Understand the trade-offs using compilers for Java applications

(From AOT to JIT and Beyond!)

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Java ecosystem has a rich history exploring native code compilation!

• JIT
  • 1999: IBM SDK for Java included productized JIT compiler originally built by IBM Tokyo Research Lab, used until Java 5.0
  • 2006: IBM SDK for Java 5.0 includes J9 JVM with “Testarossa” JIT, now open source as Eclipse OpenJ9
  • 2017: Azul released Falcon JIT based on LLVM
  • 2018: Graal compiler available as experimental high opt compiler in Java 10

• AOT
    • Statically compiled Java primarily for scientific/high performance computing on mainframes
    • Statically compile Java used GCC compiler project
    • Commercial AOT compiler
  • 2017: Experimental jaotc compiler available in OpenJDK9 uses Graal compiler
  • 2018: GraalVM project introduces native images supporting a subset of Java on SubstrateVM

• “Caching” JIT code
  • 2003: jRockit JIT introduces experimental support for cached (but not optimized) code generation
    • [https://docs.oracle.com/cd/E13188_01/jrockit/docs142/userguide/codecach.html](https://docs.oracle.com/cd/E13188_01/jrockit/docs142/userguide/codecach.html)
  • 2007: IBM “dynamic AOT” production support introduced in IBM SDK for Java 6
  • 2019: Azul Zing introduces “code stashing” as part of ReadyNow
Native compilers in today’s Java ecosystem

• Hotspot JITS
  • C1 “client” and C2 “server” JIT compilers
  • Default a.k.a. reference native compilers used in OpenJDK

• Eclipse OpenJ9’s JIT
  • JIT compiler with multiple adaptive optimization levels (cold through scorching)
  • Historically offered Java compliant AOT compilation for embedded and real-time systems
  • Today caches JIT compilations (a.k.a “dynamic AOT”) alongside classes in shared classes cache

• Azul Zing’s Falcon JIT based on LLVM
  • Alternative “high opt” compiler to C2
  • Can stash JIT compilations to disk and reload in subsequent runs

• Oracle Graal compiler
  • Written in Java
  • Since Java 9: experimental AOT compiler jaotc
  • Since Java 10: experimental alternative to C2 JIT compiler
  • Create native images using SubstrateVM (under “closed world” assumption and other limitations)
Outline

• Let’s compare:
  • JIT
  • AOT
  • Caching JIT code (== both AOT and JIT!)

• Taking JITs to the cloud

• Wrap Up
JIT = Just In Time

• JITs compile code at same time program runs
  • Adapt to whatever the program does “this time”
  • Adapt even to the platform the program is running on

• After more than two decades of sustained effort:
  • JIT is the leader for Java application performance
  • Despite multiple significant parallel efforts aimed at AOT performance

• Why is that? At least 2 reasons you may already know...
1. JITs speculate on class hierarchy

• Calls are virtual by specification
  • But many calls only have a single target (monomorphic) in a particular program run

• JITs speculate that this one target will continue to be the only target
  • Optimize aggressively and keep going deeper (calls to calls to calls....)

• Speculation can greatly expand ability to inline call targets
  • Which expands optimization scope
  • Compiling too early, though, can fool compiler to speculate wrongly
2. JITs use profile data collected as program runs

• Not all code paths execute as frequently
  • Profile data tells compiler which paths are worth optimizing

• Not all calls have a single possible target
  • Profile data can prioritize to enable method inlining most profitable target(s)

• Efficient substitute for some kinds of larger scope compiler analyses
  • Takes too long to analyze entire scope but low overhead profile data still identifies constants
  • Contributes to practical compile time
  • BUT accumulating good profile data takes time

• JIT compilers work very well if the profile data is high quality
But JIT performance advantage isn’t free

• Collecting profile data is an overhead
  • Cost usually paid while code is interpreted: slows start-up and ramp-up
  • Quality data means profiling for a while: slows ramp-up

• JIT compilers consume transient resources (CPU cycles and memory)
  • From under a millisecond to seconds of compile time, can allocate 100s MBs
  • Cost paid when compiling: slows start-up and ramp-up
  • Takes time to get to “full speed” because there may be 1000s of methods to compile

• Also some persistent resource consumption (memory)
  • Profile data, class hierarchy data, runtime assumptions, compiler meta data
## Strengths and Weaknesses

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**Everyone hopes:**
Maybe AOT helps here?
AOT = Ahead of Time

• Introduce an “extra” step to generate native code before deploying application
  • e.g. run `jaotc` command to convert class files to a platform specific “shared object”
  • Akin to approach taken by less dynamic languages: C, C++, Rust, go, Swift, etc.
  • Still considered “experimental” (JDK9+) and works on x86-64 and AArch64 platforms

• Two deployment options (decided at build time):
  • No JIT at runtime: statically compiled code runs, anything else interpreted
  • With JIT at runtime: runtime JIT (re)compiles via triggers or heuristics

• AOT has some runtime advantages over a JIT compiler
  • Compiled code performance “immediately” (no wait to compile)
  • Start-up performance can be 20-50% better especially if combined with AppCDS
  • Reduces CPU & memory impact of JIT compiler
BUT there are a few big BUTs

• No longer platform neutral
  • Different AOT code needed for each deployment platform (Linux, Mac, Windows)

• Other usability issues
  • Some deployment options decided at build time, e.g. GC policy, ability to re-JIT, etc.
  • Different platforms: different classes load and methods to compile?
  • Ongoing curation for list of classes/modules, methods to compile as your application and its dependencies evolve
  • What about classes that aren’t available until the run starts?

• How about those reasons for excellent JIT performance?
  1. Speculate on class hierarchy? Not as easy as for JIT
  2. Profile data? Not as easy as for JIT

• AOT compilers (in pure form) can only reason about what happens at runtime
Sidebar: Life of a running Java application

"Big bang"
(java process created)
Sidebar: Life of a running Java application

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JVM loaded, initialized & about to load first class to run main()
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"Big bang" (java process created)

JVM loaded, initialized & about to load first class to run main()

Finally ready to run main()

~ 750 classes loaded, handful of class loader objects active

Size and Complexity of Class Hierarchy
Sidebar: Life of a running Java application

“Big bang” (Java process created)

- JVM loaded, initialized & about to load first class to run main()
- Finally ready to run main()
- ~750 classes loaded, handful of class loader objects active

App class loading and initialisation phase, up to 100s active class loaders, 10,000s classes

Size and Complexity of Class Hierarchy

Time
Sidebar: Life of a running Java application

- "Big bang" (Java process created)
- JVM loaded, initialized & about to load first class to run main()
- Finally ready to run main()
- ~ 750 classes loaded, handful of class loader objects active
- Ready to do application work:
  - begin exercising code paths
  - May load more classes, may invalidate early assumptions

Size and Complexity of Class Hierarchy
Sidebar: Life of a running Java application

- **“Big bang”** (java process created)
  - JVM loaded, initialized & about to load first class to run main()

- **Finally ready to run main()**
  - ~ 750 classes loaded, handful of class loader objects active
  - Rampup

- **Ready to do application work:**
  - begin exercising code paths
  - May load more classes, may invalidate early assumptions

- **Code paths & profile stabilizes**
  - Size and Complexity of Class Hierarchy

- **Time**
  - Startup
JIT compiler’s view is inside the process

- JVM loaded, initialized & about to load first class to run main()
- Finally ready to run main()
  - ~ 750 classes loaded,
  - handful of class loader objects active
- Ready to do application work:
  - begin exercising code paths
  - May load more classes, may invalidate early assumptions
- Code paths & profile stabilizes

"Big bang" (java process created)

Finally ready to run main()

Time

Start up

Ramp up

Size and Complexity of Class Hierarchy

19
AOT compiler’s view is through the “big bang”

- JVM loaded, initialized & about to load first class to run main()
- "Big bang" (java process created)
- Finally ready to run main()
  ~ 750 classes loaded, handful of class loader objects active
- Ready to do application work:
  begin exercising code paths
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- Code paths & profile stabilizes

Size and Complexity of Class Hierarchy

AOT

- Startup
- Rampup

Time
So what?
Imagine two classes B,C: C.foo() calls B.bar()
Simple opportunity to inline call to b.bar()?
Imagine two classes B,C: C.foo() calls B.bar()
Can now optimize C.foo() using ‘5’

class C {
    public void foo() {
        B b = get_a_b();
        = 5; //b.bar();
        ...
    }
}
But C’s notion of B is decided by C’s class loader

class C {
    public void foo() {
        B b = get_a_b();
        = 5; //b.bar();
        ... 
    }
}

class B {
    public int bar() {
        return 5;
    }
}
C’s ClassLoader is a Java object created on heap

class C {
    public void foo() {
        B b = get_a_b();
        = 5; //b.bar();
        ...
    }
}

class B {
    public int bar() {
        return 5;
    }
}
Class loader objects can invalidate the inlining...

class C {
    public void foo() {
        B b = get_a_b();
        b.bar(); // 5 or -5?
        ...
    }
}
... and C.foo() may be what resolves B!

class C {
    public void foo() {
        B b = get_a_b();
        b.bar(); // 5 or -5?
        ...
    }
}

ClassLoader CL1

class B {
    public int bar() {
        return 5;
    }
}

ClassLoader CL2

class B {
    public int bar() {
        return -5;
    }
}

Java heap
In each run, maybe only CL1 or only CL2 or could be both: AOT probably has to hedge

class C {
    public void foo() {
        B b = get_a_b();
        b.bar(); // 5 or -5?
        ...
    }
}
Contrived example?

• Modelled on OSGi modules enabling two different versions of the same library to be loaded at the same time (i.e. jar file hell)

• But ask yourself: what prevents this scenario if classes can be loaded dynamically and even created on the fly?
  • AOT must completely understand how class loaders will operate at runtime

• JIT acts at runtime and easily deals even with both cases coexisting
  • Each “C” loads as a different j/l/Class so each C.foo() compiled independently
  • i.e. inline b.bar() returning 5 in one case and returning -5 in the other

• For AOT compiler, every inlining hedge reduces optimization scope
  • Increasing gap to JIT performance levels
Profile Directed Feedback (PDF) may help?

- **BUT:** AOT code must run all possible user executions
  - No longer compiling for “this” user on “this” run
  - Really important to use representative input data when collecting profile for AOT

- **Risk:** can be misleading to use only a few input data sets
  - AOT compiler can specialize to one data set and then run well on it
  - But PDF can lead compiler astray if data isn’t properly representative

  - Monomorphic in one runtime instance ≠ Monomorphic across all runtime instances

- **Benchmarks may not stress AOT compilers properly (not many input sets)**
  - Cross training critically important

- **Input data sets need to be curated and maintained** as application and users evolve
  - Profile data collection and curation responsibility is on the application provider

- **Observation:** PDF has not really been a huge success for static languages
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Is that as good as it gets?
Caching JIT Compiles

• Basic idea:
  • Store JIT compiled code (JIT) in a cache for loading by other JVMs (“AOT”)
  • Goal: JIT compiled code performance levels earlier
    • Also: reduce JIT compiler’s transient CPU and memory overheads

• Really different than AOT ? No and Yes
  • From perspective of second+ JVM: code loads as if it was AOT compiled
  • First JVM: JIT compiles while app runs but generates code that can be cached
    • Need meta data to validate later runs match first (i.e. same classes loaded same way)
    • If invalid, don’t use cached code: instead do JIT or even more AOT recompilations

• Return to platform neutrality!
  • Different users still get compiled code tailored for their environment
Two implementations

1. “Dynamic AOT” in Eclipse OpenJ9 open source JVM\(^1\)
   - Originally introduced in 2007 (IBM SDK for Java 6), currently in JDK8 and later
   - Stores (warm) compiled JIT code to shared memory cache (also persisted on disk)
   - Performance for loaded code within 5%-10% of peak JIT performance (getting better)
   - Resilient to application changes

2. “Compile Stashing” in Azul’s proprietary Falcon JIT\(^2\)
   - Introduced in 2018 for JDK8 and later
   - Stores compiled code to disk
   - Stashed code typically reusable in another run for 60-80% of methods
   - JIT recompilations recover remaining performance
   - Resilient to application changes

\(^2\) [https://www.slideshare.net/dougqh/readynow-azuls-unconventional-aot](https://www.slideshare.net/dougqh/readynow-azuls-unconventional-aot)
OpenJ9: Caching JIT code accelerates start-up

• OpenJ9 Shared Class Cache (SCC)
  • Memory mapped file for caching:
    • Class files*
    • AOT compiled code
    • Profile data, hints
  • Population of the cache happens naturally and transparently at runtime

• Also -Xtune:virtualized
  • Caches JIT code even more aggressively to accelerate ramp-up (under load)
  • Maybe slight (5-10%) performance drop

* Technically an internal format that can load faster than a .class file
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* After first run
Still some “not green” boxes there
...even for caching JITs...
😊
Outline

• Let’s compare:
  • JIT
  • AOT
  • Caching JIT code

• **Taking JITs to the cloud**

• Wrap Up
What if the JIT became a JIT Server

JVM client identifies methods to compile, but asks server to do the actual compilation
- JIT server asks questions to the client JVM (about classes, environment, etc.)
- Sends generated code & meta data back to be installed in client’s code cache
Benefits of an independent JIT server

• Move much of JIT induced CPU and memory spikes away from client
  • Client CPU and memory consumption dictated by application

• JIT server connected to client JVM at runtime, so:
  • Theoretically no loss in performance using same profile and class hierarchy info
  • Still adaptable to changing conditions
  • JVM client still platform neutral
Could that work?
AcmeAir rampup with JIT Server using -Xshareclasses

All JVMs run in containers, client and server on different machines with direct cable connection

Note: Hotspot takes twice as long as OpenJ9 to ramp up to about the same performance level
JITServer Performance – Daytrader 7 Throughput

Throughput benefits grow in constrained environments

Smaller memory limit

--cpus=1, -m=300m

--cpus=1, -m=256m

--cpus=1, -m=200m
What about network latency?
Won’t that hurt start up and ramp up?

Will it be practical in the cloud?
JIT Server works well on Amazon AWS!

* JITaaS == JIT Server
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* After first run  ** After first run across cluster
JIT Server Current Status

• Code is fully open source at Eclipse Open J9 and Eclipse OMR
  • Has now been merged into our master branch but not yet built-in by default

• Simple options lend well to all kinds of Java workload deployments
  • Server: `java -XX:+StartAsJITServer -XX:JITServerPort=<port>`
  • Client: `java -XX:+UseJITServer -XX:JITServerPort=<port>`
    `-XX:JITServerAddress=<host> YourJavaApp`

• Current focus is ensuring stability so it can be built into OpenJ9 by default

• Targeting early 2020 (OpenJ9 0.18 release) to be included in our release binaries (JDK8 and up) at AdoptOpenJDK
We are really just at the beginning...

• Primary focus has been on mechanics to move JIT compilation to a server

• Once compilation work is redirected to server:
  • Do that work more efficiently across a cluster of JVMS (think microservices)
  • Classify and categorize JVM clients using machine learning
  • Optimize groups of microservices together
  • …
Wrapping up

• JITs continue to provide the best peak performance

• AOT compilers can improve start-up by 20-50% but expect steady-state performance to be less than JIT performance
  • Some serious usability issues; I think caching JITs are easier to use

• Caching JIT compilers are within ~5-10% of JIT with excellent start-up and ramp-up even for large complex JakartaEE applications
  • Still room to improve both throughput and start up without sacrificing compliance

• JIT Servers are coming with Eclipse OpenJ9!
  • Hopefully built into AdoptOpenJDK binaries in early 2020!
https://adoptopenjdk.net

Select “OpenJ9” Button!!
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Backup
You can prepopulate Docker containers with Shared Caches (SCCs)

• Prepopulating Docker containers with shared caches very efficient with new **SCC layers**
  • Working in synergy with Docker layers

• Each Docker layer can prepopulate its own SCC layer that is independent of lower SCC layers

• Each SCC layer can be trimmed-to-fit because upper layers won’t add to it

• Layers are **transparent** at runtime
  • Classes and code will load from correct layer

• Significant reduction in disk footprint of Docker images that package a SCC

• Faster pushing/pulling of Docker images from a Docker registry