OpenJDK on Morello
Port Status and Initial Lessons

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with input from many other team members

Soteria & MOJO projects funded by UK DSbD programme

Spoiler Alert

- Most memory safe languages (e.g. Java, Javascript, Ruby, …) execute on managed runtime environments
- Managed runtime environments tend to be written in C/C++
  - JVMs are a key part of the Morello software ecosystem
- We have managed to port interpreted OpenJDK to Morello
  - Next steps are JIT & garbage collection
- Unlike other managed languages & runtimes (e.g. Javascript), the Java APIs expose longs as pointers
- Porting to Morello requires modifications to core Java classes as well JVM internals

Java Virtual Machine (JVM)

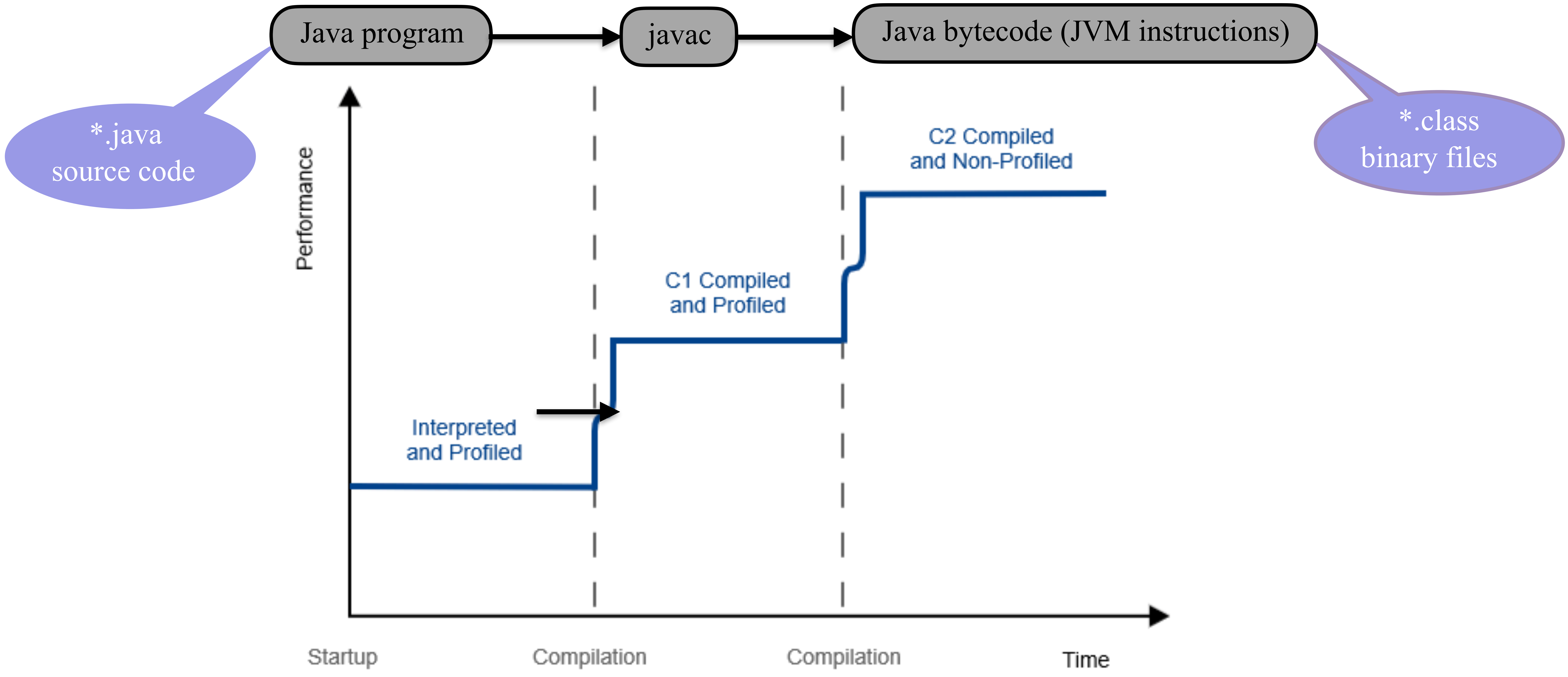
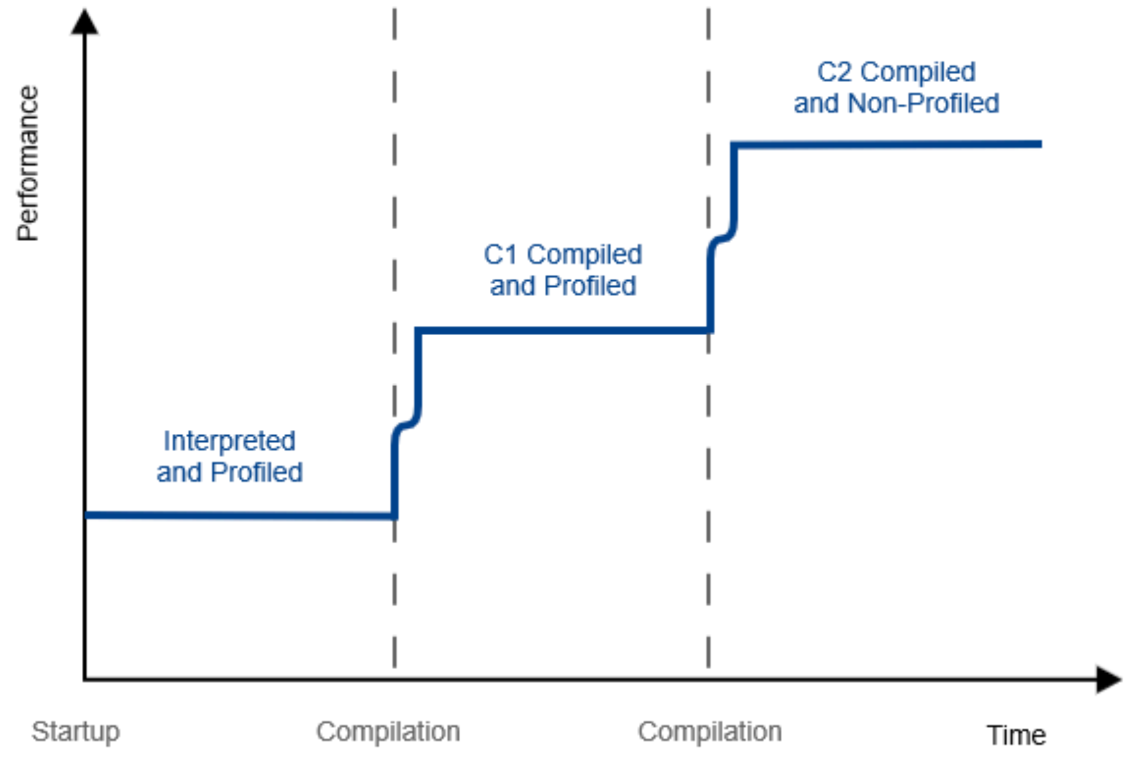
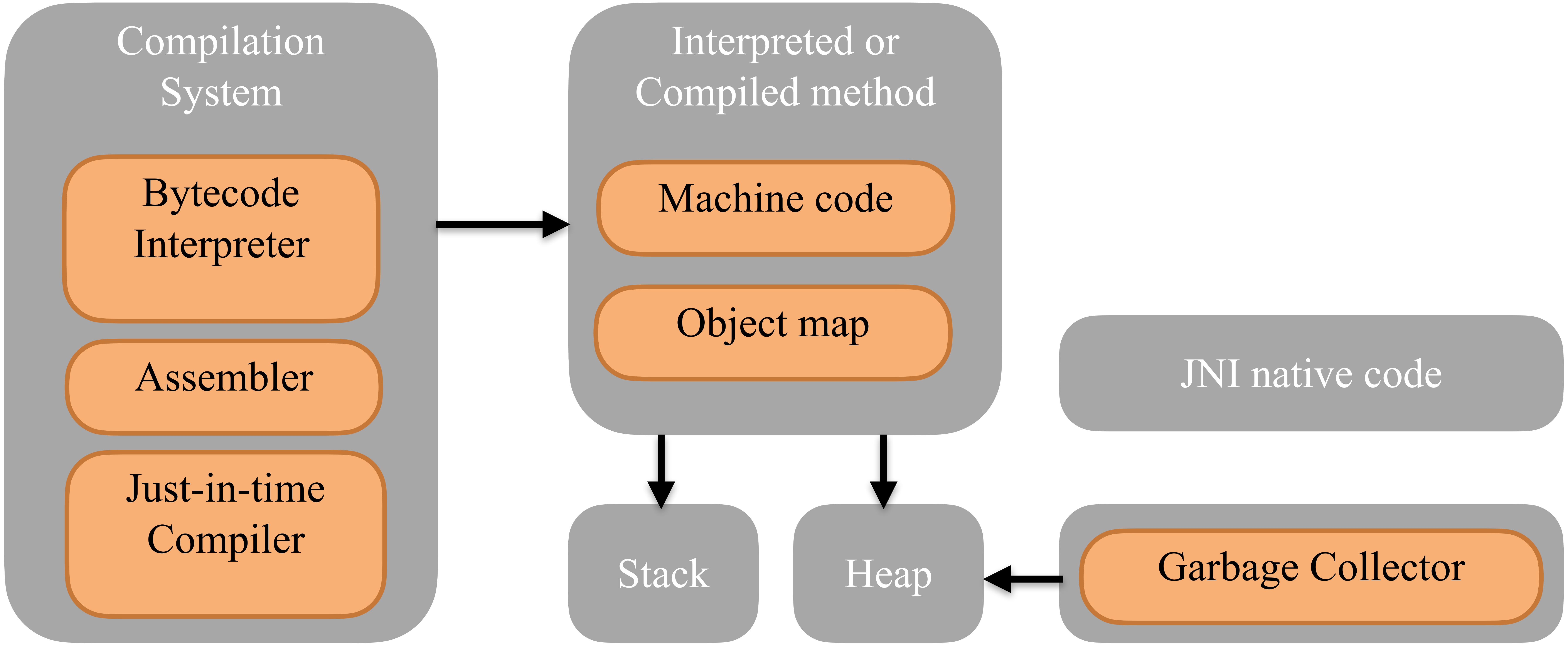


Image source https://www.baeldung.com/wp-content/uploads/2021/07/1.png

JVM Internals: >1.2M LOC

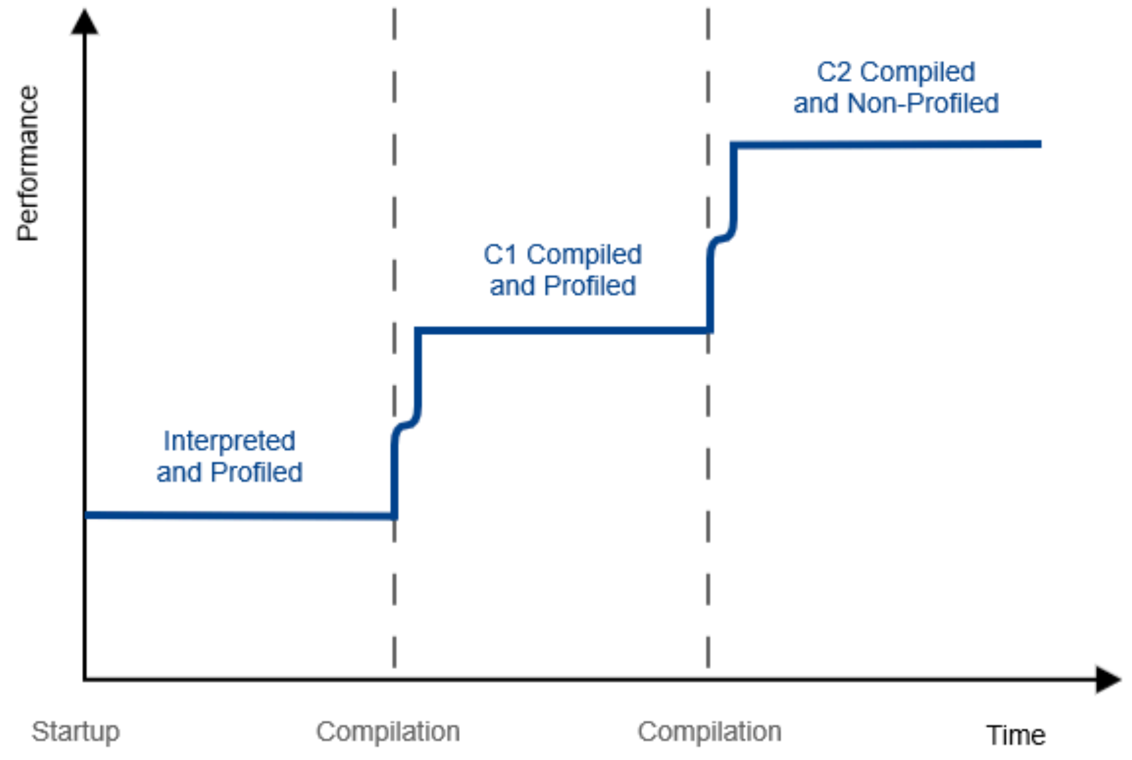


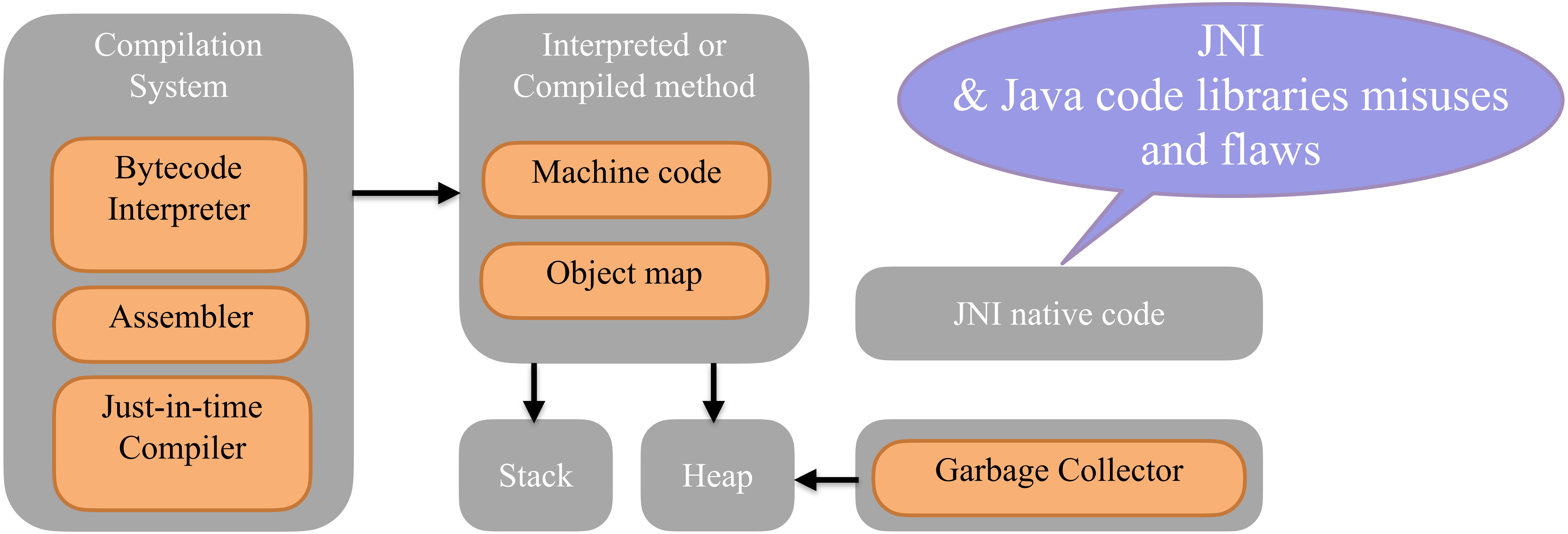


Roadmap for the talk

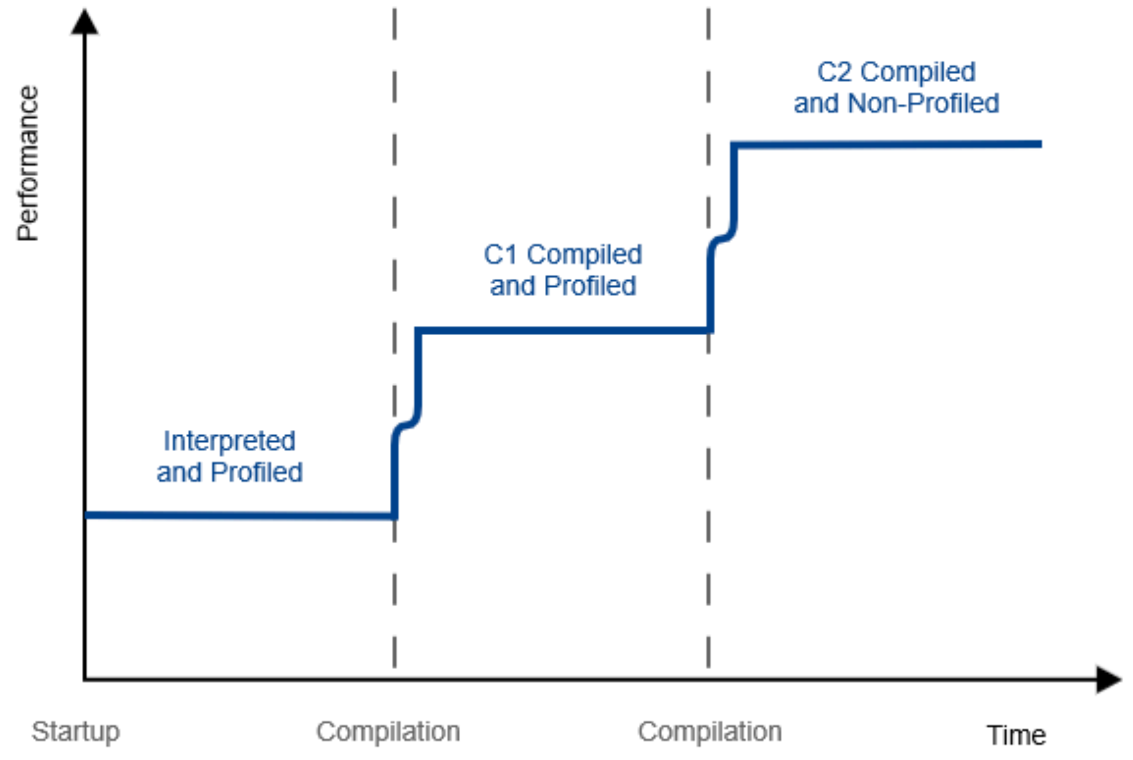
- Overview of attacks & exploits on Java/JVMs
- JVM porting strategy to Morello
- **Preliminary** Performance Results
- Status/development plans for JVM ports
- Future Work/Questions

Threat Model Guided By CVEs

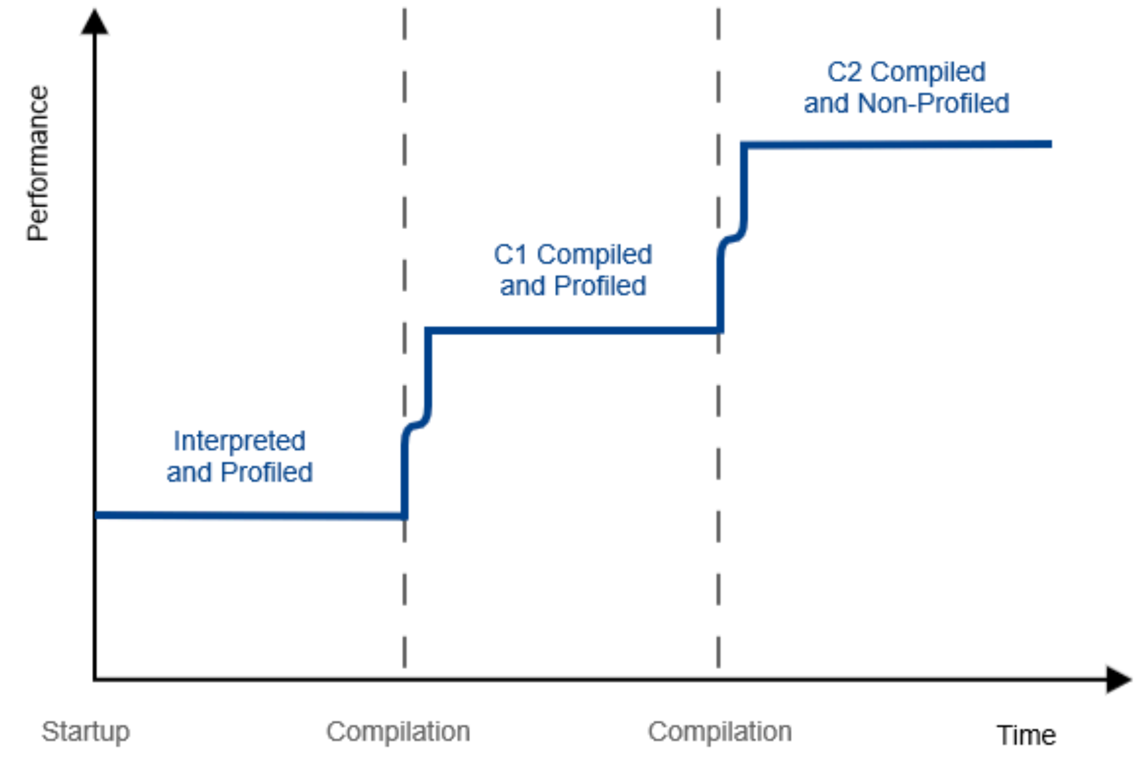




Threat Model Guided By CVEs



Threat Model Guided By CVEs



Malformed inputs *.class and program inputs target

JVM internals
- Class Loading
- Type checking
- Object de/serialisation

Compilation System
- Bytecode Interpreter
- Assembler
- Just-in-time Compiler

Interpreted or Compiled method
- Machine code
- Object map

Stack

Heap

JNI native code

Garbage Collector

Threat Model Guided By CVEs

- JNI/Java code libraries misuse/flaws
  - Especially that related to XML/JSON processing
- JVM internals
  - JIT compilation
  - ClassLoading/type verification
  - Object serialization/deserialization

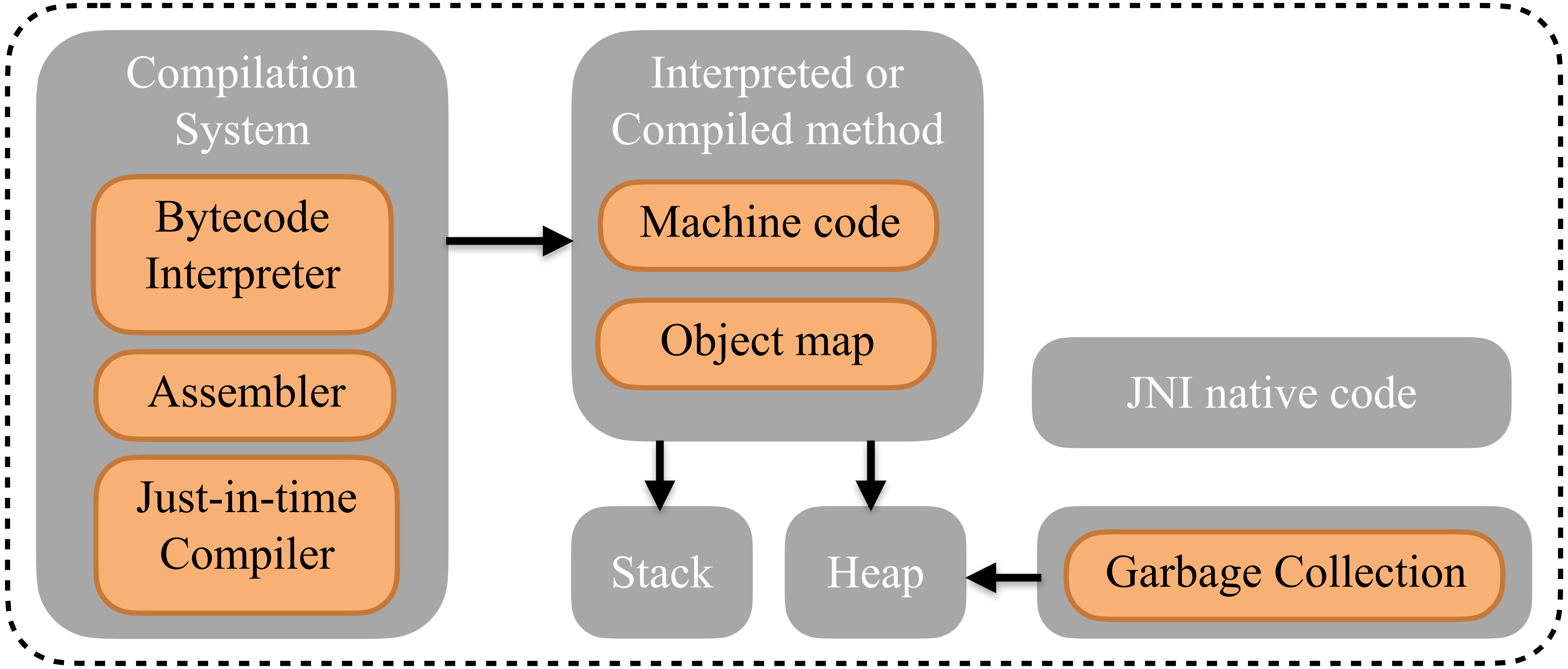
Outline of JIT Compilation Threats

- **Long history of attacks on JavaScript**
  - **JIT is disabled** Microsoft Edge security & iOS16 Lockdown modes
- Code is injected via JIT/heap spraying
- Control flow is directed into JIT-ted code at an altered PC
  - Altering the PC delivers a different instruction sequence
  - One that can be used to construct malicious actions
  - Typically involves taking control of the execution stack
- Data only attacks corrupting a JIT’s intermediate representation
  - Cause malicious code to be “legally” generated

Protecting the JVM with Capabilities

Options & stages in protecting a JVM

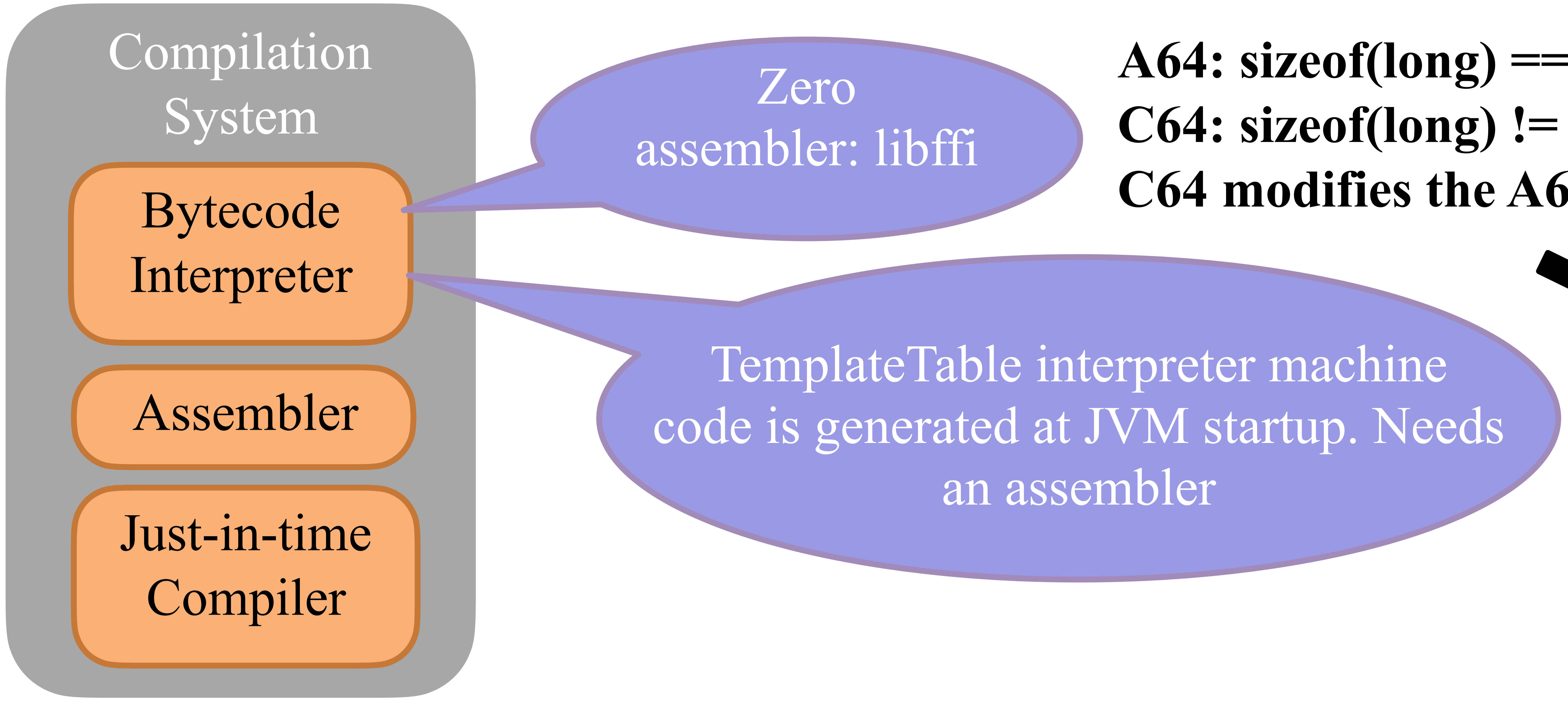
- Morello pure capabilities - referential & spatial memory safety for free
- Temporal safety - requires revoke/invalidate capabilities
- Compartments



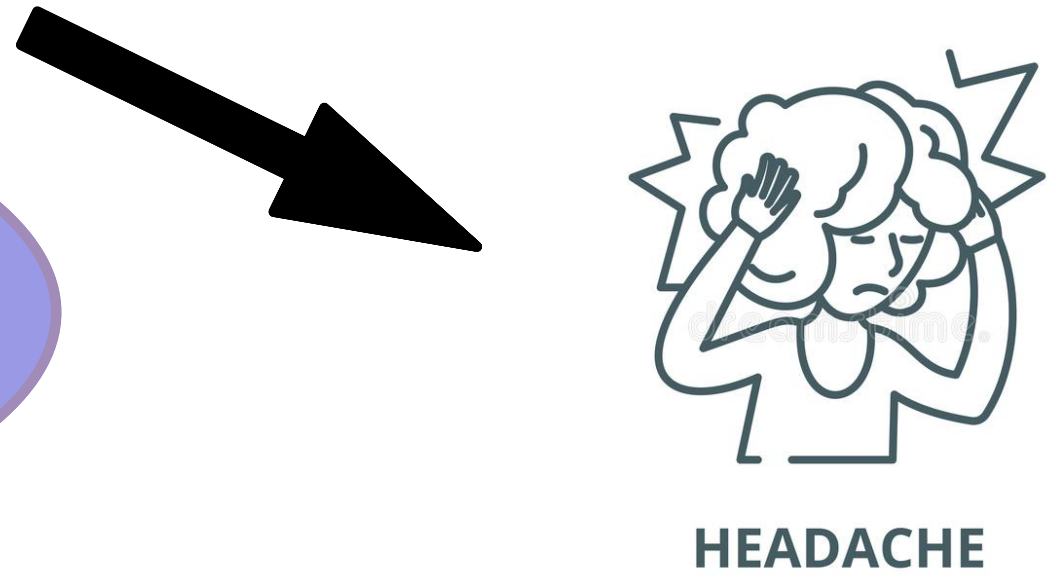
Porting a JVM to (Morello) a new CPU

Target spatial memory safety using pure capability C64 mode

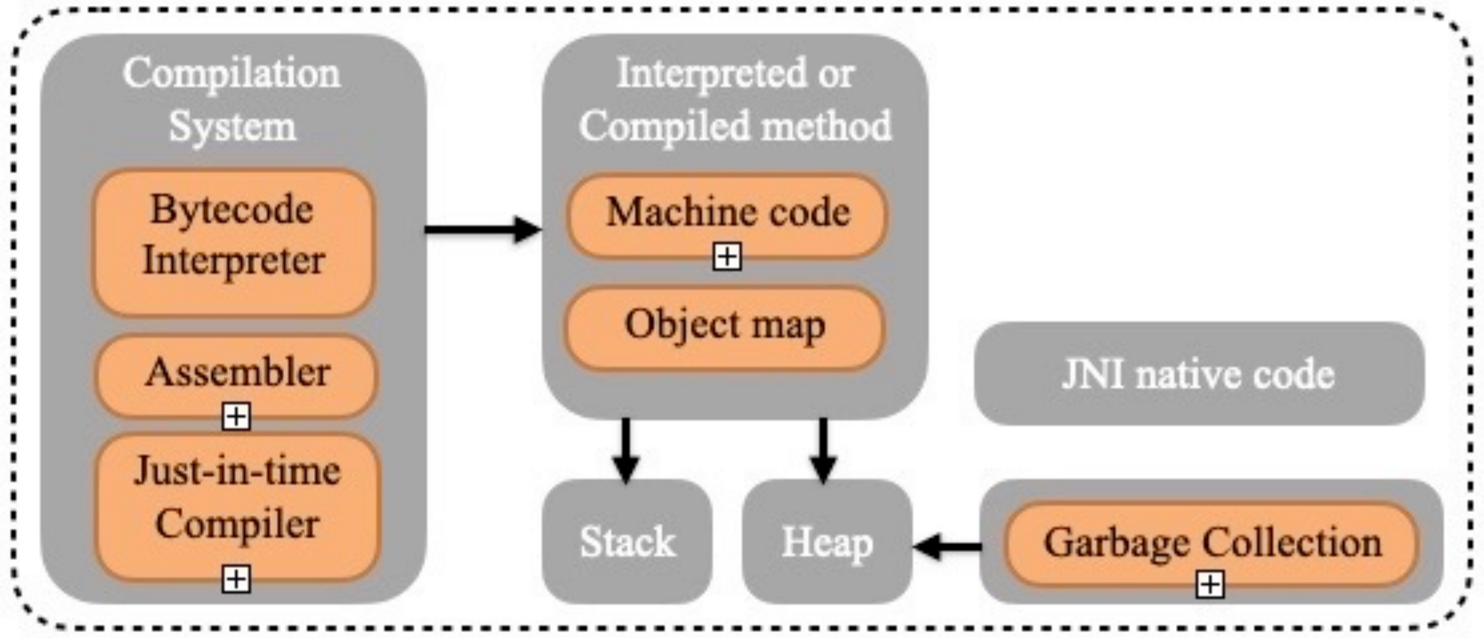
- Interpreter, then GC, then JIT
- Morello has **A64** and **C64 purecap** execution modes
- C64: object layout changes, longs cannot represent addresses



A64: sizeof(long) == sizeof(void*)
C64: sizeof(long) != sizeof(void*)
C64 modifies the A64 ISA



Zero Assembler Interpreter



Entire JVM runs in purecap C64

- Fixed JVM assumptions
- Java API issues with longs
- Spatial memory protection

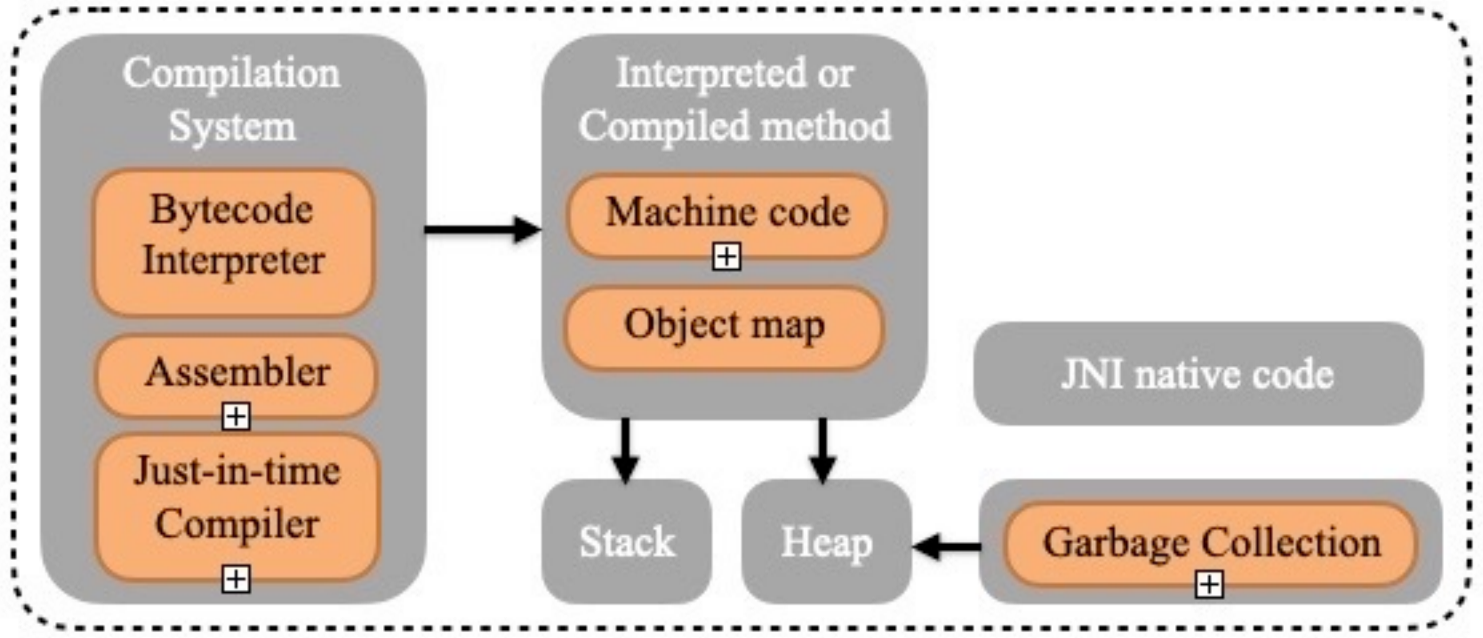
Zero Assembler Bytecode Interpreter

Broke object layout

Machine code address fields/arguments in Java API must use capabilities

EpsilonGC no GC

TemplateInterpreter



Faster and enables profiling to trigger JIT compilation

JVM code runs in A64

- Generates interpreter's instructions
- Tests interpreter usage of C64 ISA
- Manages A64/C64 transitions

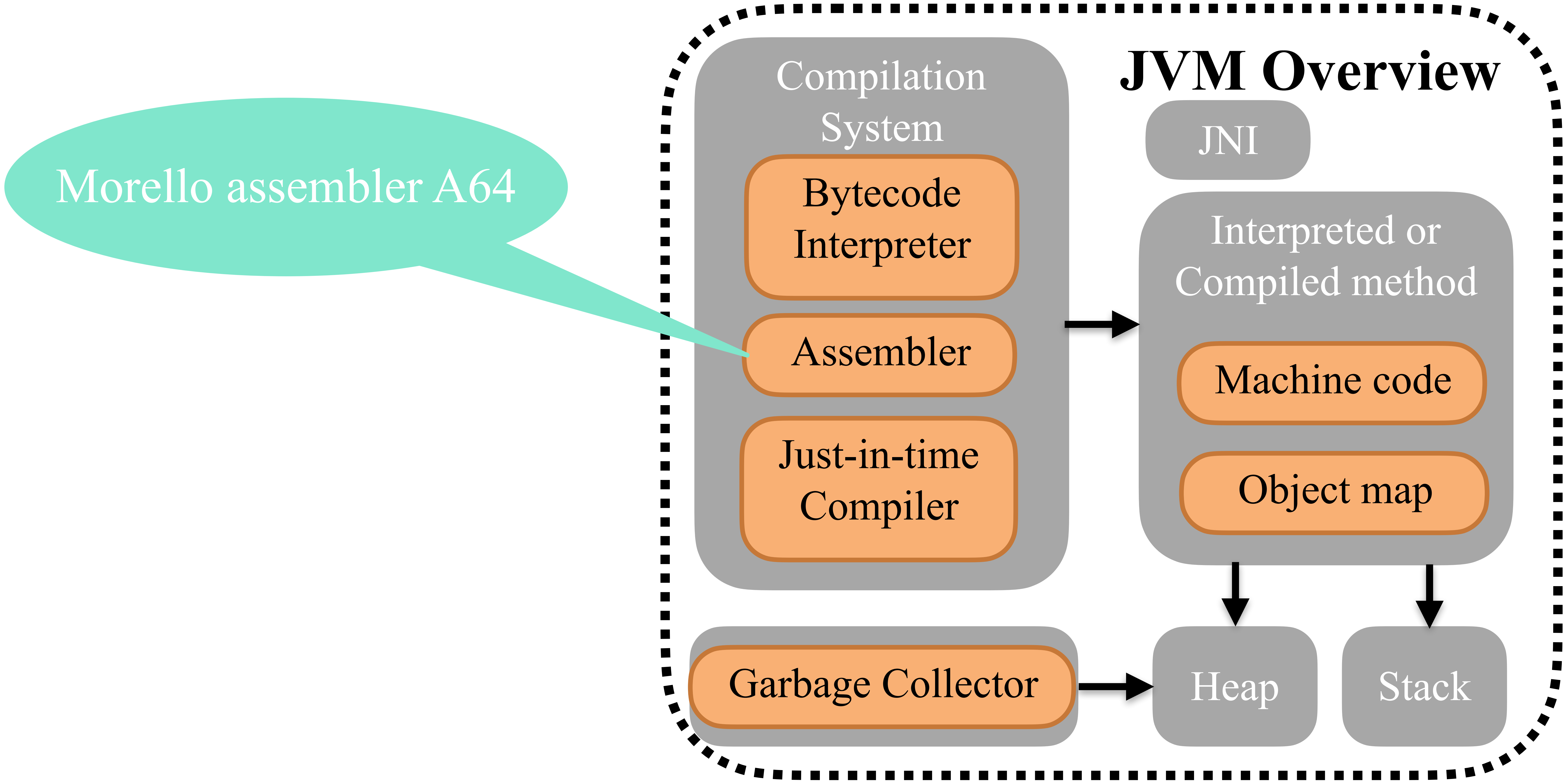
Morello Assembler (A64)

TemplateTable Bytecode Interpreter machine code (C64)

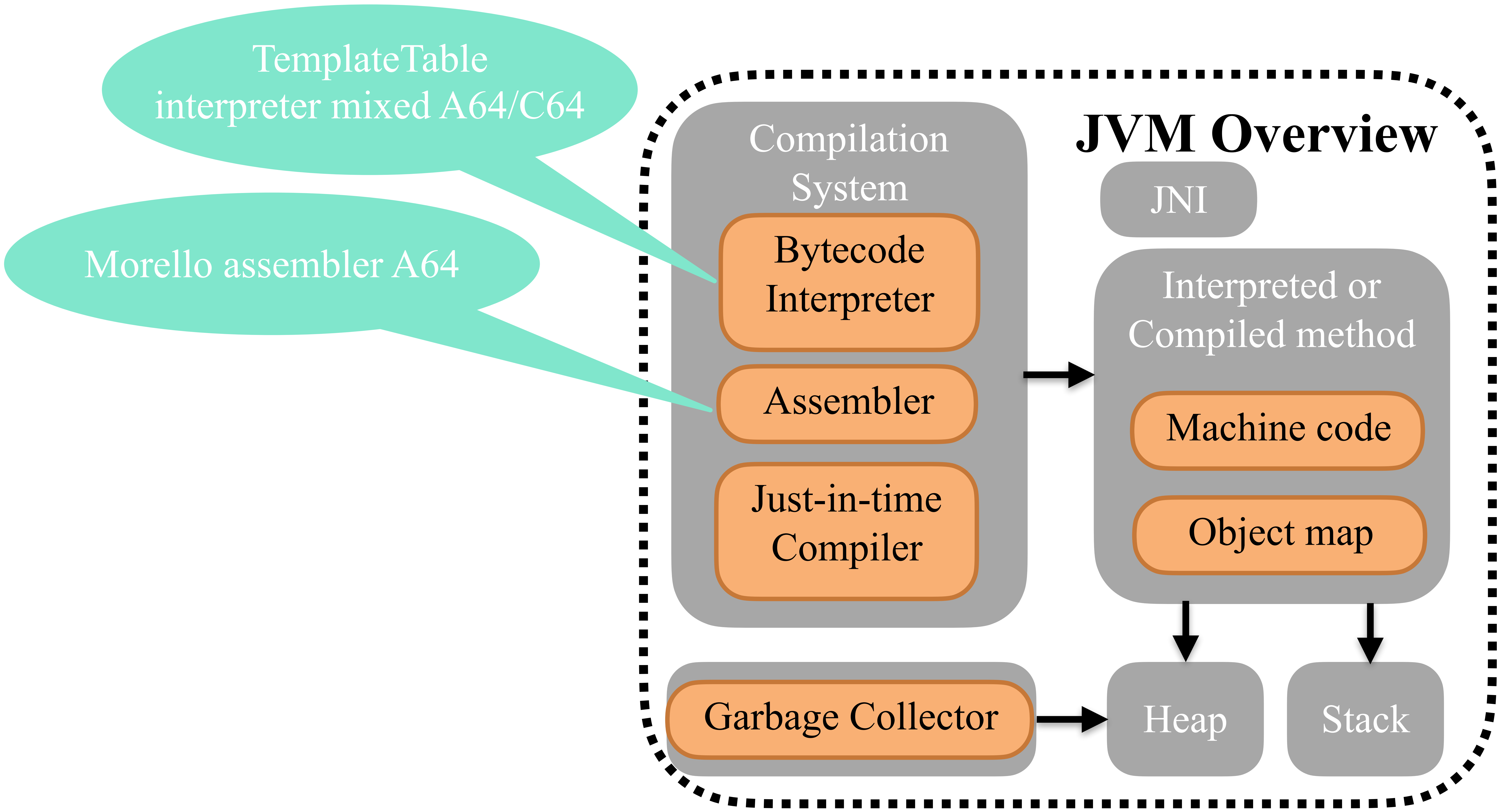
Limited spatial protection until it becomes fully purecap

JIT compilation can be added

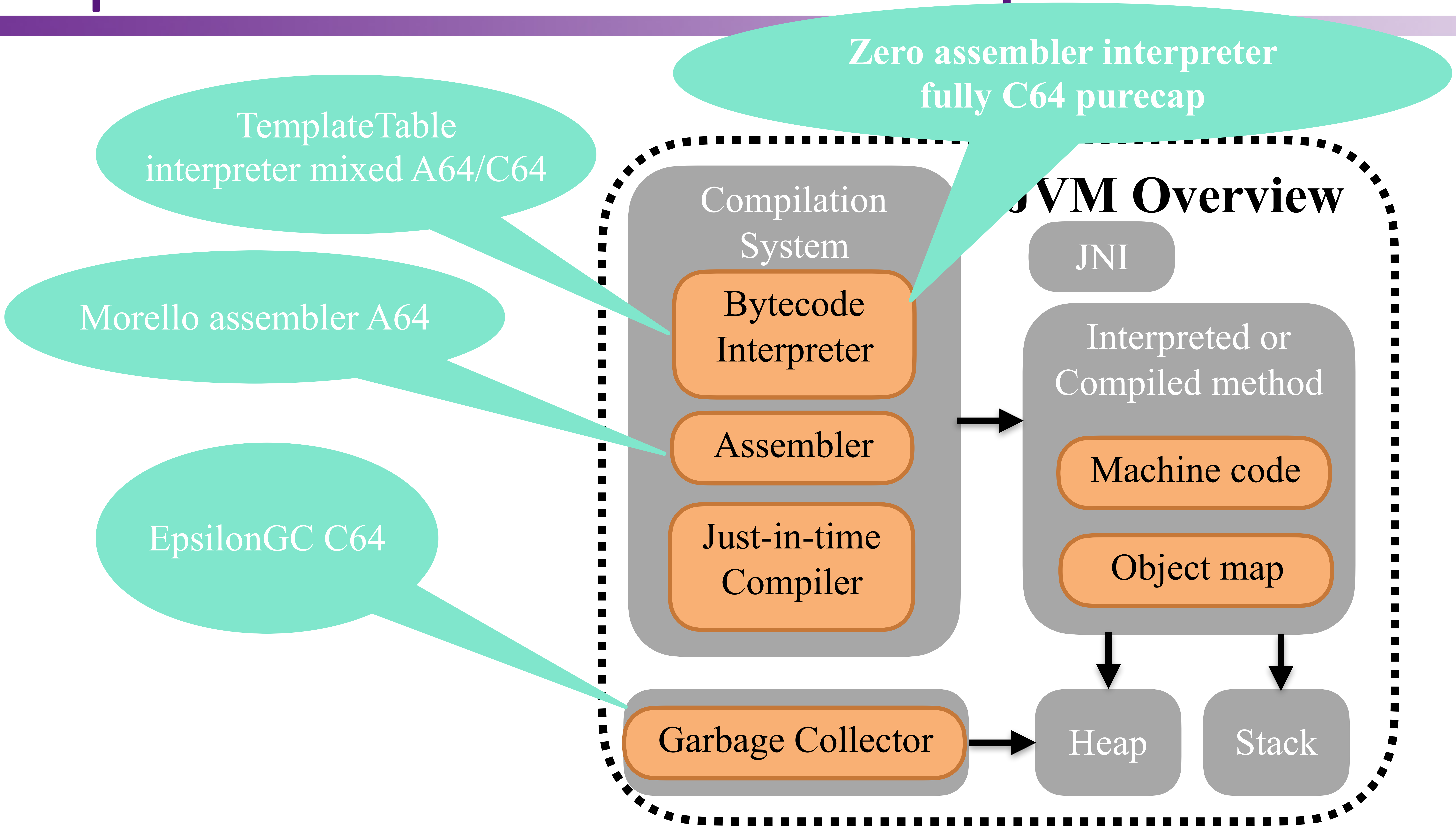
OpenJDK17 Initial Port Steps & Status



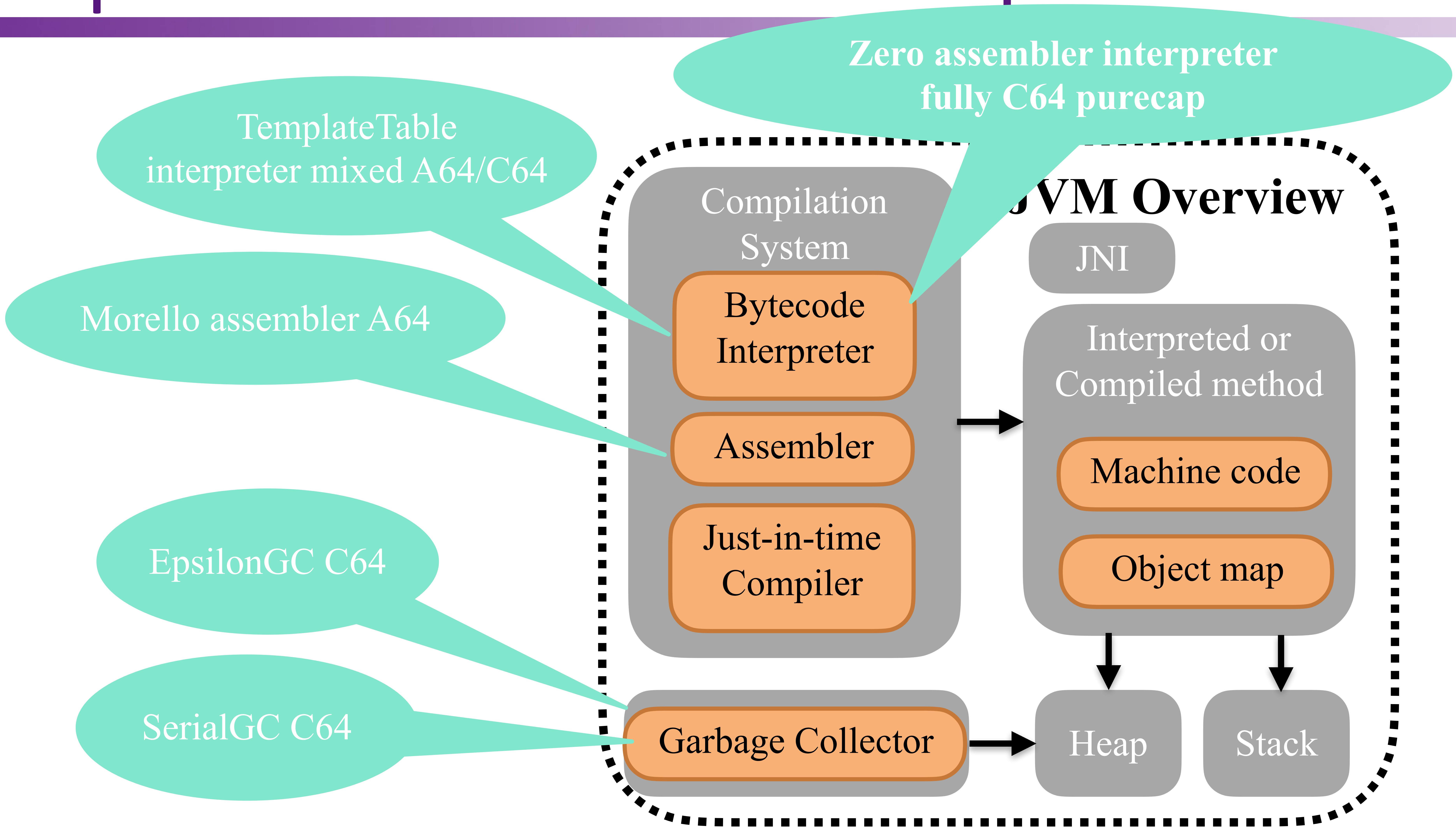
OpenJDK17 Initial Port Steps & Status



OpenJDK17 Initial Port Steps & Status



OpenJDK17 Initial Port Steps & Status



Preliminary JDK17 SciMark Composite Results

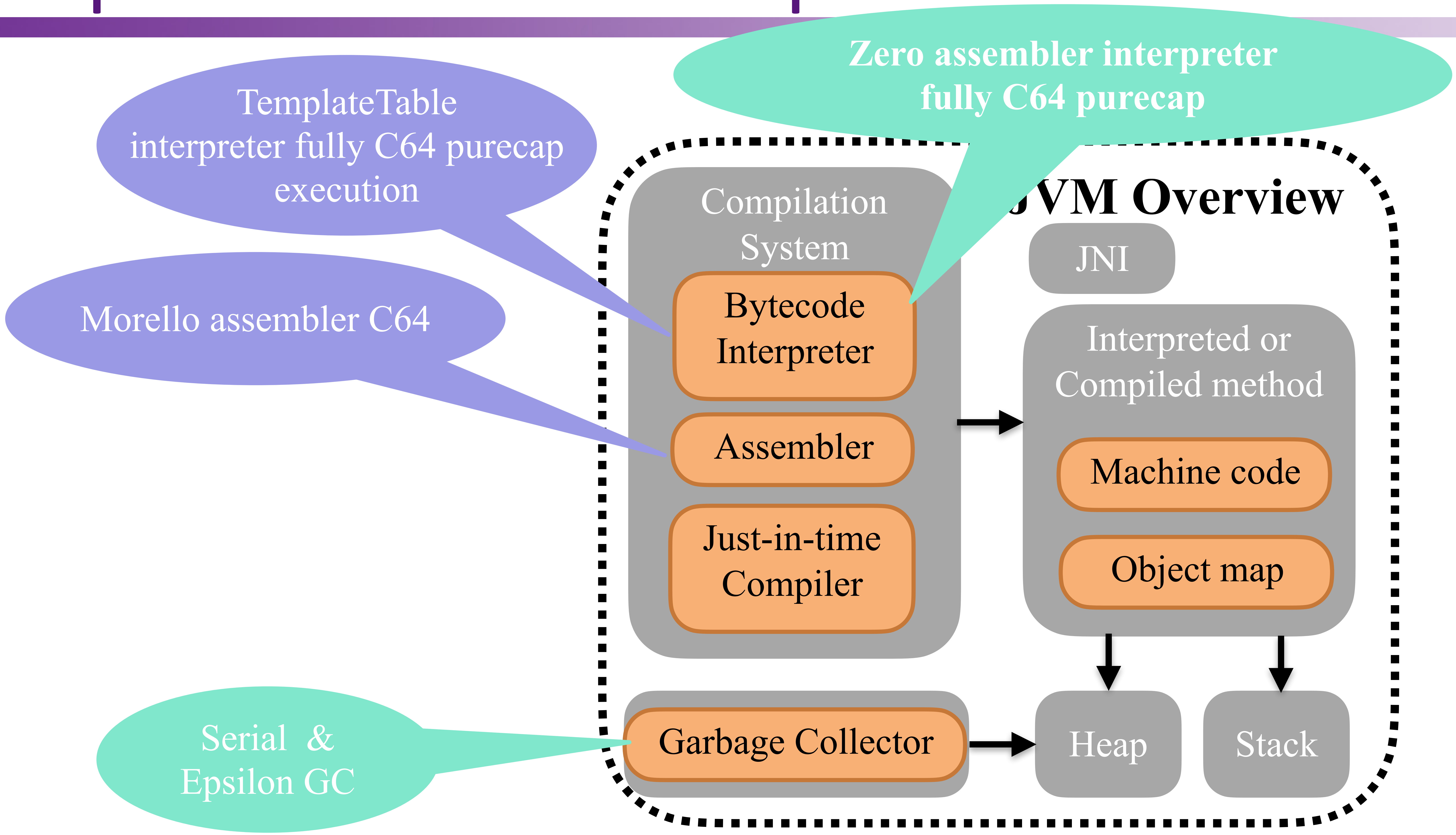
Preliminary means performance has not been optimised, and thus results are expected to be worst case

- Zero purecap assembler interpreter performance is 50% of the equivalent AArch64 JVM
- Template interpreter hybrid A64/C64 is 13x faster than AArch64 Zero assembler interpreter
- Template interpreter AArch64 is 20x faster than the AArch64 Zero assembler interpreter
- Template interpreter hybrid A64/C64 performance is 66% of the equivalent AArch64 JVM

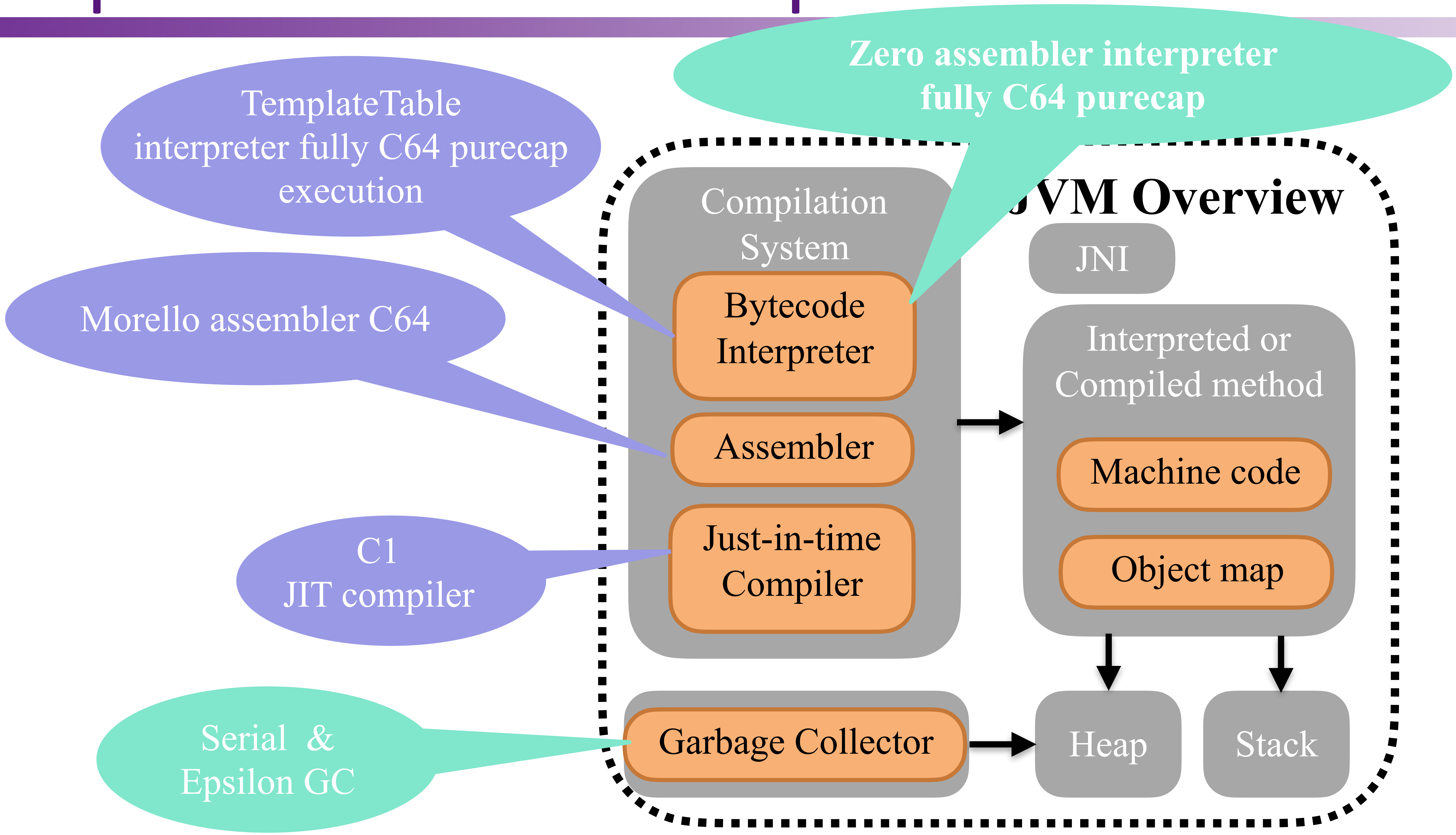
Recap: OpenJDK Port

- Significant effort to get here
- Preliminary relative performance of AArch64 vs. Morello
- Demonstrated benefits of the templateInterpreter
- SciMark benchmark - subset of SpecJVM

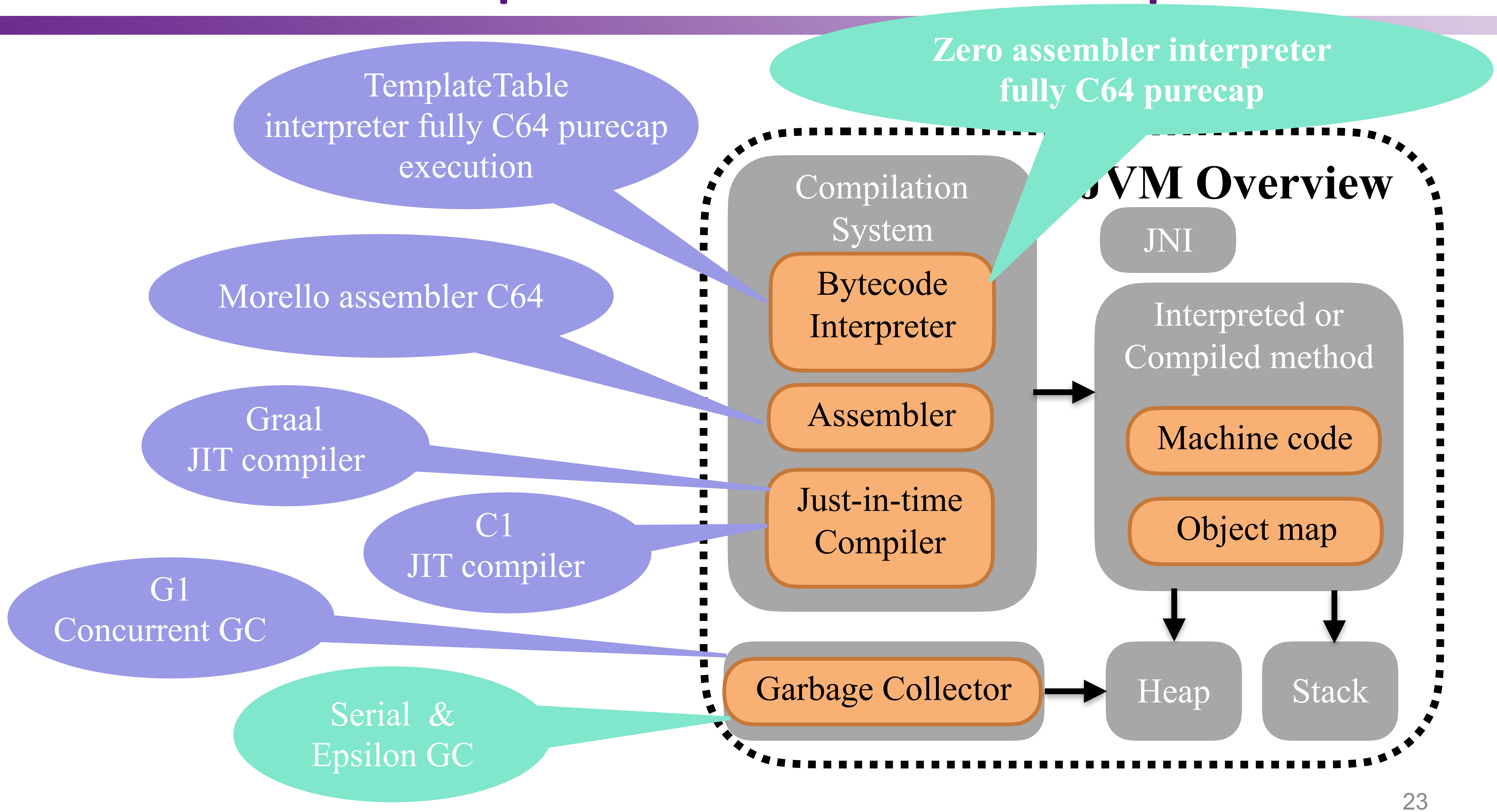
OpenJDK17 Next Steps



OpenJDK17 Next Steps



MOJO: OpenJDK17 Next Steps



Takeaways for Porting Managed Languages

- Problems if managed language does not encapsulate machine code addresses (Java longs in API core classes)
- Hybrid A64/C64 execution needs detailed knowledge of codebase
- Moving to C64 execution can "break everything"
  - Object layout changes, field offset calculations
  - C64 code pointers have LSB set (problems in assembly stubs)
    - Usage of LSBs for VM housekeeping potentially problematic
  - Necessary to port in incremental steps
    - Make individual VM components C64 aware
    - Use capabilities derived from the A64 default-data capability

Ongoing/Future Work

- Improving OpenJDK port functionality/usage of capabilities
  - Supporting Guest languages JavaScript/Python on Java
- Improving security
  - Fine-grained constraints for base/limit of capabilities
  - Temporal safety
  - Compartmentalization models/APIs JNI/JIT compilers …
- Evaluate threat weaknesses in JVMs
  - Exploit attack injection techniques for specific classes using modified JVMs

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Soteria & MOJO team

Soteria & MOJO projects: much more than just OpenJDK

Andy Nisbet, Tim Hartley, Kunjian Song, David Jackson, Nikos Foutris, John Mawer, Guillermo Callaghan, Cosmic Gorgovan, Igor Wodiany, Lucas Cordeiro, Christos Kotselidis, Pierre Olivier, Giles Reger, Konstantin Korovin, Mikel Lujan: ***University of Manchester***

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Questions?