Compile ahead of time. It's fine?

Hotspot & AOT

Java Your Next (Cloud)

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Program Agenda

Safe Harbor Statement

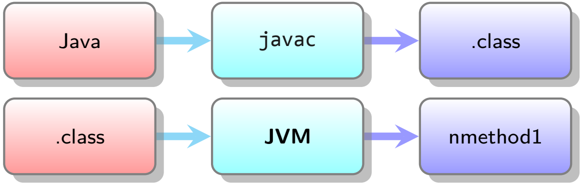
JEP 295 in JDK 9 and beyond

AOT 9: Components

- JEP 295: Ahead-of-Time Compilation
  http://openjdk.java.net/jeps/295
  JDK 9 EA build 150
- JEP 243: Java-Level JVM Compiler Interface
  http://openjdk.java.net/jeps/243
- Graal Compiler
  https://github.com/graalvm/graal-core

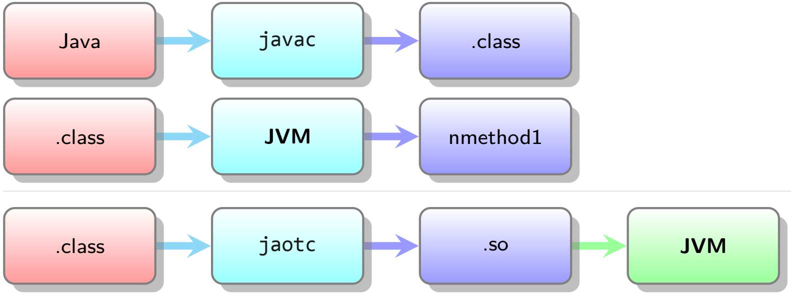
AOT 9: Workflow

Regular



AOT 9: Workflow

Pre-compilation



AOT 9: Targeted Problems

- Application Warm-up
  - Startup Time
  - Time to Performance
- Steady state
  - Peak Performance
  - Application Latency
- Complex case
  - Bootstrapping (meta-circular implementations)
- Possible impact
  - Density
  - Power Consumption

AOT 9: Solutions

- Pre-compile initialization code
  - No interpreter for class loading, initializers etc.
  - Spare resources for compilation
  - May stay at AOT
- Pre-compile critical code
  - Start with much better than interpreter performance
  - Spare resources for compilation
  - May stay at AOT
- Collect same profiling info as tier 2
  - Reach peak performance

Java on Java

Java on Java: Targeted Problems

- Simple maintenance
- Faster development
- Better security
- Embeddable VM

Java on Java: Write parts in Java

- Current
  - Class library
  - Method handles
  - Graal/JVMCI
  - AOT
- Possible
  - Replace C1, C2, interpreter
  - Runtime routines
  - Compiler routines

Java on Java: Project Metropolis

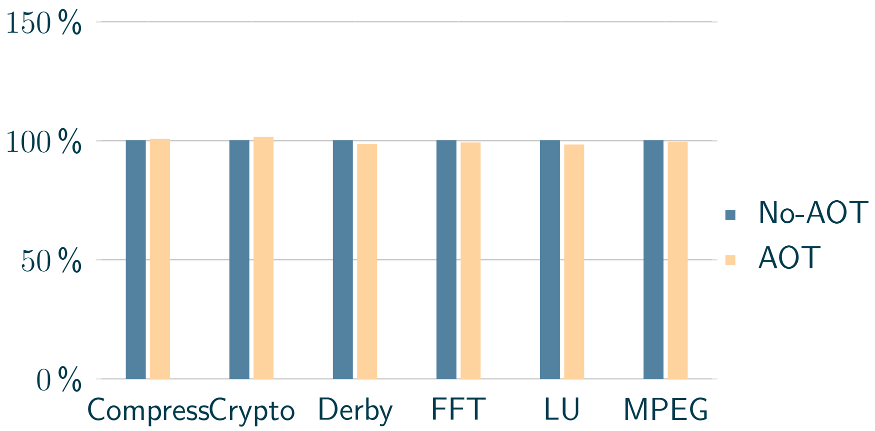
- JDK 10 based
- Translated parts of Hotspot
- Graal
- AOT

AOT 9: Measurements

- JDK 9 EA build 162
- Linux x64
- G1
- Compressed oops
- Dedicated server hardware or small machine

AOT 9: AOT vs. JIT

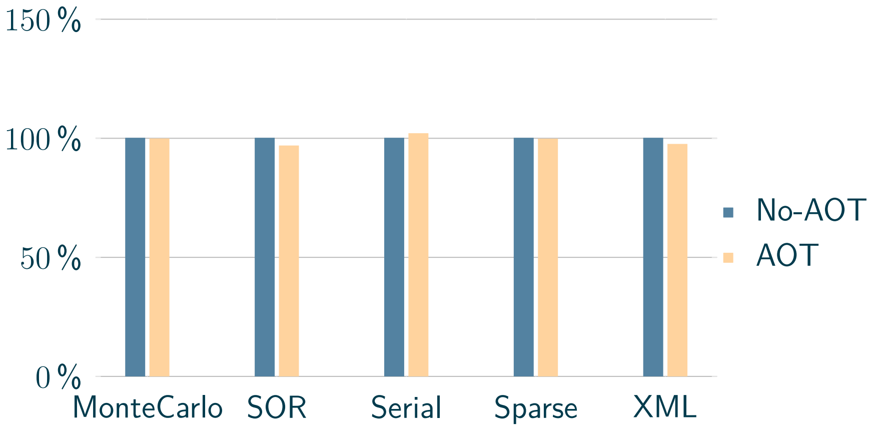
naïve



SPECjvm2008
G1
Tiered AOT
of java.base
Linux x64

AOT 9: AOT vs. JIT

naïve



SPECjvm2008
G1
Tiered AOT
of java.base
Linux x64

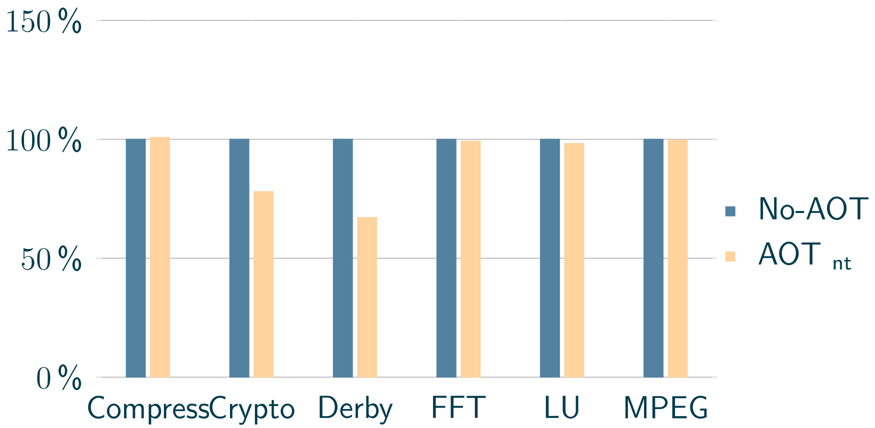
AOT 9: Tiered AOT throughput

Not so useless

- ✓ It works
- ✓ Ensure peak performance in steady state
- ✓ There may be differencies
  - Treated as bugs
  - Ignored

AOT 9: AOT vs. JIT

Frustrating



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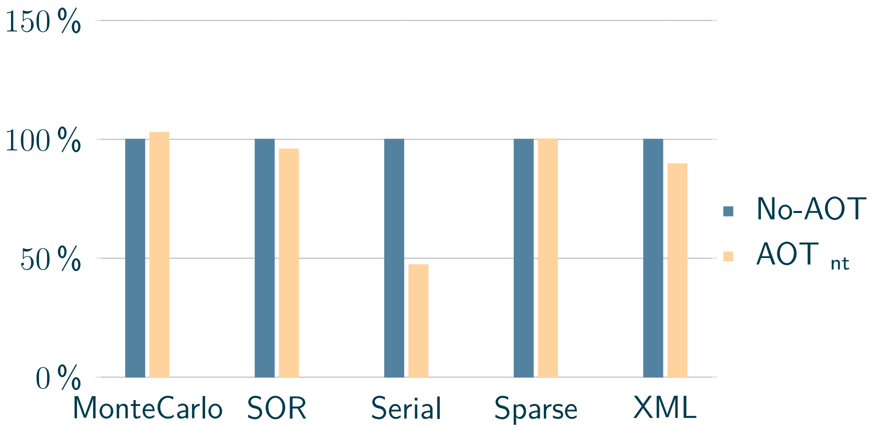
AOT 9: AOT vs. JIT

Frustrating



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Non-tiered AOT of java.base
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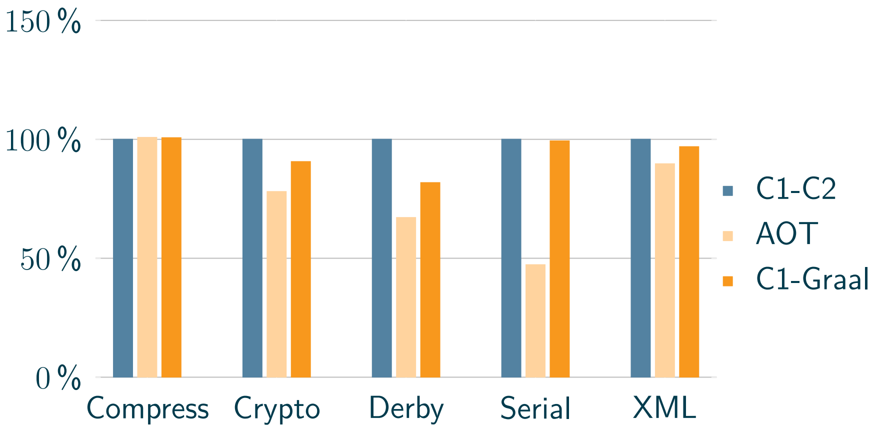
AOT 9: Is it Graal?

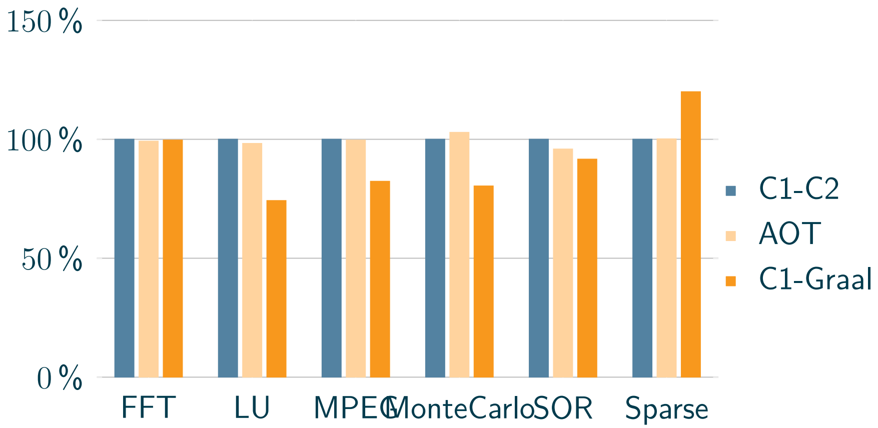
Ones regressed with AOT may not differ



SPECjvm2008
G1
Non-tiered AOT of java.base
Linux x64

AOT 9: Is it Graal?

Ones may only differ with Graal as JIT



SPECjvm2008
G1
Non-tiered AOT
of java.base
Linux x64

AOT 9: AOT throughput

- Benchmarks regressed with AOT may not differ with Graal as JIT
- Benchmarks may only differ with Graal as JIT
- Same for other large benchmarks (e.g. SPECjbb)
- Same for many JVM micro-benchmarks
- It's common to see NN% difference

Generated Library

Generated Libraries: Auto-loaded

Original / striped, compressed oops

	jmod	Methods	Tiered G1	NT G1	Tiered Par
base	19M	50673	416M / **286M**	318M / 201M	395M / 264M
logging	118K	532	3.8M / 2.6M	2.9M / 1.8M	3.6M / 2.3M
nashorn	2.2M	11865	84M / 54M	64M / 37M	79M / 49M
jvmci	386K	1750	12M / 8.5M	8.9M / 5.8M	12M / 7.6M
graal	5.5M	18166	163M / 104M	127M / 73M	154M / 95M
javac	6.3M	12446	115M / 75M	91M / 55M	109M / 69M

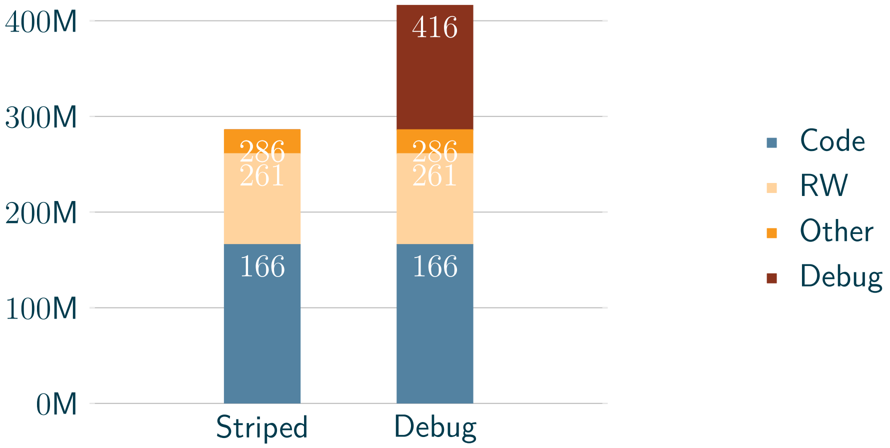
Generated Libraries: Basic subsets

Original / striped, compressed oops

	Methods	Tiered G1
java.base-CDS	22375	163M / 112M
java.base-Hello	615	5.3M / 3.5M
hello	2	99K / **76K**

Generated Libraries: libjava.base-coop.so

```
readelf -S, size -A -d
```



Generated Libraries: Shared library

- Shareable
- Native debug information
- Code
- Metadata
  - .so $\rightarrow$ VM linkage
  - VM $\rightarrow$ .so linkage
  - Runtime support

Generated Libraries: Hello World

```
./objconv -dh any-aot.so.dbg | ...
```

```
.hash                 Symbol hash table
.dynsym
Dynamic linker symbol table
.dynstr               String table
.rela.dyn             Relocation w addends
.text                 Program data
.metaspace.names      Program data
.klasses.offsets      Program data
.methods.offsets      Program data
.klasses.dependencies Program data
.stubs.offsets        Program data
.header               Program data
.code.segments        Program data
.method.constdata     Program data
```

```
.config            Program data
.eh_frame          Program data
.dynamic           Dynamic linking info
.metadata.got      Program data
.method.metadata   Program data
.hotspot.linkage.got Program data
.metaspace.got     bss
.method.state      bss
.oop.got           bss
.shstrtab          String table

.symtab            Symbol table
.strtab            String table
```

Generated Libraries: Hello World

```
./objdump -d hello.so.dbg | ...

00000000000023a0 <test.HelloWorld.<init>()V>:
0000000000002520 <test.HelloWorld.main([Ljava/lang/String;)V>:
0000000000002b48 <M1_375_java.io.PrintStream.write(Ljava/lang/String;)V_plt.entry>:
0000000000002b5b <M1_375_java.io.PrintStream.write(Ljava/lang/String;)V_plt.jmp>:
0000000000002b68 <M1_391_java.io.PrintStream.newLine()V_plt.entry>:
0000000000002b7b <M1_391_java.io.PrintStream.newLine()V_plt.jmp>:
...
```

Generated Libraries: Hello World

```
./objdump -d hello.so.dbg | ...

0000000000002c20 <Stub<AMD64MathStub.log>>:
...
0000000000005e20 <Stub<NewInstanceStub.newInstance>>:
0000000000005f20 <Stub<NewArrayStub.newArray>>:
0000000000006020 <Stub<ExceptionHandlerStub.exceptionHandler>>:
...
0000000000007ca0 <Stub<test_deoptimize_call_int(int)int>>:
...
0000000000007d80 <plt._aot_jvmci_runtime_new_instance>:
0000000000007d88 <plt._aot_jvmci_runtime_new_array>:
0000000000007d90 <plt._aot_jvmci_runtime_exception_handler_for_pc>:
...
0000000000007e58 <plt._aot_backedge_event>:
0000000000007e60 <plt._aot_jvmci_runtime_thread_is_interrupted>:
0000000000007e68 <plt._aot_jvmci_runtime_test_deoptimize_call_int>:
```

Generated Libraries: Cold HelloWorld startup

Slow HDD. Size matters

	real	**user**	**sys**
No-AOT	1.8s	0.2s	0.0s
java.base (used)	**12.5s**	0.4s	0.4s
Large unused	2.1s	0.2s	0.1s
App	1.8s	0.2s	0.0s

Generated Libraries: Warm HelloWorld startup

	real	**user**	**sys**
No-AOT	0.12s	0.15s	0.02s
java.base	0.15s	0.13s	0.02s

Generated Libraries: Profiling strategies

```
jaotc -J-Dgraal.ProfileSimpleMethods=false
```

	Tiered G1	**Tiered no-PSM**	**Non-tiered G1**
java.base	416M / 286M	370M / **252M**	318M / 201M

Generated Libraries: Profiling strategies

```
org.graalvm.compiler.hotspot.phases.profiling.FinalizeProfileNodesPhase

    @Override
    protected void run(StructuredGraph graph, PhaseContext context) {
        if ( simpleMethodHeuristic(graph) ) {
            removeAllProfilingNodes(graph);
            return;
        }

        assignInlineeInvokeFrequencies(graph);
        if (ProfileNode.Options.ProbabilisticProfiling.getValue()) {
            assignRandomSources(graph);
        }
    }
```

Generated Libraries: Profiling strategies

```
org.graalvm.compiler.hotspot.phases.profiling.FinalizeProfileNodesPhase

    private static boolean simpleMethodHeuristic(StructuredGraph graph) {
        if (Options.ProfileSimpleMethods.getValue()) {
            return false;
        }

        // Check if the graph is smallish..
        if (graph.getNodeCount() > Options.SimpleMethodGraphSize.getValue()) {
            return false;
        }

        // Check if method has loops
        if (graph.hasLoops()) {
            return false;
        }
...
```

Generated Libraries: Patching Graal

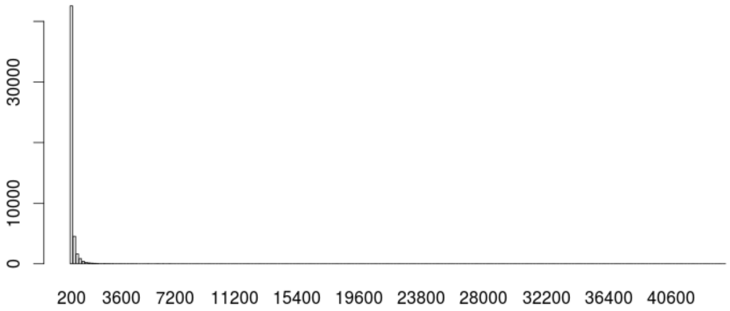
```
org.graalvm.compiler.hotspot.phases.profiling.FinalizeProfileNodesPhase

    static ExecutorService io = Executors.newSingleThreadExecutor();
    @Override
    protected void run(StructuredGraph graph, PhaseContext context) {
      int nodeCount = graph.getNodeCount();
      // int nodeCount = graph.getNodes().filter(InvokeNode.class).count(); etc.
      io.execute(() -> {
        try {
          File hist = new File("hist.csv");
          if(!hist.exists()) hist.createNewFile();
          BufferedWriter bw = new BufferedWriter(new FileWriter(hist.getName(), true));
          bw.write(Integer.toString(nodeCount)); bw.write("\n");
          bw.close();
        } catch (IOException e) { };
      });
...
```

Generated Libraries: Patching Graal

```
javac --patch-module jdk.internal.vm.compiler=. \\
 org/graalvm/compiler/hotspot/phases/profiling/FinalizeProfileNodesPhase.java

jaotc -J--patch-module -Jjdk.internal.vm.compiler=/home/tp/aot/patching \\
 -J-XX:+UseCompressedOops -J-XX:+UseG1GC -J-Xmx4g \\
 --info --module java.base --compile-for-tiered --output ignored.so
```

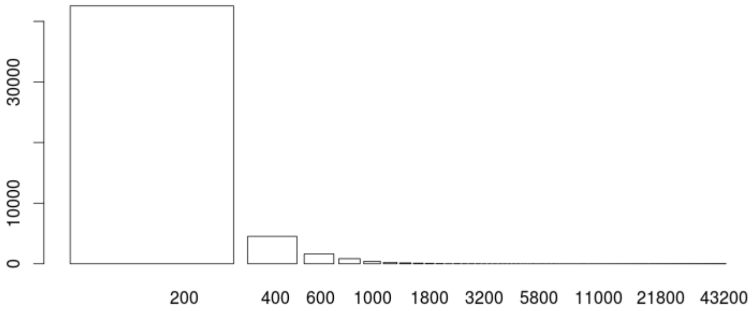
Generated Libraries: Number of nodes in method graphs

java.base



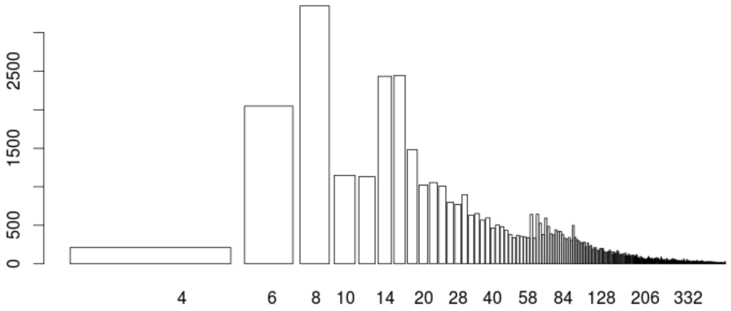
Generated Libraries: Number of nodes in method graphs

java.base



Generated Libraries: Number of nodes in method graphs

java.base



External Tools

Profiling: Flames

- CPU Flame Graphs

  http://www.brendangregg.com/FlameGraphs/cpuflamegraphs.html

- Perf a fork after warm-up

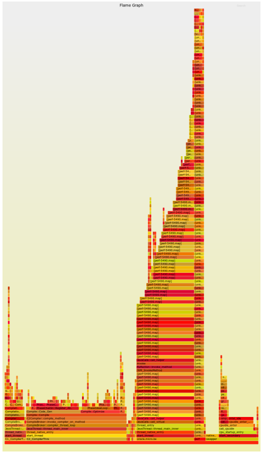
  ```
  perf record -F 399 -a -g -- javac-javac
  
  -XX:+PreserveFramePointer
  ```

- AOT'ed modules

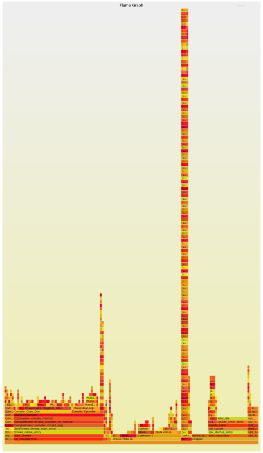
  `java.base, jdk.compiler`

- No `perf-map-agent`

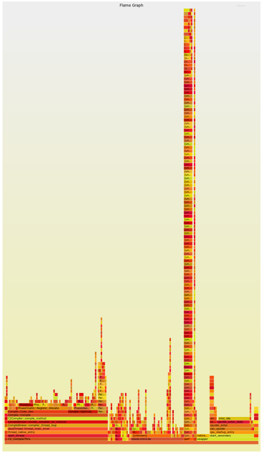
Profiling: Flames



No-AOT



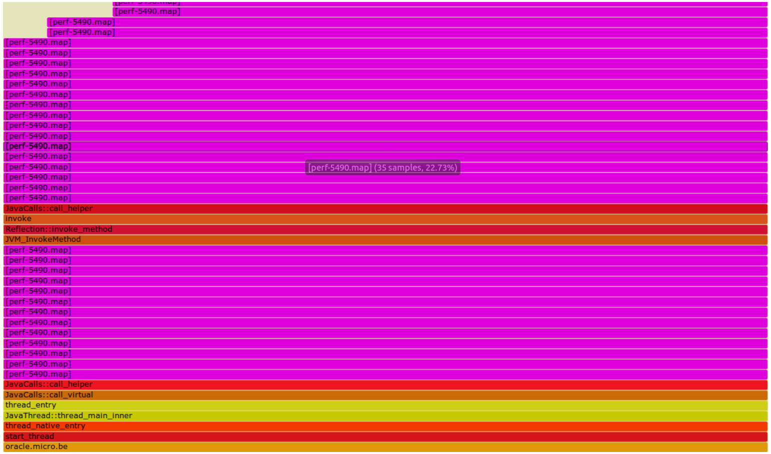
AOT without debug info



AOT with debug info

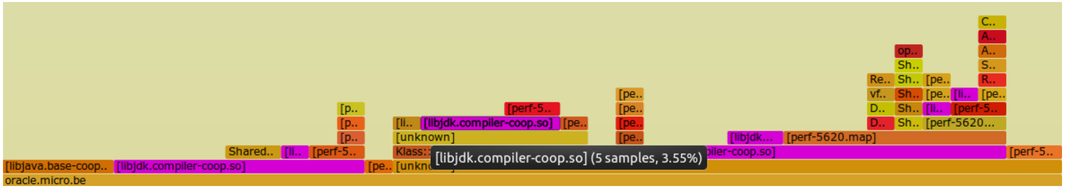
Profiling: Flames

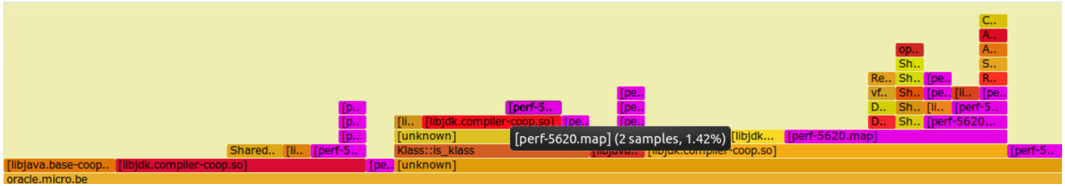
No-AOT



Profiling: Flames

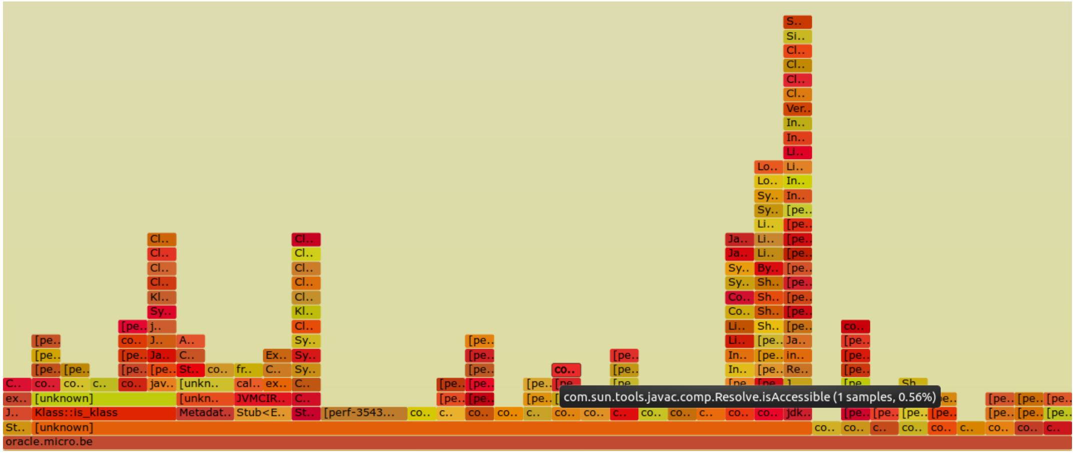
AOT without debug info





Profiling: Flames

AOT with native debug info



Performance

Time: Startup*

	No-AOT	java.base+app
Javac-Hello	1.8s	−20%
Javac-Javac	17.1s	−24%

Time: Startup*

	No-AOT	**java.base+app**	**java.base-nt+app-nt**
Javac-Hello	1.8s	−20%	−38%
Javac-Javac	17.1s	−24%	−32%

* Multi-threaded (T=32)

Time: Startup*

	No-AOT	java.base+app	java.base-nt+app-nt
Javac-Hello	1.8s	−20%	−38%
Javac-Javac	17.1s	−24%	−32%

* Multi-threaded (T=32)

Single-threaded (T=1):

	No-AOT	java.base+app	java.base-nt+app-nt
Javac-Hello	0.5s	−11%	+2%
Javac-Javac	4.5s	+8%	+10%

Warmup: Contended

- No profiling $\rightarrow$ no contention
- -J-Dgraal.ProbabilisticProfiling=true
  - Tuning
  - Multiple Graal threads
  - Switch off when $T = 1$
- -J-Dgraal.ProfileSimpleMethods=true
  - Pick strategy to not profile
  - Would it be better to inline simple ones?

Warmup: Contended

ProbabilisticProfiling

```
HotSpotAOTProfilingPlugin.java

-J-Dgraal.TierAInvokeNotifyFreqLog=13
-J-Dgraal.TierABackedgeNotifyFreqLog=16
-J-Dgraal.TierAInvokeProfileProbabilityLog=8
-J-Dgraal.TierABackedgeProfileProbabilityLog=12
```

```
globals.hpp

-XX:Tier2InvokeNotifyFreqLog=11
-XX:Tier2BackedgeNotifyFreqLog=14
```

- Profile method
- Notify counters
- Logarithm of denominator

Time: Startup & Post-warmup

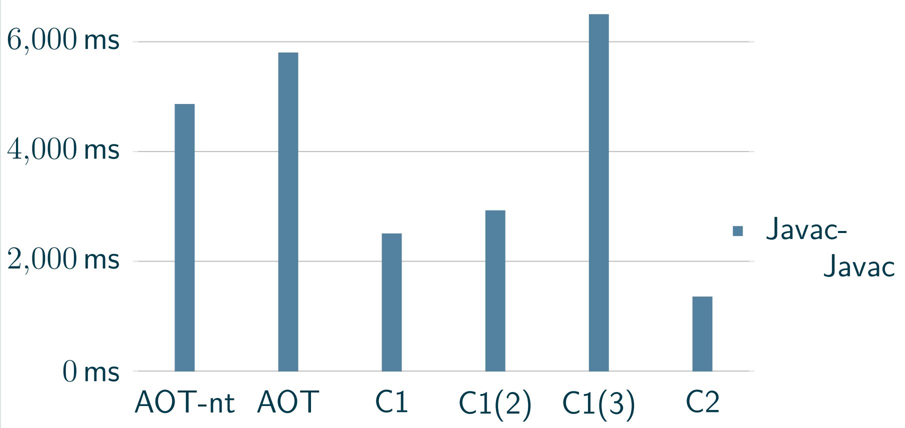
- C1, C1(2), C1(3)

  `-XX:TieredStopAtLevel=`k

- C2
- AOT-nt. java.base-nt & app-nt
- AOT. java.base & app

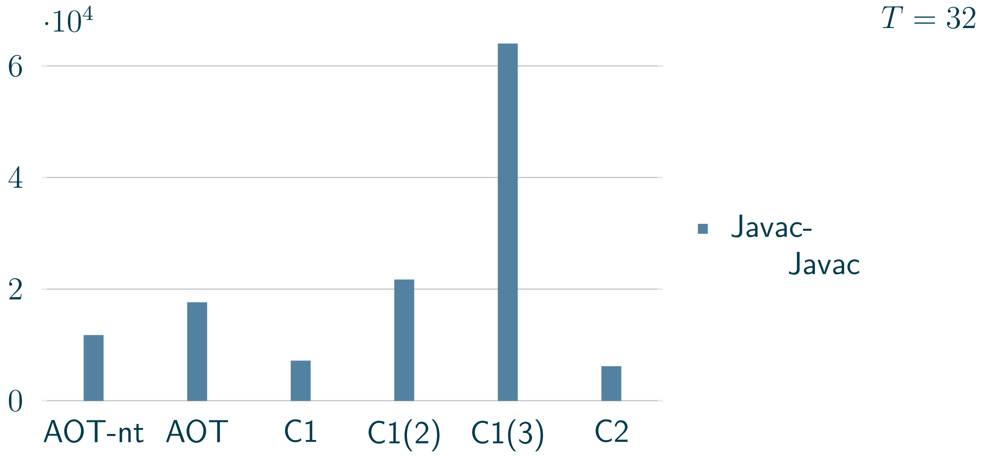
```
-XX:Tier3AOTInvocationThreshold=2000000000

-XX:Tier3AOTMinInvocationThreshold=2000000000

-XX:Tier3AOTCompileThreshold=2000000000

-XX:Tier3AOTBackEdgeThreshold=2000000000

-XX:CICompilerCount=2 -XX:TieredStopAtLevel=2
```

Time: Startup & Post-warmup



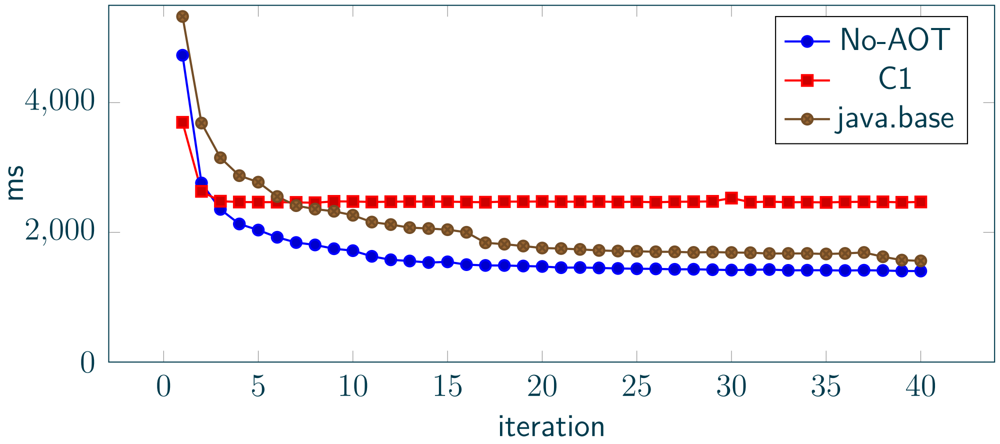
$T = 1$

Time: Startup & Post-warmup



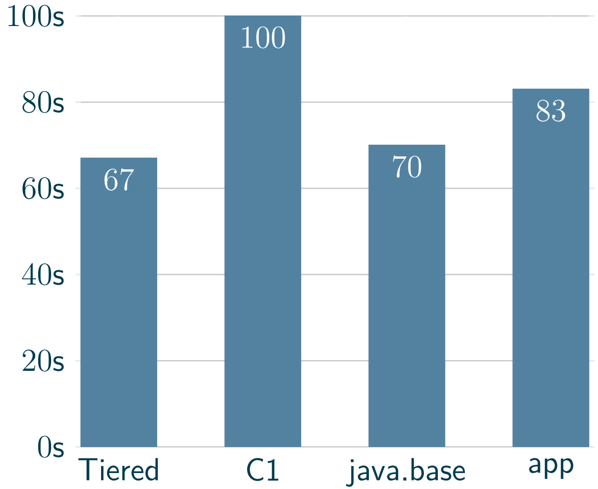
Warmup: Single threaded

Javac-javac, tiered



Warmup: Time to iterate

Javac-javac, tiered



Warmup: Tiered

```
vm/runtime/globals.hpp
```

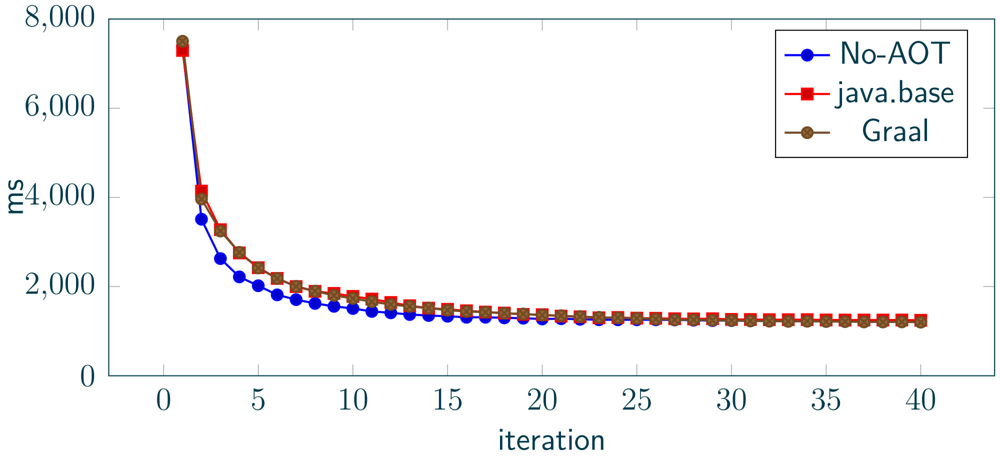
```
-XX:Tier3AOTInvocationThreshold=10000
-XX:Tier3AOTMinInvocationThreshold=1000
-XX:Tier3AOTCompileThreshold=15000
-XX:Tier3AOTBackEdgeThreshold=120000
```

```
-XX:Tier3InvocationThreshold=200
-XX:Tier3MinInvocationThreshold=100
-XX:Tier3CompileThreshold=2000
-XX:Tier3BackEdgeThreshold=60000
```

- Thresholds are different
- Delay tier 3 on startup
- No qualitative effect on long warmup

Warmup: Single threaded C1-Graal

Javac-javac, tiered



Throughput: Measurement

What may be interesting

- AOT'ed code calling other code
- AOT'ed code touching other data
- java.base

```
@State(Thread)
public class OpsBench {
  @Benchmark
  public Result maybeFromAot() {
    return OpsClass1.doOp(<args>);
  }
}
```

```
@CompilerControl(DONT_INLINE)
public class OpsClass1 {
  public static Result doPr(String s) {
    // May use OpsClass2, may be .so
  }
}
```

Throughput: Simple method calls

	VM	**.so→VM**	**VM→.so**	**1.so→2.so**	**.so**
instance final	3.1	3.5	3.1	3.5	3.5
static direct	2.7	3.1	2.7	3.1	3.1
static indirect self	4.7	3.1	4.7	3.1	3.1
static indirect other	4.7	3.5	4.6	3.5	3.5
infra	0.4				

ns/op, $\pm$0.5ns

- Non-tiered AOT
- It's hard to measure directly

Throughput: Simple method calls

VM→.so, perfasm

```
....[Distribution by Source]..............
46.57%  45.21%  c2, level 4
25.62%  25.60%  c1, level 1
25.62%  27.22%      lib2.so
 0.75%   0.71%       kernel
 0.69%   0.61%     libjvm.so

....[Hottest Methods (after inlining)]....
37.83%  41.27%  c2, level 4  micro.generated.CallBench_invokeStaticOther_jmhTest::invokeS
25.60%  25.17%  c1, level 1  micro.TargetClass1::staticThatTarget, version 543
24.90%  26.19%      lib2.so  micro.TargetClass2.staticEmptyTarget()V
 8.94%   5.80%  c2, level 4  micro.generated.CallBench_invokeStaticOther_jmhTest::invokeS
 1.72%   0.79%       kernel  [unknown]
 0.08%   0.18%     libjvm.so  ElfSymbolTable::lookup
```

Throughput: Simple method calls

-XX:-TieredCompilation

	VM	**.so→VM**	**VM→.so**	**1.so→2.so**	**.so**
instance final	3.1	3.1	3.1	3.5	3.5
static direct	2.7	3.1	2.7	3.1	3.1
static indirect self	4.2	3.1	4.2	3.1	3.1
static indirect other	4.3	3.5	4.6	3.5	3.5
infra	0.4				

ns/op, $\pm$0.5ns

- It's still hard to measure directly

Throughput: Simple method calls

C2, perfasm

VM

```
....[Hottest Regions].....................
52.39%   59.81%         c2  micro.generated.CallBench_invokeStaticOther_jmhTest::invokeSta
27.36%   24.16%         c2  micro.TargetClass1::staticThatTarget, version 133 (31 bytes)
19.69%   15.97%         c2  micro.TargetClass2::staticEmptyTarget, version 134 (17 bytes
```

VM→.so

```
....[Hottest Regions].....................
60.71%   52.88%    lib1.so  micro.TargetClass1.staticThatTarget()V (70 bytes)
39.17%   47.10%         c2  micro.generated.CallBench_invokeStaticOther_jmhTest::invokeSta
```

Someone is missing!

```
objdump -d
```

Throughput: Simple method calls

@CompilerControl is not enough

Working no Graal inlining during AOT:

```
jaotc -J-XX:CompileCommand=dontinline,*/*.*
```

Broken alternative:

```
jaotc -J-Dgraal.Inline=false -J-Dgraal.InlineDuringParsing=false
```

Our non-local guy:

```
2347:   callq   23a0 <M3_39_micro.TargetClass2.staticEmptyTarget()V_plt.entry>
```

Throughput: Simple method calls

-XX:-TieredCompilation, no inlining in .so

	VM	.so→VM	VM→.so	1.so→2.so	.so
instance final	3.1	3.5	3.1	3.5	3.5
static direct	2.7	3.1	2.7	3.1	3.1
static indirect self	4.2	6.2	4.8	6.2	6.2
static indirect other	4.3	5.8	4.6	6.2	6.2
infra	0.4				

ns/op, ±0.5ns

- Finally makes sense

Throughput: Read data

		VM	.so→VM
	Read own static integer	5.8	5.8
→	Read length of other's static string	6.5	**10.1**

ns/op, ±0.5ns

Throughput: Read data

String length, perfnorm

	VM	.so→VM
Time, ns/op	6.5	8.8
L1 dcache loads	16.4	26.5
Branches	6.1	13.3
Cycles	17.3	26.9
Instructions	39.8	67.4

Throughput: Read data

String length, perfasm

```
....[Hottest Region 2]....................
c2, level 4,
micro.AccessClass1::staticThatStrlen,
version 544 (52 bytes)
```

```
....[Hottest Region 1]....................
lib1.so,
micro.AccessClass1.staticThatStrlen()I
(159 bytes)
```

Throughput: Read data

String length, asm

Constants in C2

```
0x00007f4d596b7aac: mov     $0x8eff8e70 ,%r10
     ;   {oop(a &apos;java/lang/Class&apos;{0x000000008eff8e70}
      = &apos;micro/AccessClass2&apos;)}
....
0x00007f4d596b7adb: callq  0x00007f4d51c0dc00  ; ImmutableOopMap{}
                           ;*invokevirtual length {reexecute=0 rethrow=0 return_oop=0}
```

Checks & references in AOT

```
2541:    mov    0x20fad8(%rip),%rcx # 212020 <got.init.Lmicro/AccessClass2;>
2548:    test   %rcx,%rcx
254b:    je     25e2 <micro.AccessClass1.staticThatStrlen()I+0xc2>
2551:    mov    0x20fad0(%rip),%rcx # 212028 <got.L/micro/AccessClass2;>
...
25d8:    callq  73a0 <Stub<resolve_klass_by_symbol(Word,Word)Word>>
...
```

Throughput: Checks & references

- ? Convert code to unshareable
- ? Mix code with known class data to use constants
- ✓ Simple code is good
  - But not inlineable

Throughput: Checks & references

java.base

	Unique	of classes	Avg. in method
got.init.L<class>	779	14%	4.5
got.L<class>	1394	24%	8.0

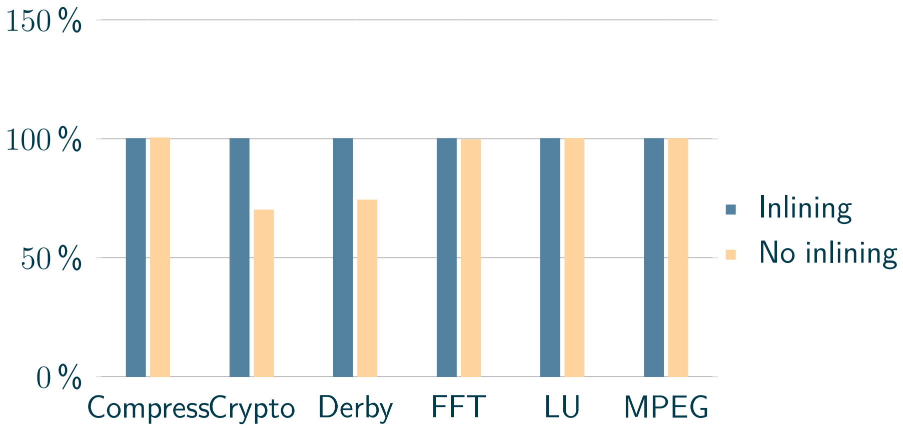
- United class list $\xrightarrow{\text{AppCDS}}$ 21 M .jsa
- Graal stats are close (4.9, 9.5)
- Intersection with CDS list: [`908` [`496`] `658`]

Throughput: Inlining

Library size

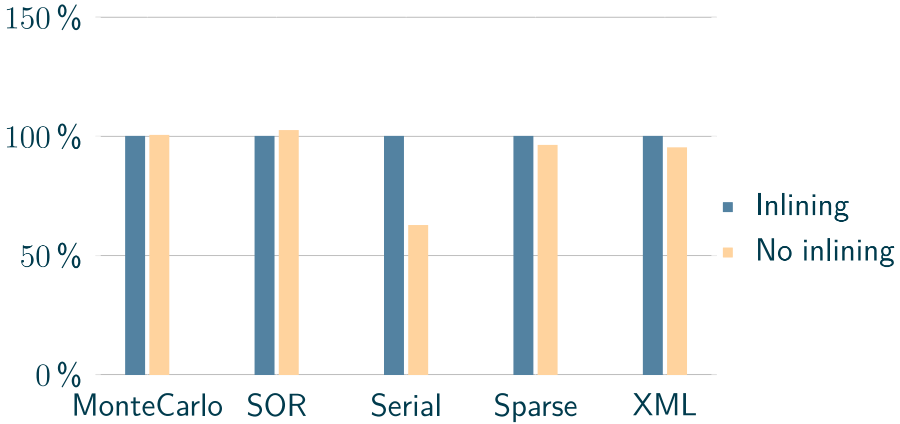
	Non-tiered G1	No inlining
java.base	318M / 201M	236M / **128M**

Throughput: Inlining



SPECjvm2008
G1
Non-tiered AOT of java.base
Linux x64

Throughput: Inlining



SPECjvm2008
G1
Non-tiered AOT of java.base
Linux x64

Latency: Garbage collection

With AOT

- Some additional GC work
- No sensitive impact on mean
- No sensitive impact on max
- Same distributions

Startup: Applications

	No-AOT	java.base	java.base-nt
Jetty	0.5s	−15%	−22%
Simple GUI	0.6s	−8%	−11%
Rich GUI	1.9s	−4%	−8%

Startup: Applications

Graal bootstrap

	No-AOT	java.base	java.base+graal+jvmci
Javac-Hello	0.8s	−29%	−29%
Jetty	0.5s	0%	0%
Javac-Javac	4.6s	−6%	−5%
Javadoc-Small	2.7s	−2%	+2%
Simple GUI	0.7s	−17%	
Rich GUI	2.4s	−13%	

Startup: Applications

WLS

base_domain System Classloader	no-AOT no-CDS	java.base no-CDS	no-AOT AppCDS	java.base AppCDS
Startup	11.4s	−17%	−33%	−48%
Footprint [x1]				
resident	478 M	+25%	−3%	+25%
unique	466 M	−6%	−15%	−18%
Footprint [x10]				
total	4652 M	−3%	−11%	−13%

Future Directions

Future Directions: Extensions & improvements

- More OSes
  - Other *NIX with ELF
  - PEF (macOS)
  - PE (Windows)
- More CPUs
  - ARM64 port
- Cross-AOT

Future Directions: Features convergence

- Solve class data access problem
  - CDS
  - AppCDS
  - Shared strings
- Boilerplate
  - AOT of pre-generated stuff
- Product features
  - WLS
- Cloud
  - Containers

Conclusion: AOT

- ✓ It works in 9
- ✓ Performance is measurable
- ✓ Current results are questionable but already promising
- ✓ Known problems are to be fixed
- ✓ There are big plans