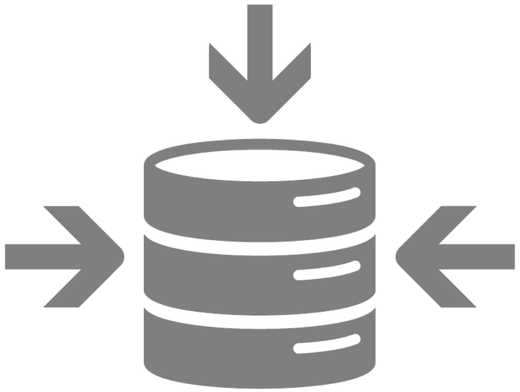
Challenges

- **Tiered compilation increases amount of code by 2-4X**
- **All code is stored in a single code cache**
  - Different types with different characteristics
  - Different usage frequencies (hotness)
  - Access to specific code requires full iteration
- **High fragmentation and bad locality**



Properties of compiled code

Optimization level

Size

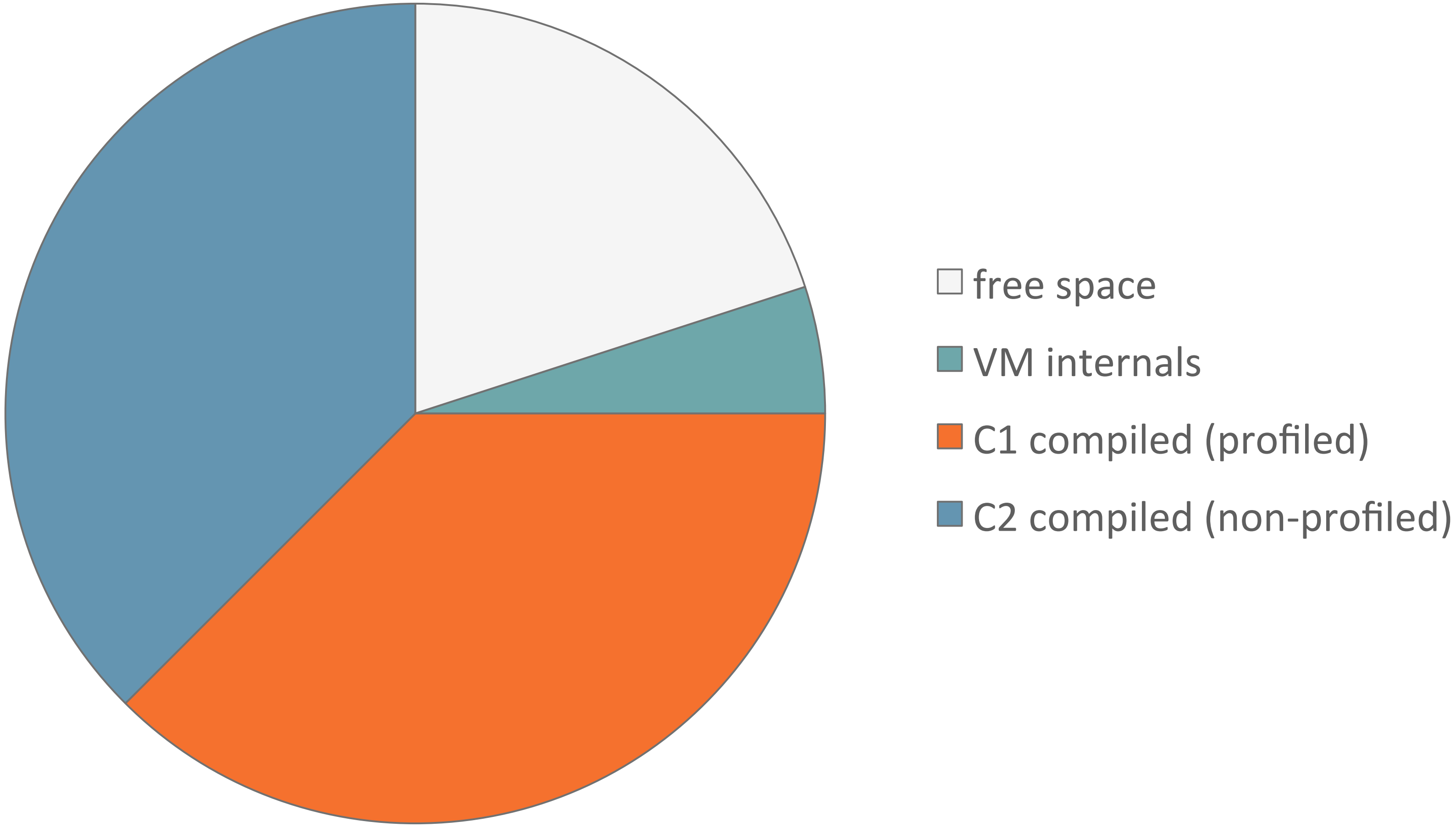
Cost of compilation

Lifetime

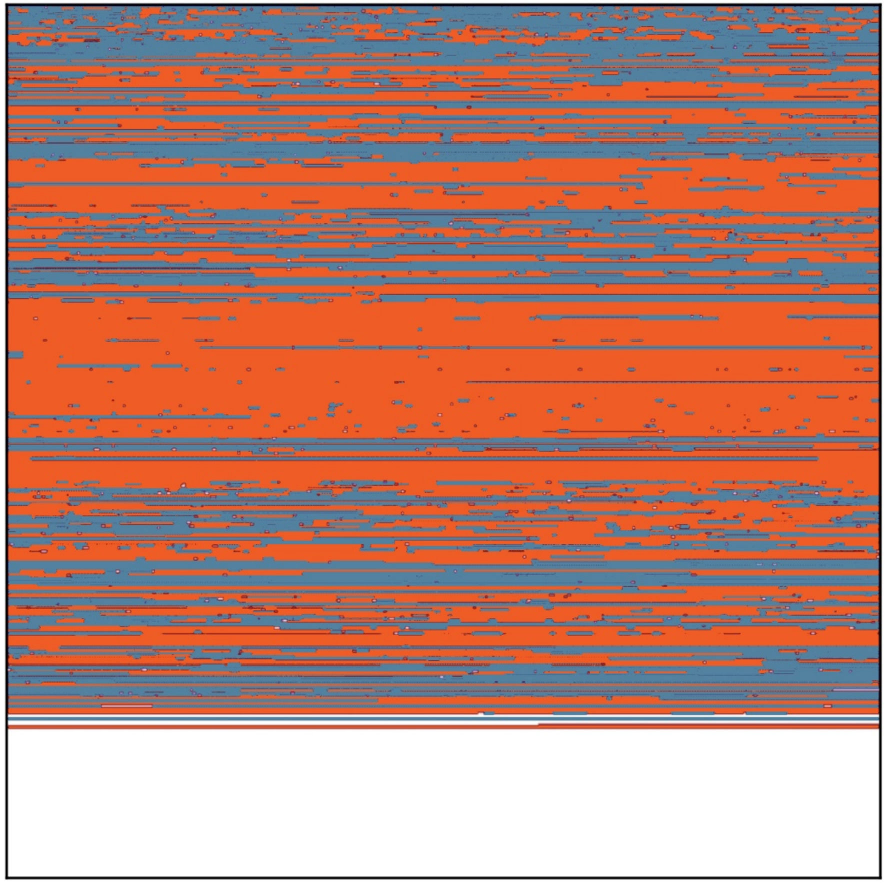
Types of compiled code

Non-method code	optimized	small	cheap	immortal
Profiled code (C1)	instrumented	medium	cheap	limited
Non-profiled code (C2)	highly optimized	large	expensive	long

Code cache usage



Code cache usage: Reality



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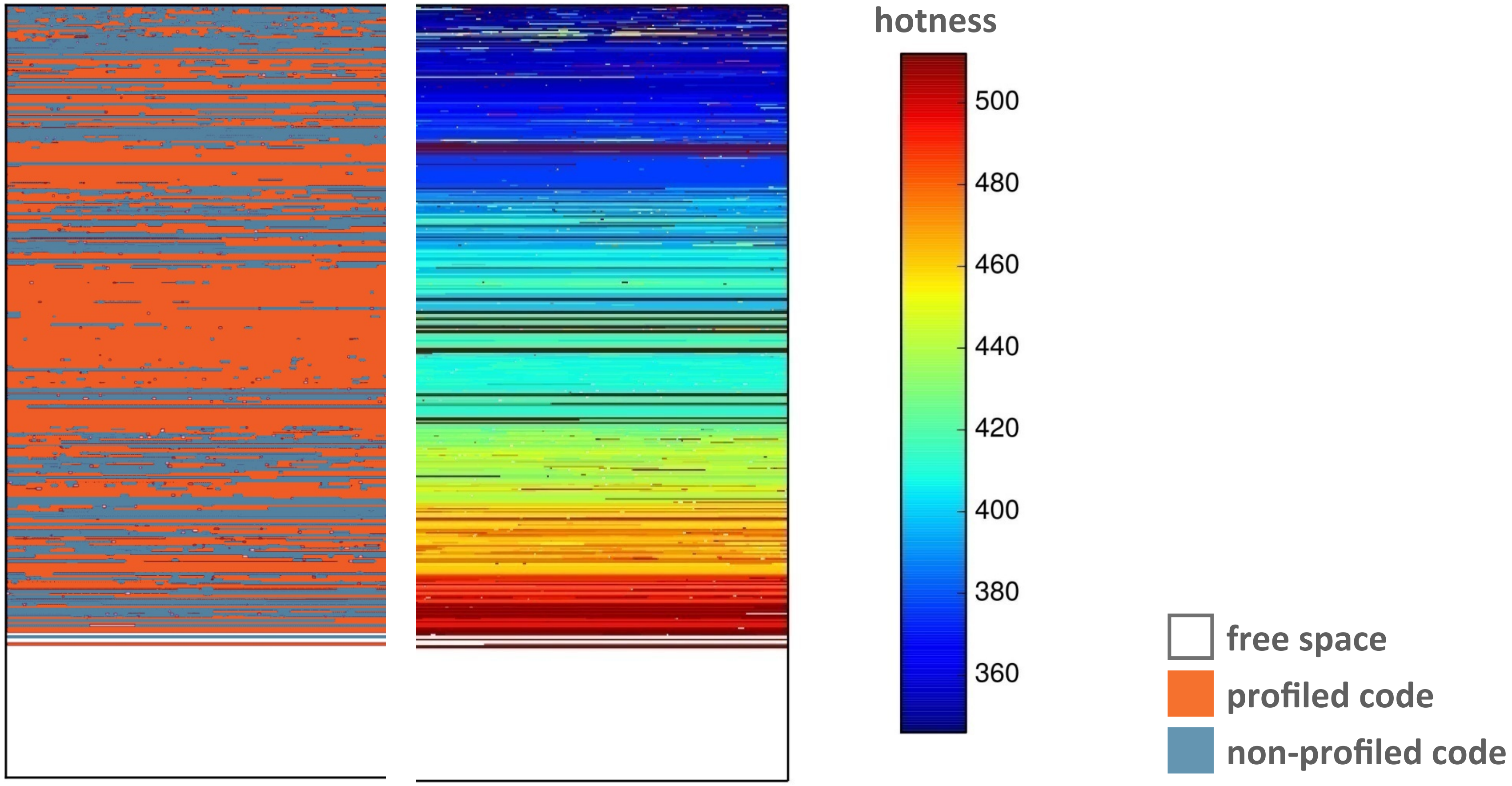

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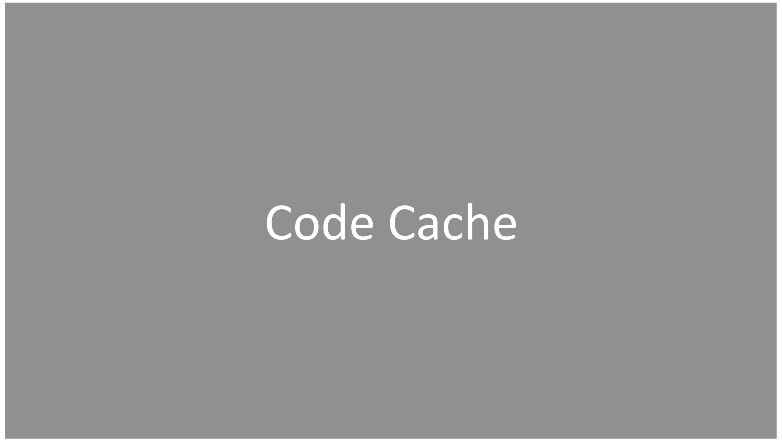
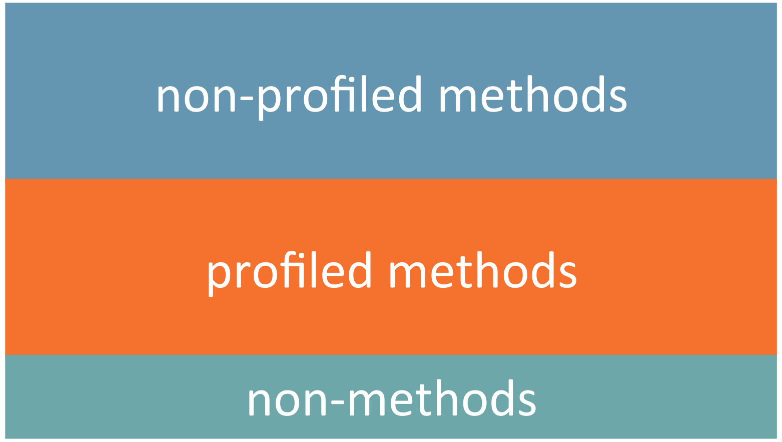
Design

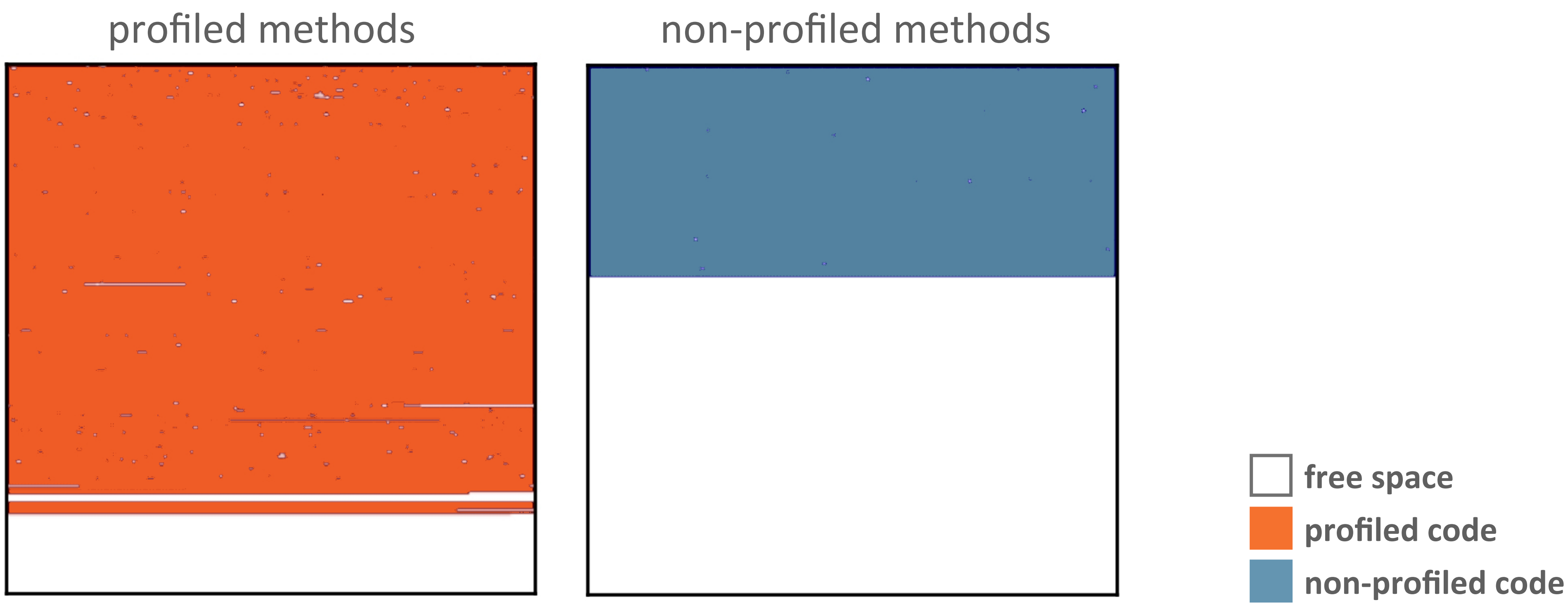
- **Without Segmented Code Cache**



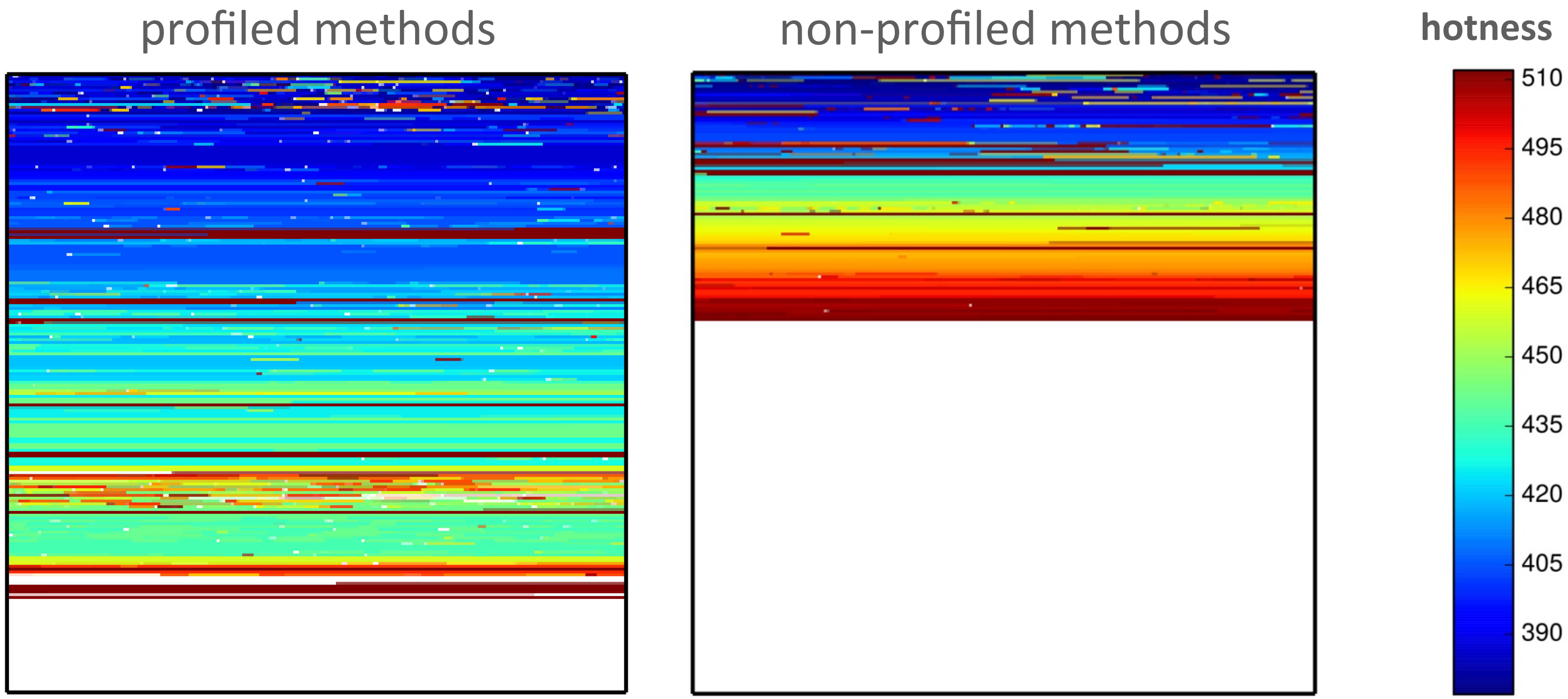
- **With Segmented Code Cache**



Segmented Code Cache: Reality



Segmented Code Cache: Reality



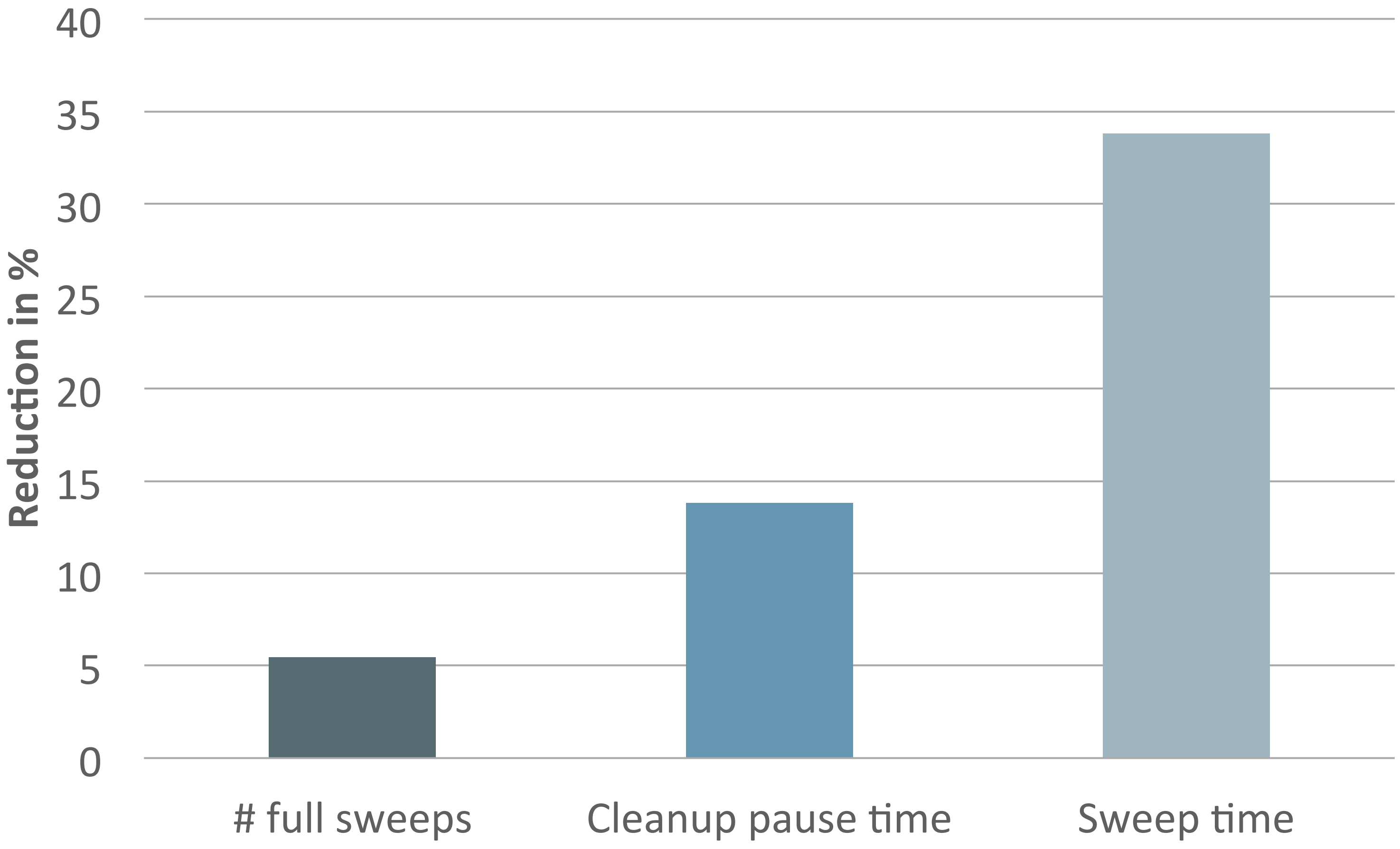
Program Agenda

Evaluation: Code locality

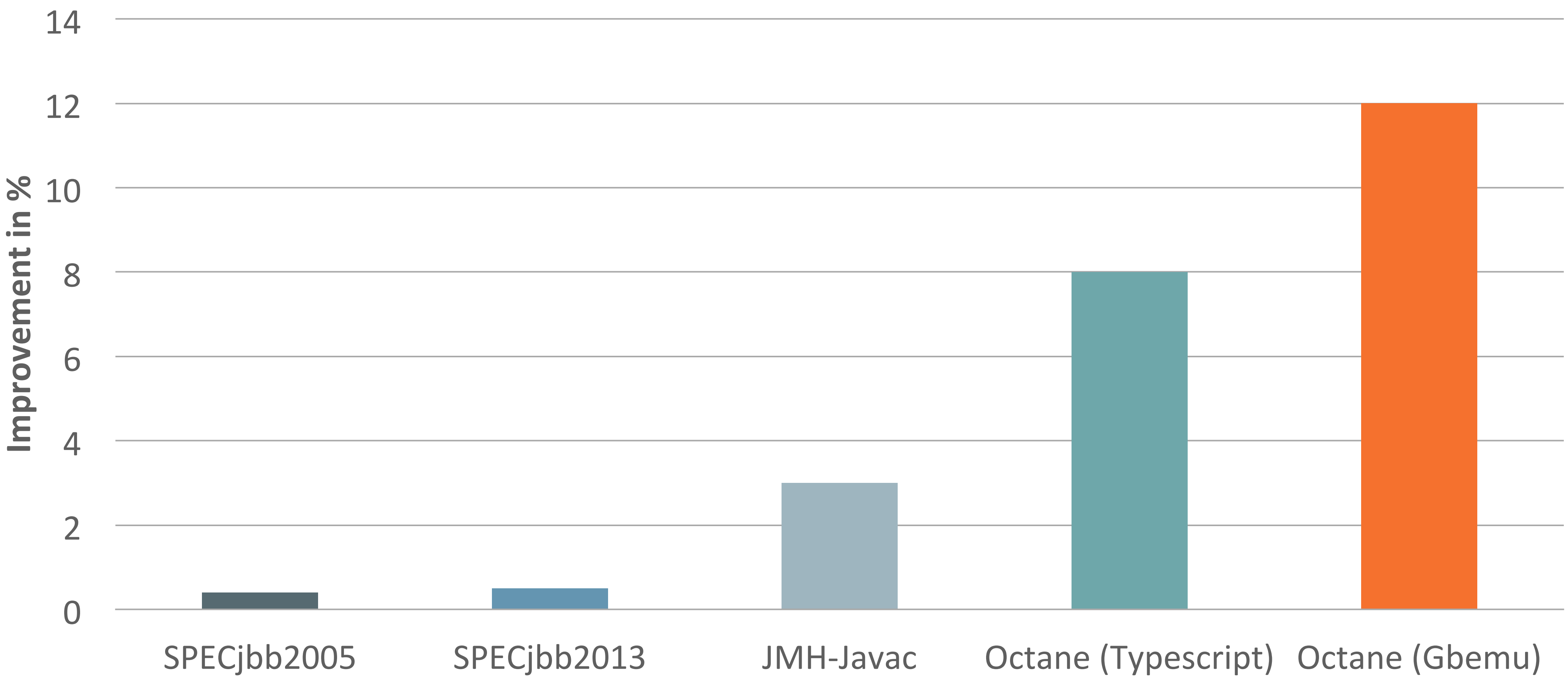
- **Instruction Cache (ICache)**
  - 14% less ICache misses
- **Instruction Translation Lookaside Buffer (ITLB[1])**
  - **44% less ITLB misses**
  - **9% speedup** with microbenchmark

[1] caches virtual to physical address mappings to avoid slow page walks

Evaluation: Sweeper



Evaluation: Runtime



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1 Background

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4 Evaluation

5 **Conclusion**

Conclusion

- **Code layout matters**
  - **Significant impact on performance**
  - Code locality reduces iTLB misses
- **Segmented Code Cache helps**
  - Less sweeper overhead
  - Reduced fragmentation
- **Base for future extensions**
  - New code types
  - Separation of code and metadata

Part 2: Compact Strings

Improve VM internal handling of Strings

Program Agenda

1. Java Strings
2. Project Goals
3. Design
4. Evaluation
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Program Agenda

Java Strings

```
public class HelloWorld {
    public static void main(String[] args) {
        String myString = "HELLO";
        System.out.println(myString);
    }
}
```

Java Strings

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```java
public final class String {
    private final char value[];
    ...
}
```

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```java
public final class String {
    private final char value[];
    ...
}
```

	H	E	L	L	O	
`char value[] =`	0x0048	0x0045	0x004C	0x004C	0x004F	**UTF-16 encoded**

2 bytes

“Perfection is achieved, not when there is nothing more to add, but when there is nothing more to take away.”

– **Antoine de Saint Exupéry**

There is a lot to take away here..

- UTF-16 encoded Strings always occupy **two bytes** per char
- **Wasted memory** if only Latin-1 (one-byte) characters used:

	H	E	L	L	O
`char value[] =`	0x0048	0x0045	0x004C	0x004C	0x004F

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	H	E	L	L	O
`char value[] =`	0x0048	0x0045	0x004C	0x004C	0x004F

2 bytes

- But is this a problem in **real life**?

Real life analysis: char[] footprint

- **950 heap dumps from a variety of applications**
  - char[] footprint makes up **10% - 45% of live data**
  - Majority of characters are **single byte**
  - 75% of Strings are smaller than 35 characters
  - 75% of Characters are in Strings of length < 250
- **Predicted footprint reduction of 5% - 10%**

Program Agenda

1 Java Strings

2 **Project Goals**

3 Design

4 Evaluation

5 Conclusion

Project Goals

- Memory footprint reduction by improving space efficiency of Strings
- Meet or beat throughput performance of baseline JDK 9
- Full compatibility with related Java and native interfaces
- Full platform support
  - x86/x64, SPARC, ARM
  - Linux, Solaris, Windows, Mac OS X

Program Agenda

1. Java Strings
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3. **Design**
4. Evaluation
5. Conclusion

Design

- String class now uses a byte[] instead of a char[]

```
public final class String {
    private final byte value[];
    private final byte coder;
    ...
}
```

- Additional 'coder' field indicates which encoding is used

	H		E		L		L		O		
byte value[] =	0x00	0x48	0x00	0x45	0x00	0x4C	0x00	0x4C	0x00	0x4F	UTF-16 encoded
byte value[] =	0x48	0x45	0x4C	0x4C	0x4F						Latin-1 encoded
	H	E	L	L	O						

Design

- **If all characters have a zero upper byte**
  → String is compressed to **Latin-1** by stripping off high order bytes
- **If A character has a non-zero upper byte**
  → String cannot be compressed and is stored **UTF-16** encoded

`byte value[] =` | 0x00 | 0x48 | 0x00 | 0x45 | 0x00 | 0x4C | 0x00 | 0x4C | 0x00 | 0x4F | **UTF-16 encoded**

↓ **Compression** ↑ **Inflation**

`byte value[] =` | 0x48 | 0x45 | 0x4C | 0x4C | 0x4F | **Latin-1 encoded**

Design

- **Compression / inflation needs to fast**
- **Requires HotSpot support in addition to Java class library changes**
  - **JIT compilers**: Intrinsics and String concatenation optimizations
  - Runtime: String object constructors, JNI, JVMTI
  - GC: String deduplication
- **Kill switch to enforce UTF-16 encoding (-XX:-CompactStrings)**
  - For applications that extensively use UTF-16 characters

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Evaluation

- New and existing unittests
- Microbenchmarks at the String API level
- Large benchmarks to measure overall performance

Microbenchmark: LogLineBench

```
public class LogLineBench {
    int size;

    String method = generateString(size);

    public String work() throws Exceptions {
        return "[" + System.nanoTime() + "] " +
               Thread.currentThread().getName() +
               "Calling an application method \"" + method +
               "\" without fear and prejudice.";
}
```

LogLineBench results

	Performance ns/op			Allocated b/op		
	1	10	100	1	10	100
Baseline	149	153	231	888	904	1680
CS disabled	152	150	230	888	904	1680
CS enabled	142	139	169	504	512	904

- Kill switch works (no regression)
- **27% performance** improvement and **46% footprint** reduction

Large workloads

- **SPECjbb2005**
  - 21% footprint reduction
  - 27% less GCs
  - 5% throughput improvement
- **SPECjbb2015**
  - 7% footprint reduction
  - 11% critical-jOps improvement
- **Weblogic (startup)**
  - 10% footprint reduction
  - 5% startup time improvement

Program Agenda

Conclusion

Compact Strings helps our applications a lot.

Ongoing effort: Indify String Concat, Fused Strings

Try out JDK 9 early access: jdk9.java.net/download/

.. and tell us how it performs with your applications!

Future

- **AOT: Ahead-of-time compilation**
  - Compile to native code (not to Java bytecodes)
  - More information: https://www.youtube.com/watch?v=Xybzyv8qbOc (45-minute talk from JVMLS'15)
- **JVMCI: Java Virtual Machine Compiler Interface**
  - Current compilers written in C/C++
  - JVMCI: Interface to allow Java code to intercept JVM activity and plug-in native code
  - Experimental feature, Graal and SubstrateVM use it

Conclusions

- **Java – a vibrant platform**
  - New features: Segmented Code Cache, Compact Strings, JVMCI
  - … and many other features to be released with JDK 9
  - Stay tuned!
- **The future of the Java platform**

> *"Our SaaS products are built on top of Java and the Oracle DB—that's the platform."*
>
> *Larry Ellison, Oracle CTO*

Thank you for your attention!

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Backup slides