# 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: Hotspot JVM ( https://en.wikipedia.org/wiki/HotSpot ) released by Sun Microsystems
  - 1999: IBM SDK for Java included productized JIT compiler originally built by IBM Tokyo Research Lab, used until Java 5.0
  - 2000: jRockit released by Appeal Virtual Machines (https://en.wikipedia.org/wiki/Appeal_Virtual_Machines)
  - 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
  - 1997: IBM High Performance Compiler for Java (https://link.springer.com/chapter/10.1007/978-1-4615-4873-7_60)
    - Statically compiled Java primarily for scientific/high performance computing on mainframes
  - 1998: GNU Compiler for Java (gcj) (https://en.wikipedia.org/wiki/GNU_Compiler_for_Java)
    - Statically compile Java used GCC compiler project
  - 2000: Excelsior JET (https://en.wikipedia.org/wiki/Excelsior_JET)
    - 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
  - 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

| | JIT |
|---|---|
| Code Performance (steady state) | |
| Runtime: adapt to changes | |
| Ease of use | |
| Platform neutral deployment | |
| Start up (ready to handle load) | |
| Ramp up (until steady state) | |
| Runtime: CPU & Memory | |

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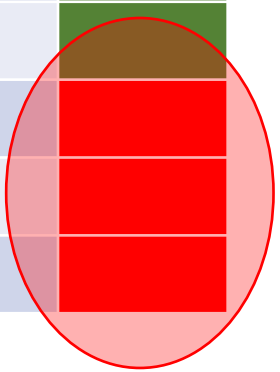


**Everyone hopes:**
**Maybe AOT helps here?**

# 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

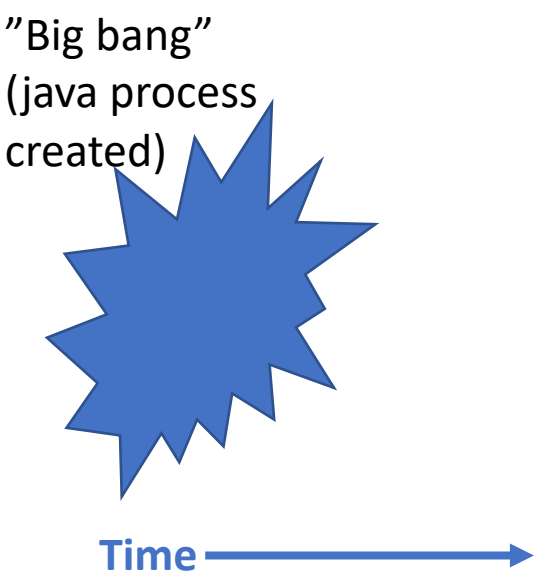
- Two deployment options (decided at build time):
  - No JIT at runtime: statically compiled code runs, anything else interpreted
  - With JIT at runtime: runtime JIT (re)compiles via triggers or heuristics

- 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



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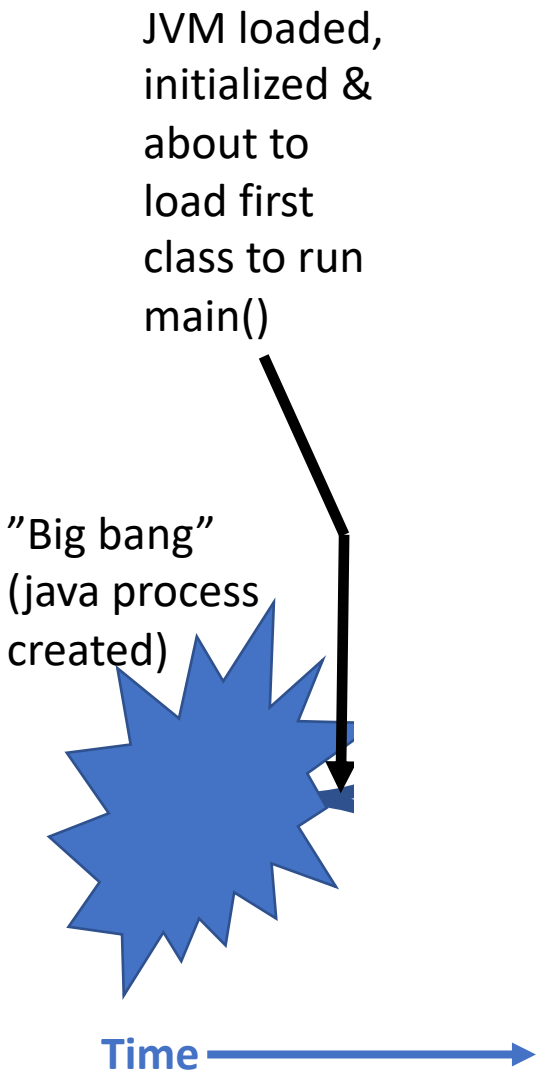

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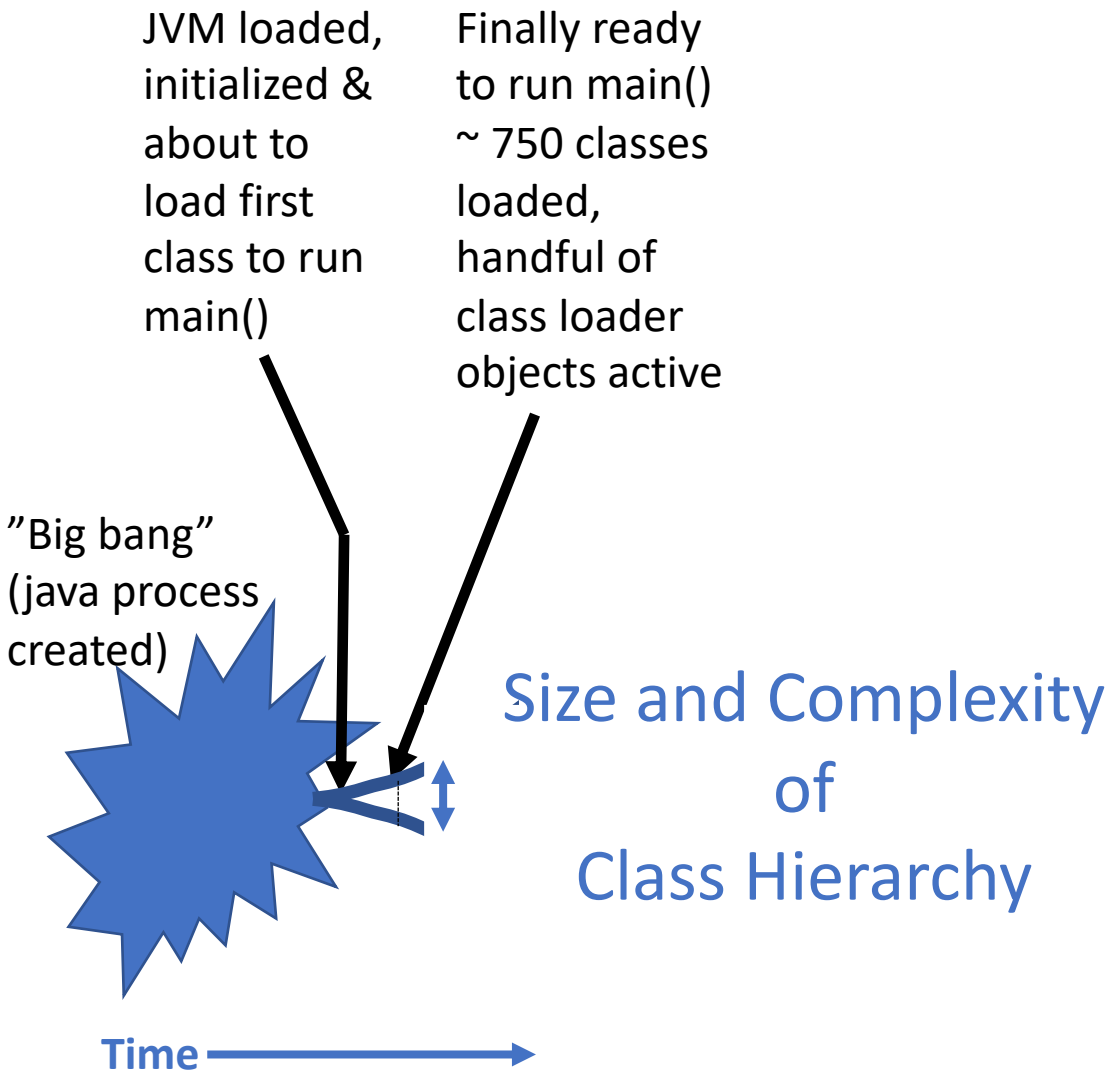

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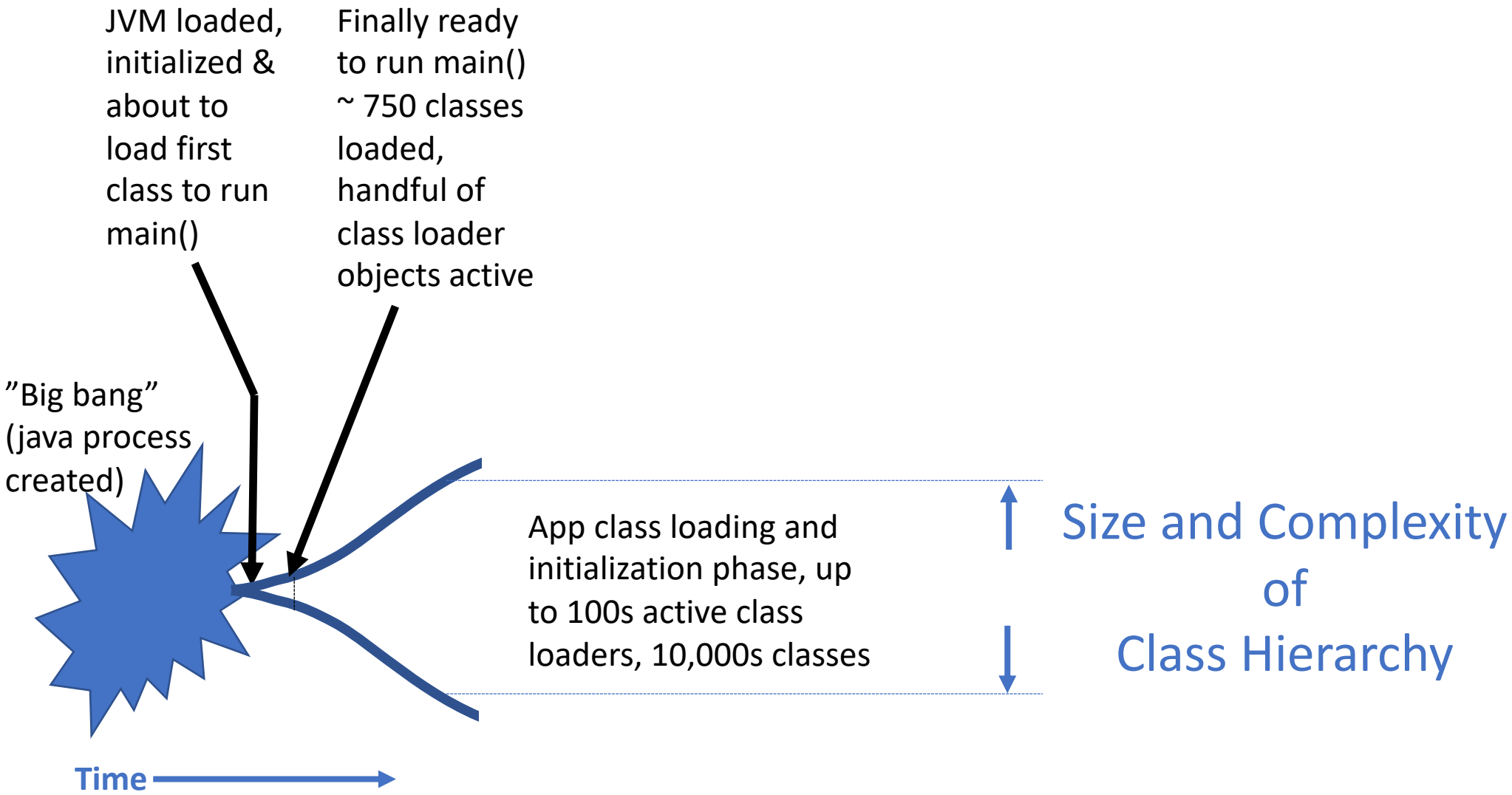

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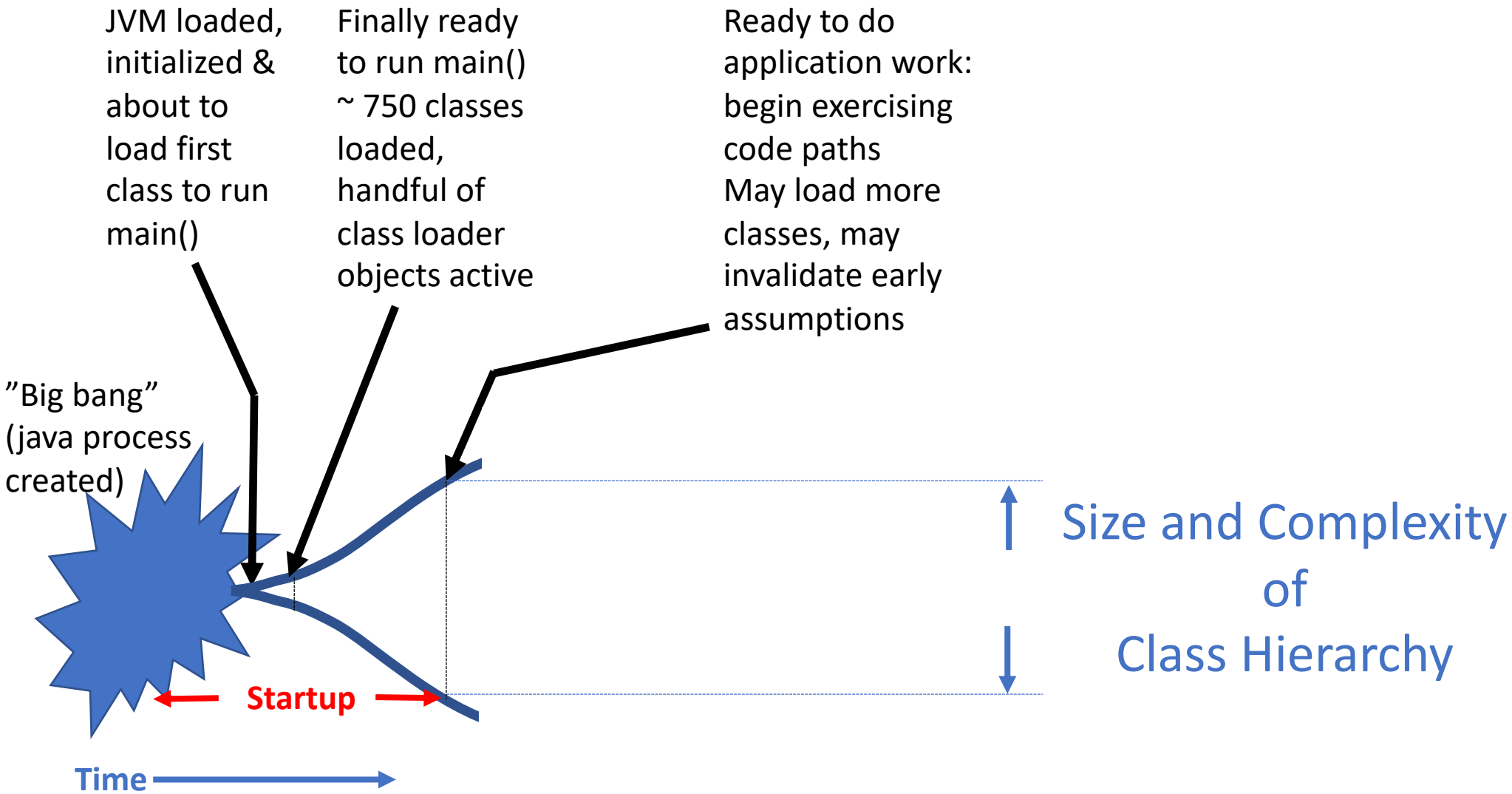

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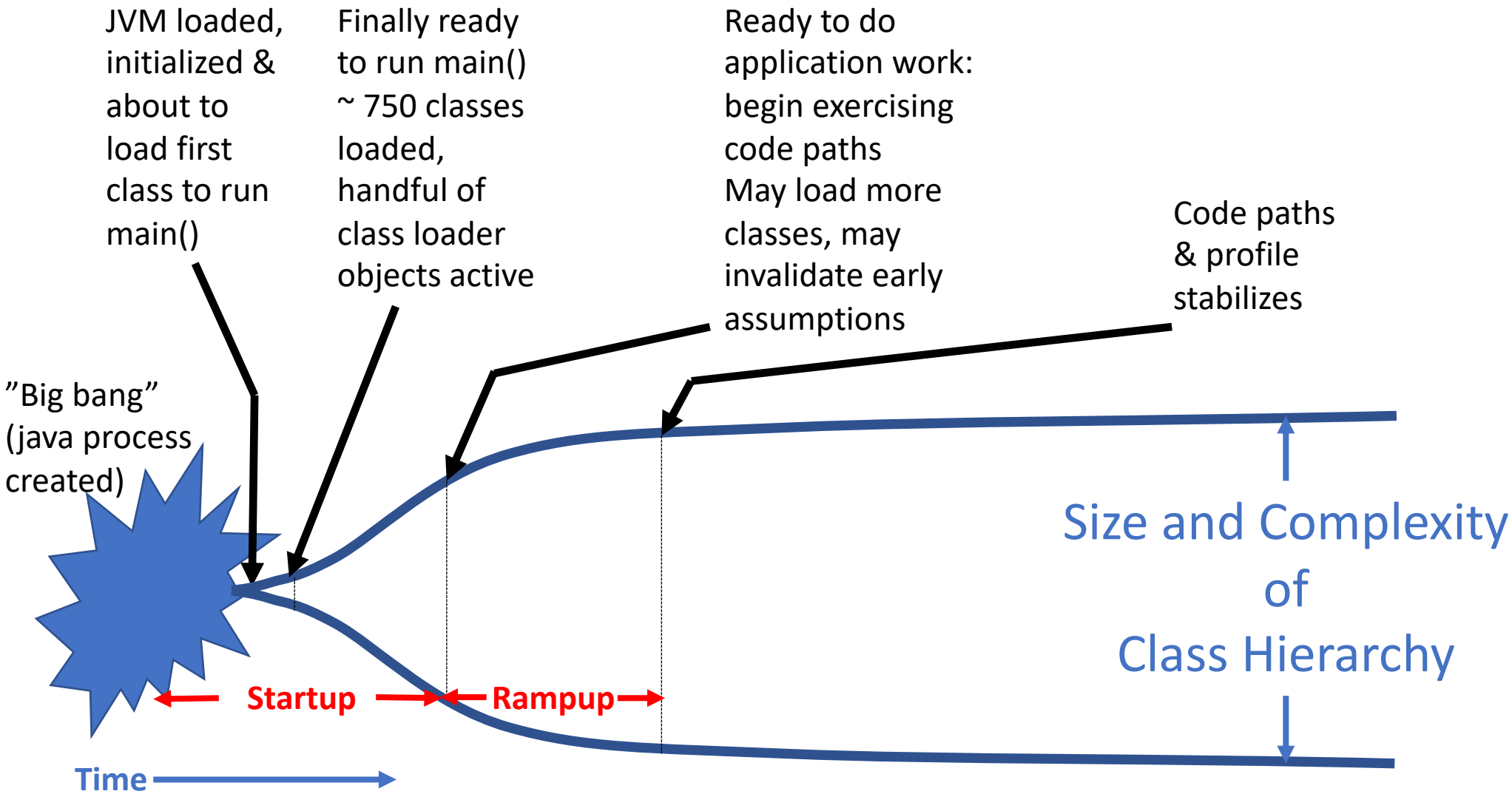
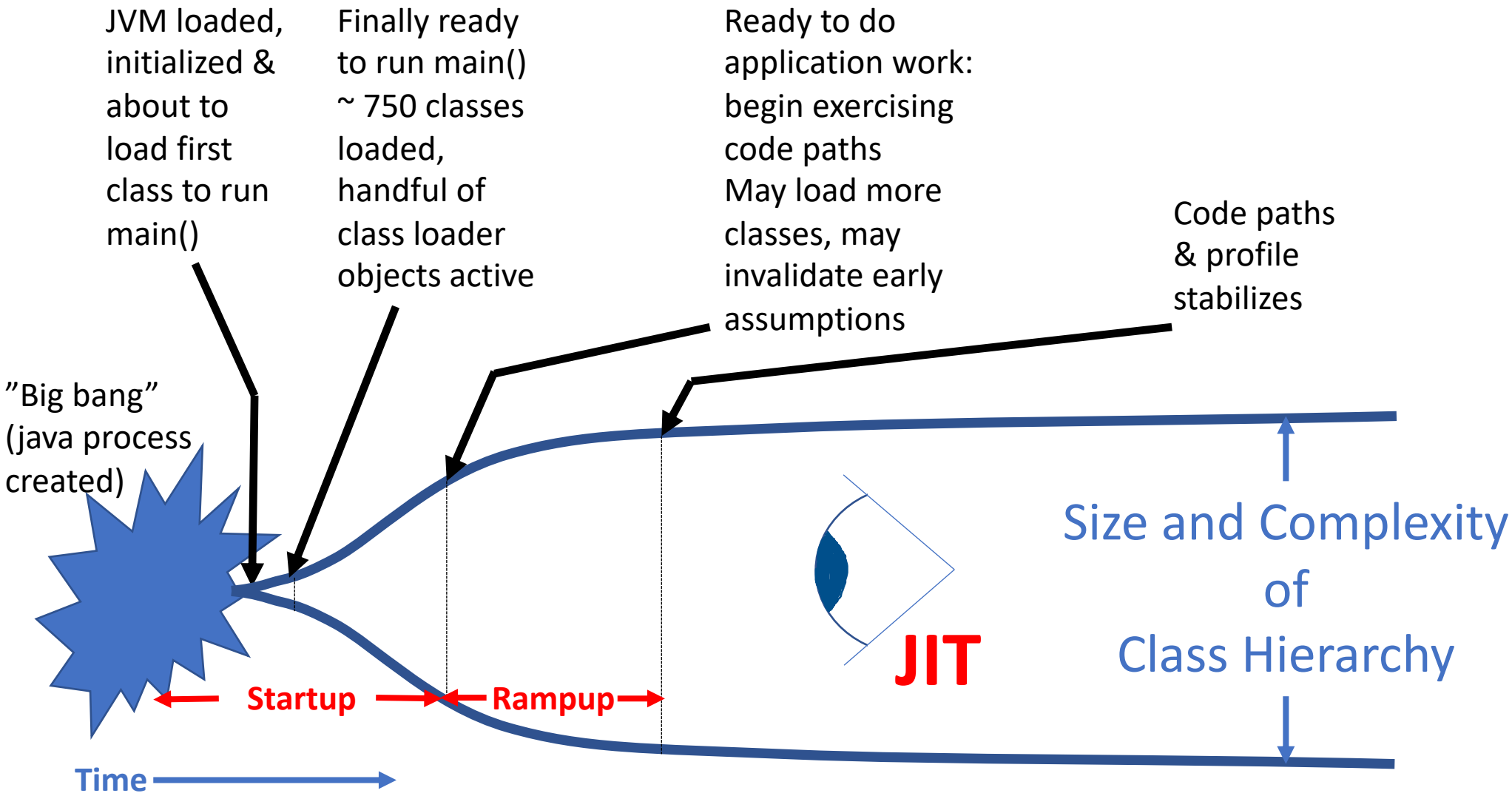
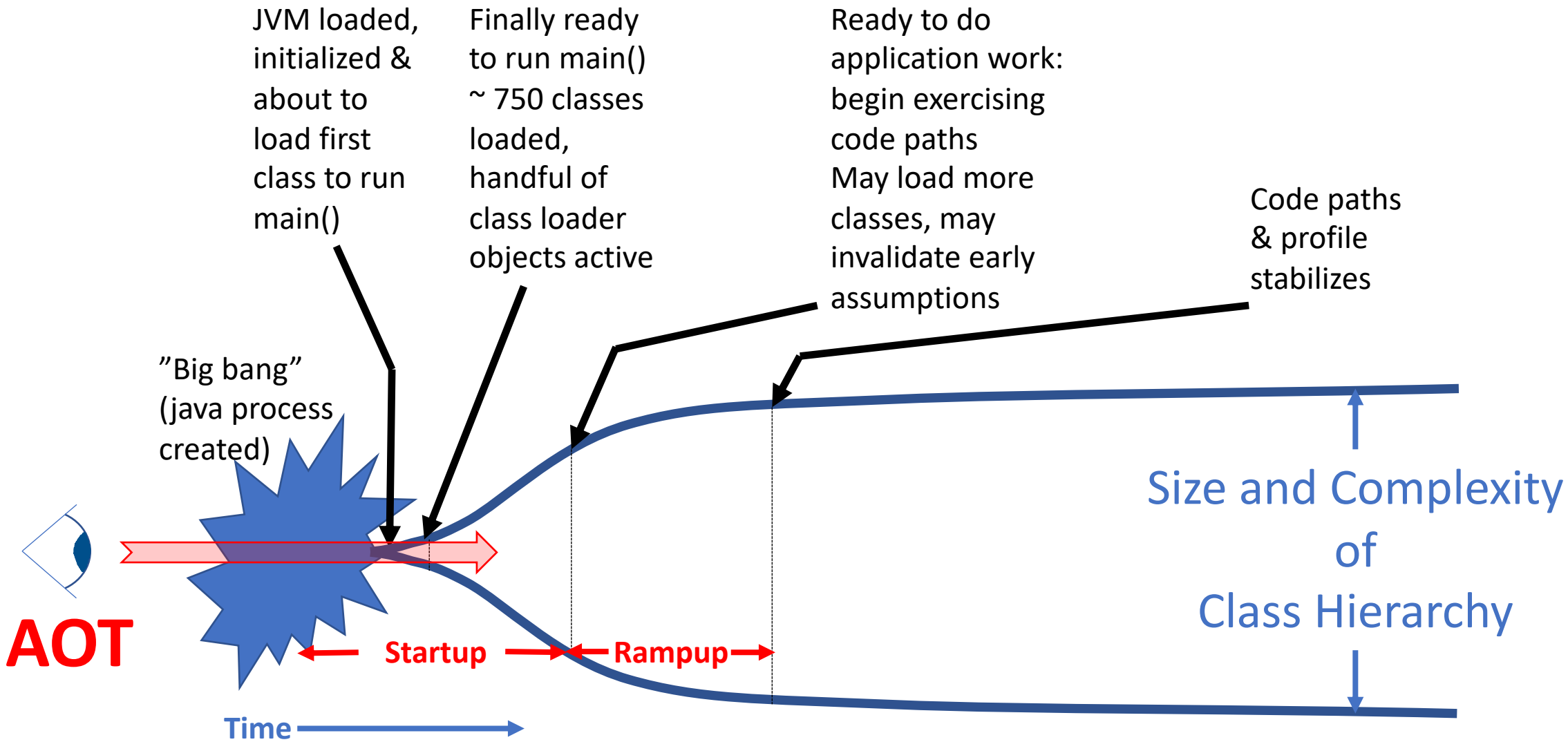


# JIT compiler's view is inside the process



# AOT compiler's view is through the "big bang"



# So what?

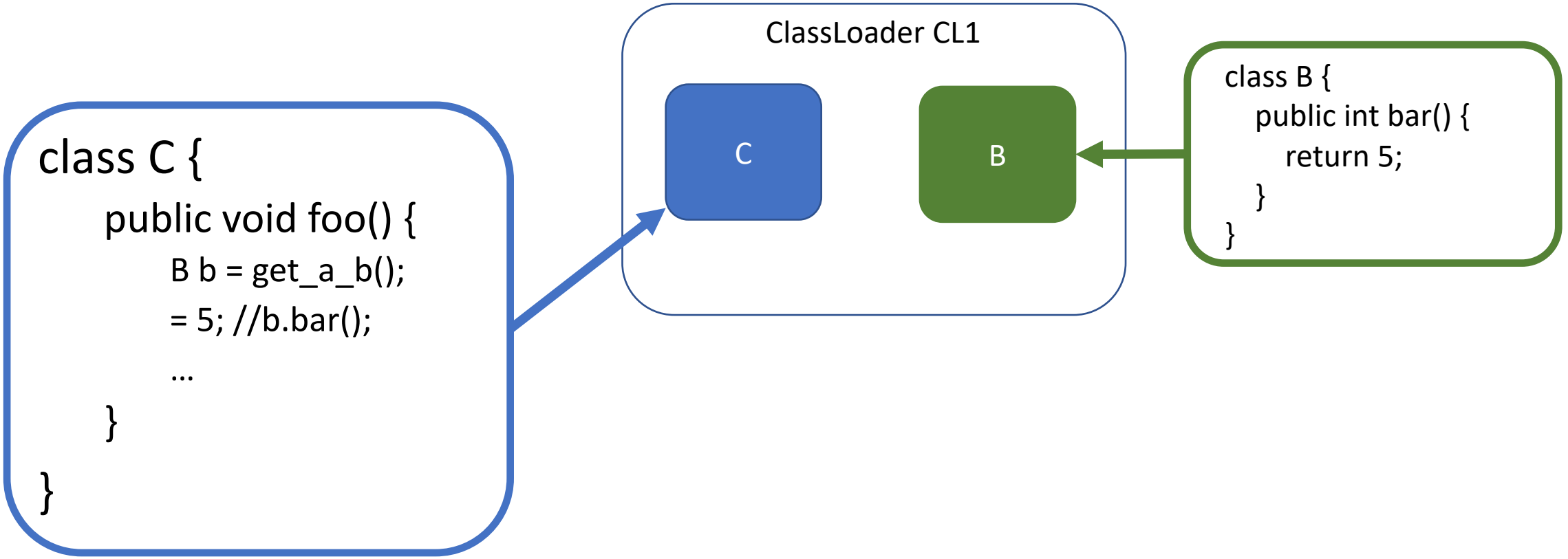
# Imagine two classes B,C: C.foo() calls B.bar() Simple opportunity to inline call to b.bar()?

# Imagine two classes B,C: C.foo() calls B.bar() Can now optimize C.foo() using ‘5’

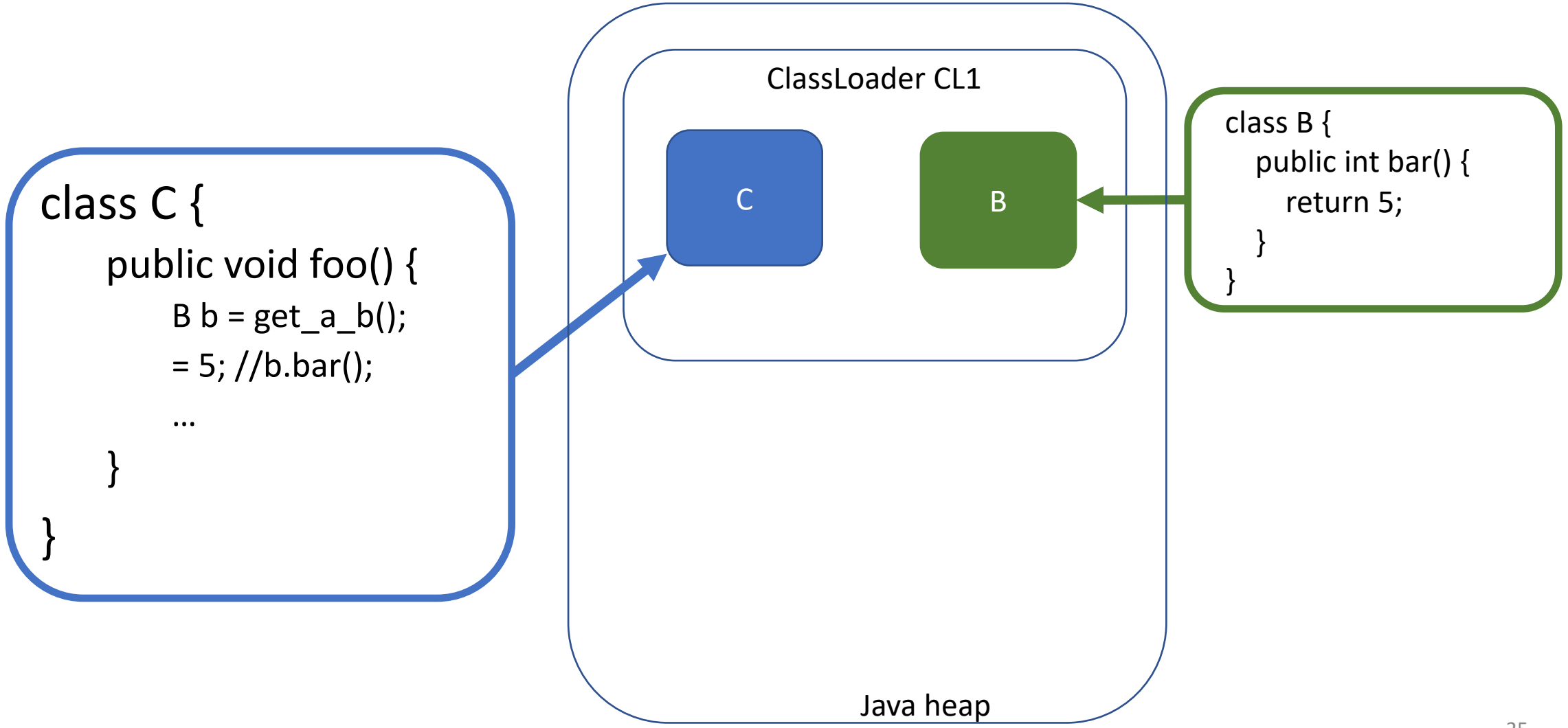
```
class C {
    public void foo() {
        B b = get_a_b();
        = 5; //b.bar();
        …
    }
}
```

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

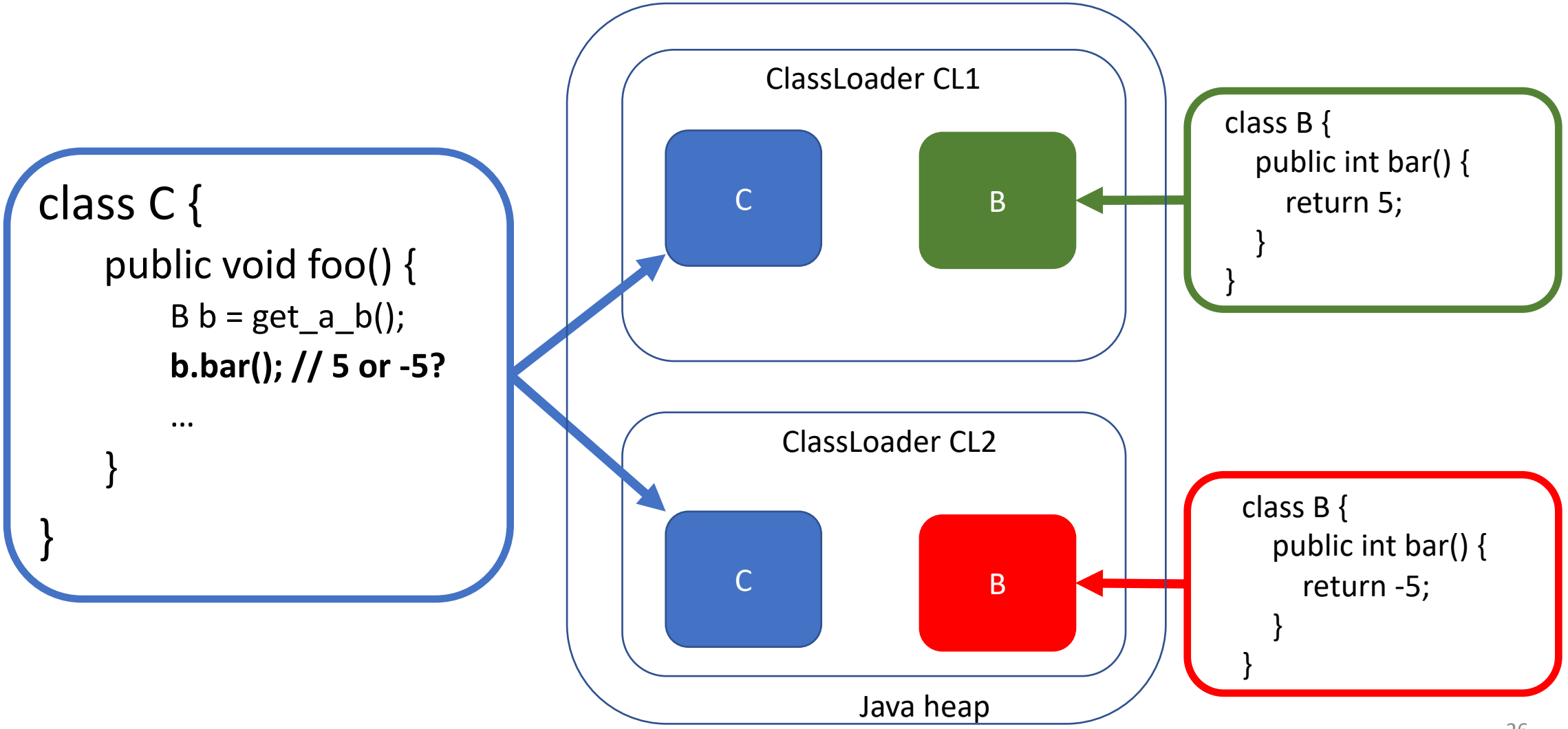
# But C's notion of B is decided by C's class loader



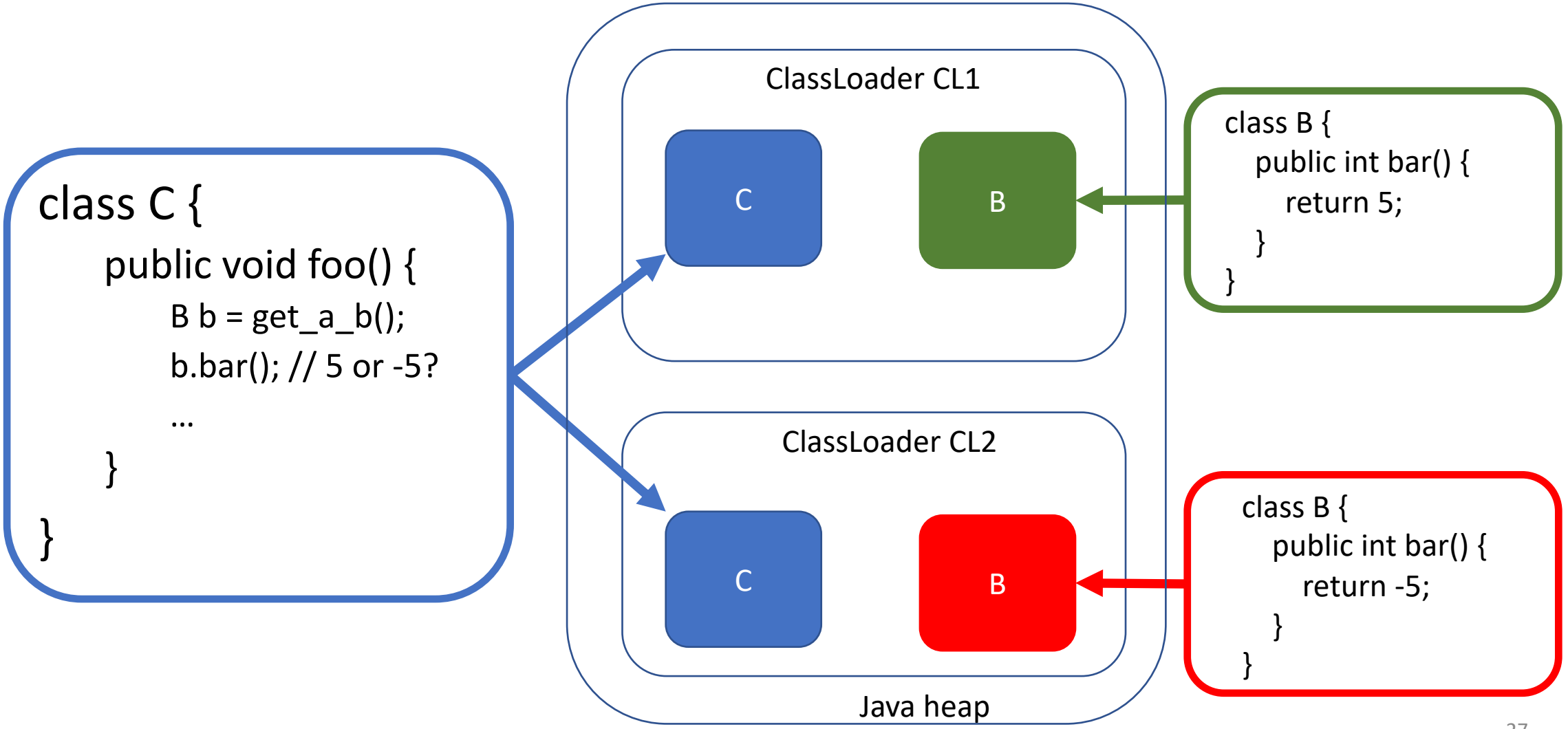
# C's ClassLoader is a Java object created on heap



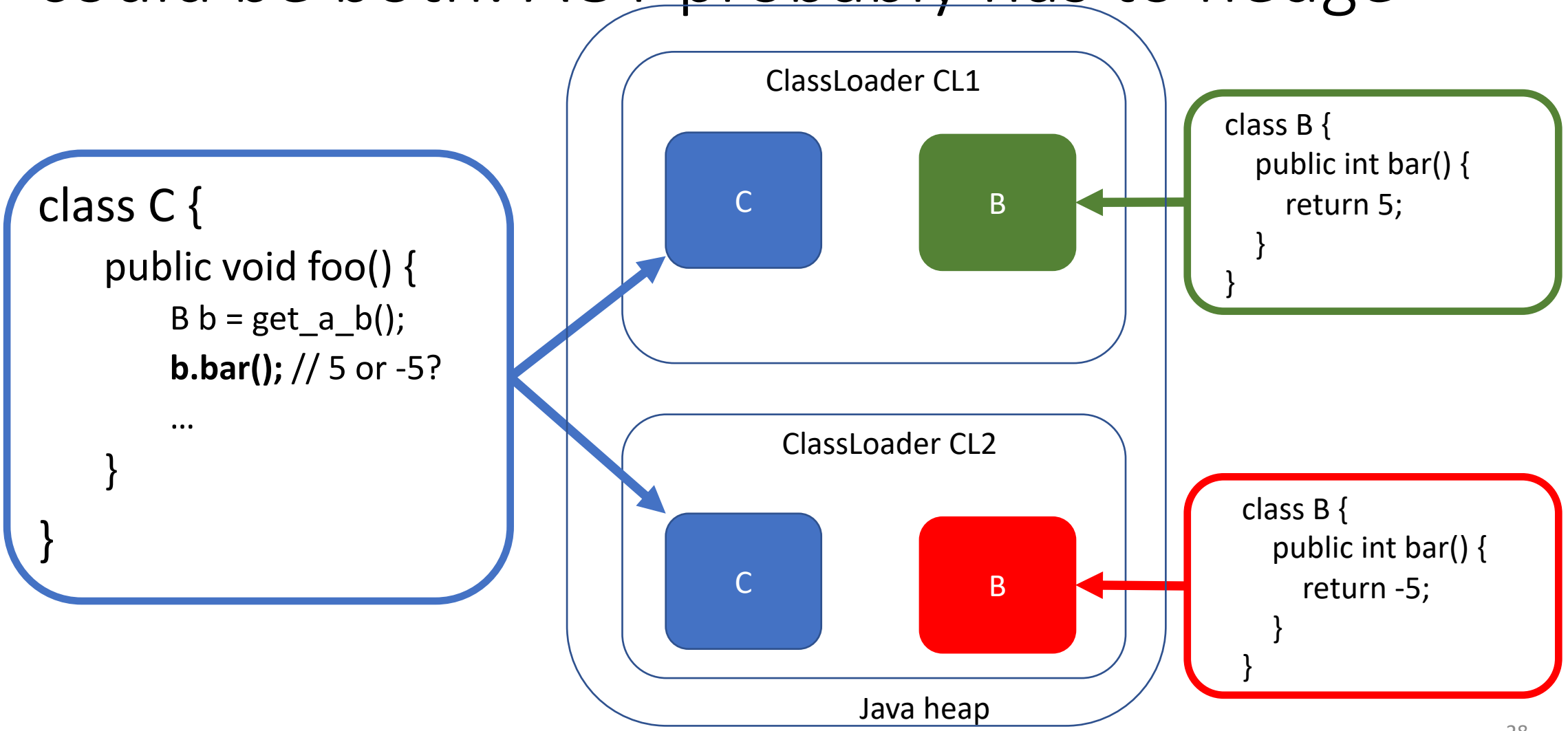
# Class loader objects can invalidate the inlining…



# … and C.foo() may be what resolves B !



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



# 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

# Strengths and Weaknesses

| | JIT | AOT |
|---|---|---|
| Code Performance (steady state) | | |
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| Platform neutral deployment | | |
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| Runtime: CPU & Memory | | |

# Strengths and Weaknesses

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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

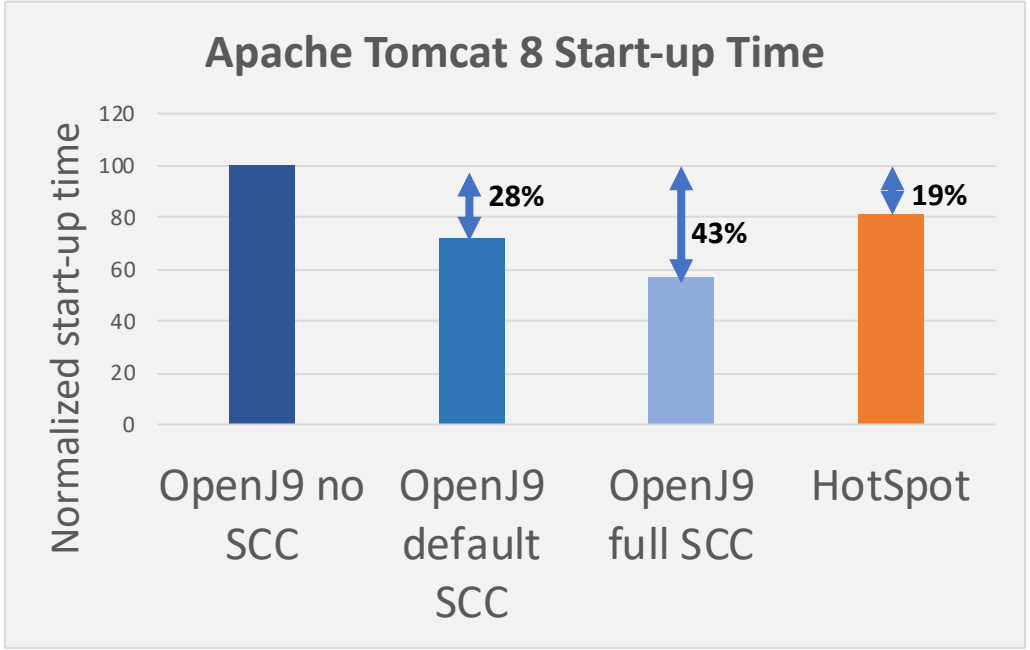
2. “Compile Stashing” in Azul’s proprietary Falcon JIT [2]
   - Introduced in 2018 for JDK8 and later
   - Stores compiled code to disk
   - Stashed code typically reuseable in another run for 60-80% of methods
   - JIT recompilations recover remaining performance
   - Resilient to application changes

[1] https://blog.openj9.org/2018/10/10/intro-to-ahead-of-time-compilation/
[2] 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

- SCC for JCL bootstrap classes enabled by default
- Use `-Xshareclasses` option for full sharing




* Technically an internal format that can load faster than a .class file

# Strengths and Weaknesses

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| Ramp up (until steady state) | | | | * |
| Runtime: CPU & Memory | | | | * |

* After first run

Still some “not green” boxes there

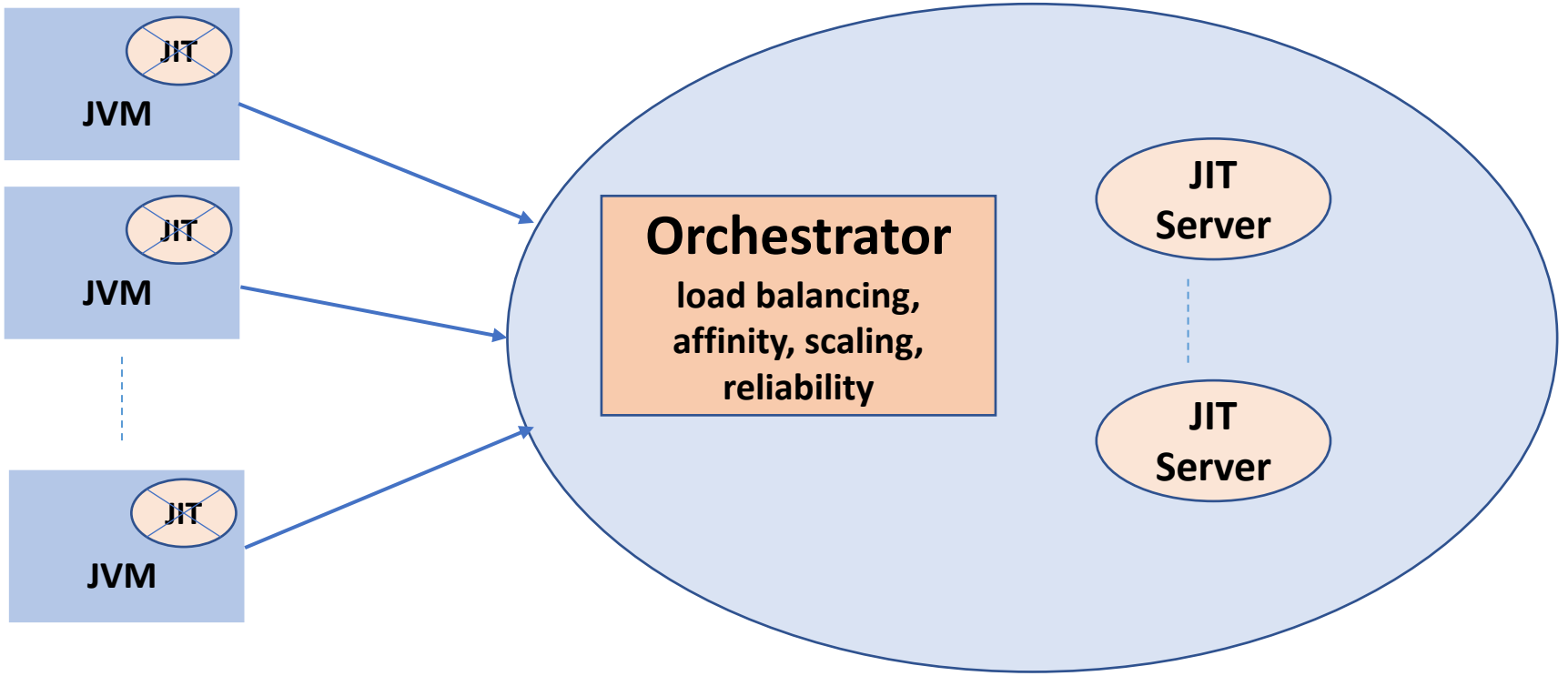
…even for caching JITs…

☹

# Outline

- Let’s compare:
  - JIT
  - AOT
  - Caching JIT code
- **Taking JITs to the cloud**
- Wrap Up

# What if the JIT became a JIT Server



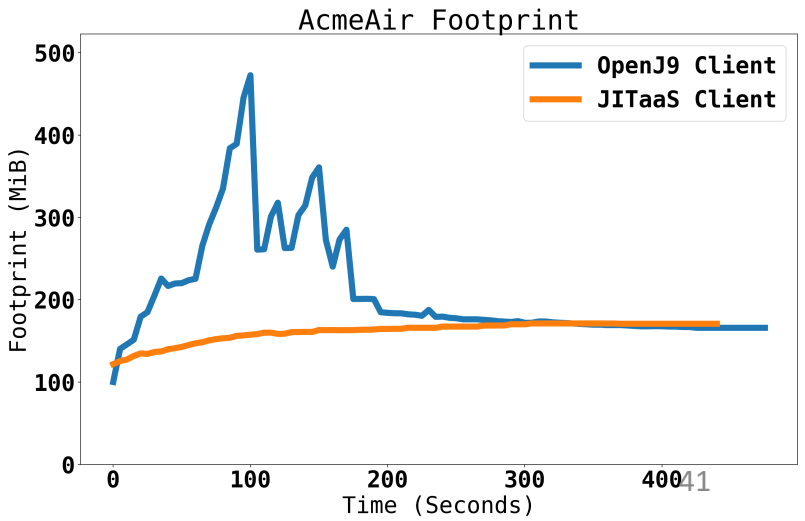

JVM client identifies methods to compile, but asks server to do the actual compilation

- 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

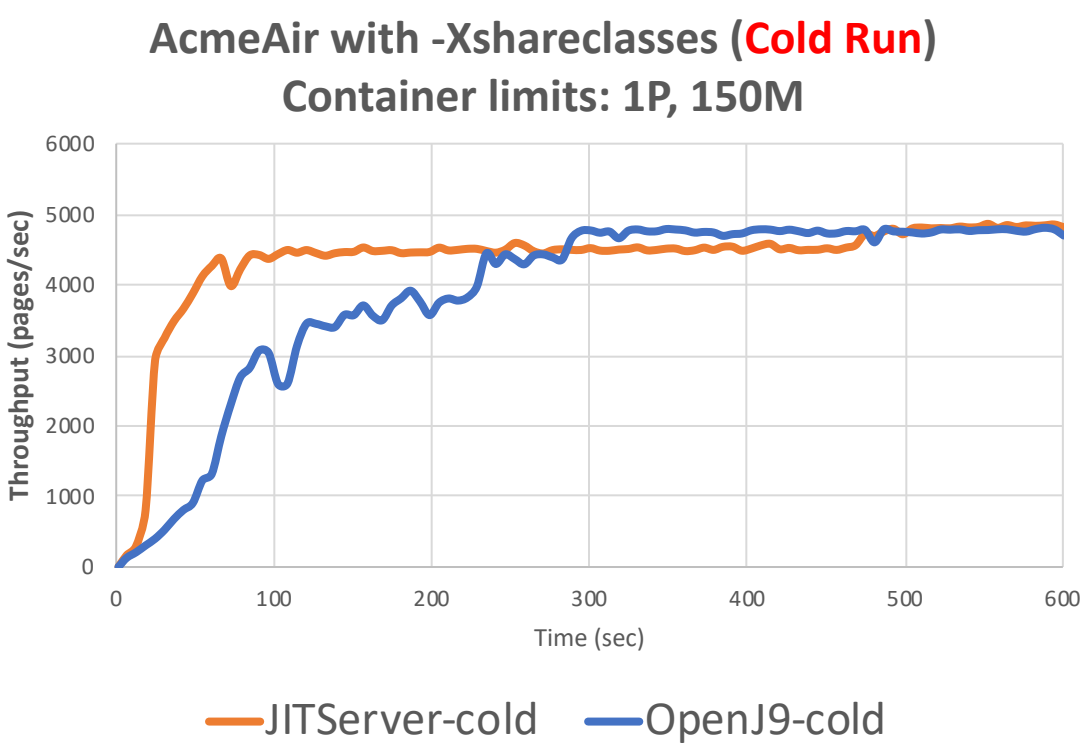
- Move much of JIT induced CPU and memory spikes away from client
  - Client CPU and memory consumption dictated by application

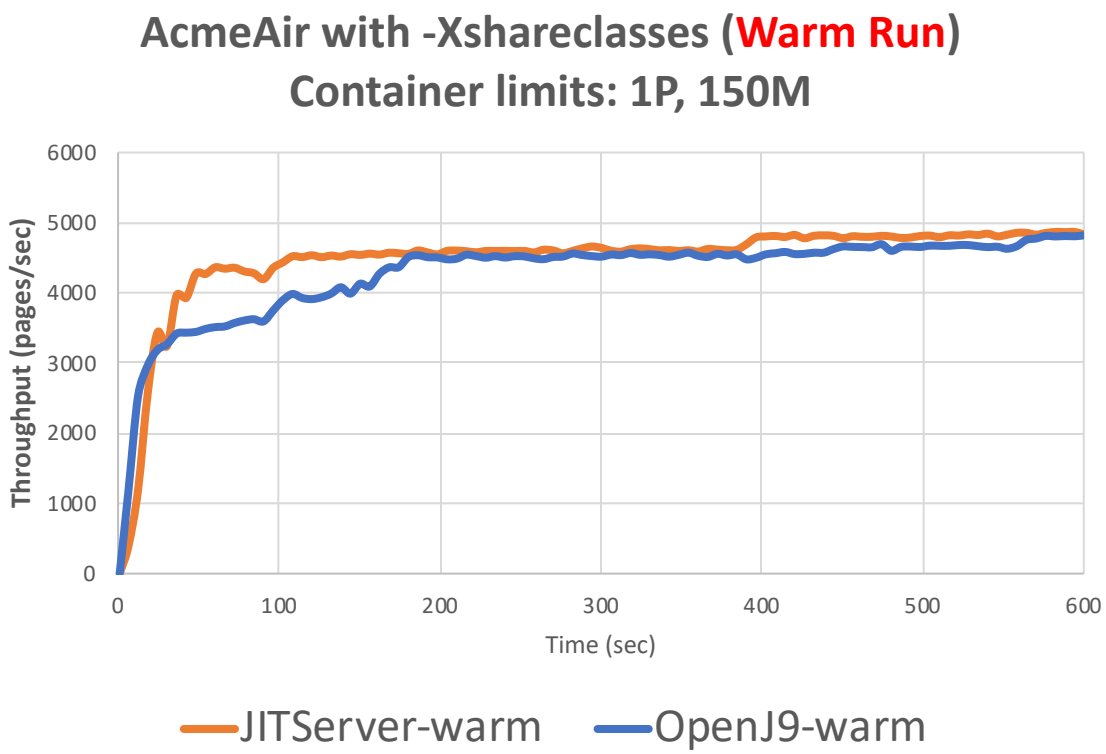
- JIT server connected to client JVM at runtime, so:
  - Theoretically no loss in performance using same profile and class hierarchy info
  - Still adaptable to changing conditions
  - JVM client still platform neutral



# Could that work?

# AcmeAir rampup with JIT Server using `-Xshareclasses`

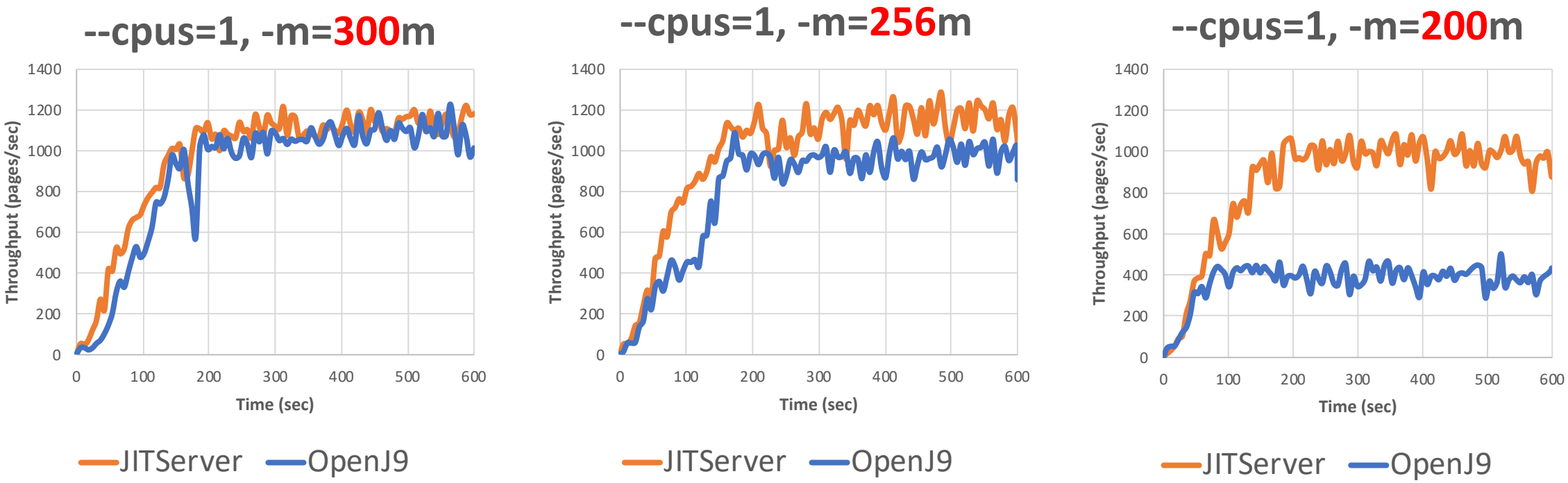



All JVMs run in containers, client and server on different machines with direct cable connection

**Note: Hotspot takes twice as long as OpenJ9 to ramp up to about the same performance level**

# JITServer Performance – Daytrader 7 Throughput




Smaller memory limit

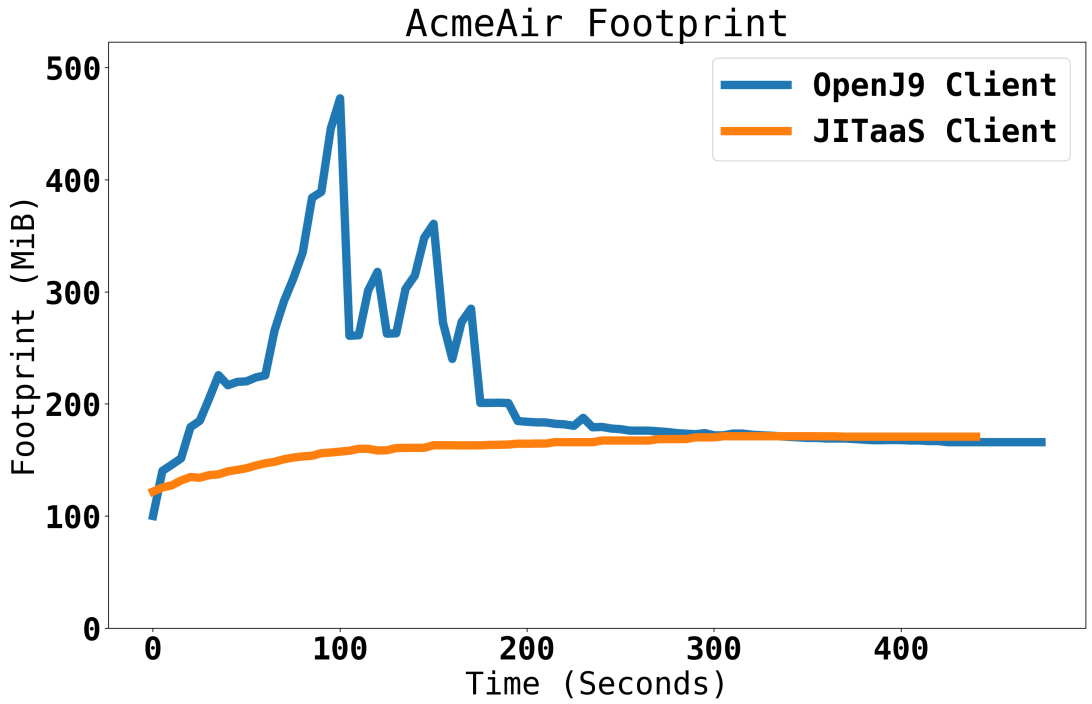
**Throughput benefits grow in constrained environments**

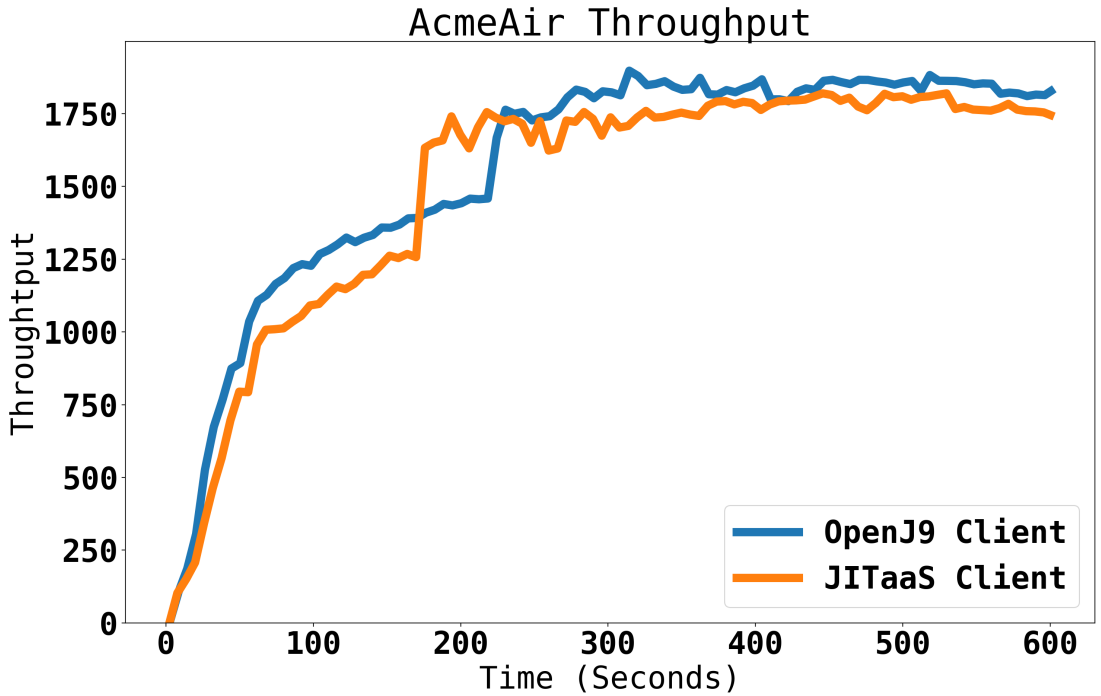
What about network latency?

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

# Strengths and Weaknesses

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| Ramp up (until steady state) | | | | * | ** |
| Runtime: CPU & Memory | | | | * | |

* 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

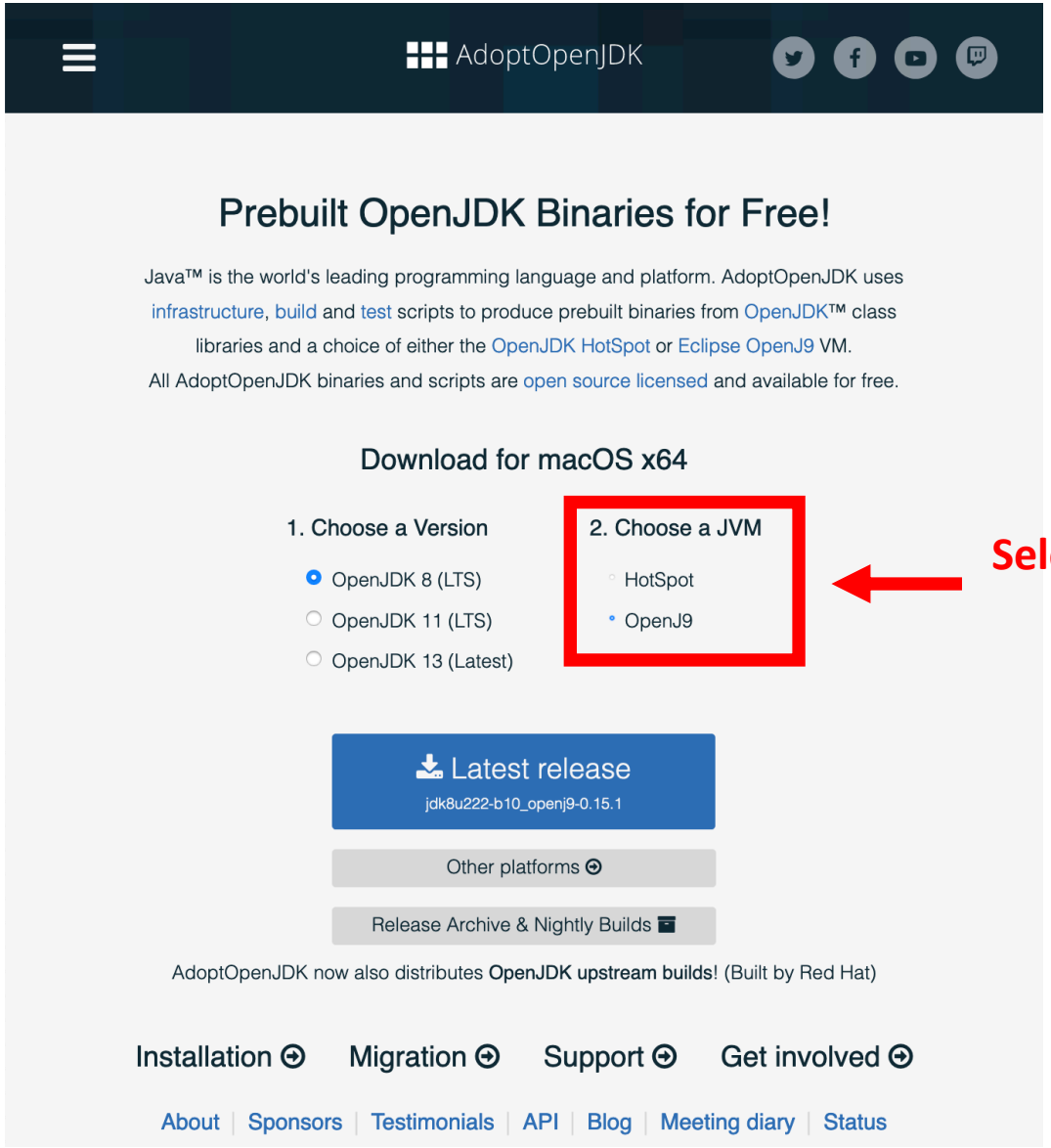
# We are really just at the beginning…

- 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!!**


Thank You
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Maake
Asante
Shukria
Dhanyavadagalu
Vinaka
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спасибо
Kiitos
Manana
Dankon
Suksama
Dank Je
Maururu
Biyan
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Dziekuje
Chokrane
Juspaxar
Arigato
Gracias
Grazie
Taiku
Diolch i Chi
Gratias Tibi
Terima Kasih
Najis Tuke
Matur Nuwun
감사합니다
धन्यवाद
cảm ơn bạn
Ua Tsaug Rau Koj
Bedankt
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Nirringrazzjak
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Di Ou Mèsi
Rahmat
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Hvala
Хвала
Danke
Merci
Go Raibh Maith Agat
Eskerrik Asko
Salamat
ขอขอบคุณคุณ
Tingki
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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