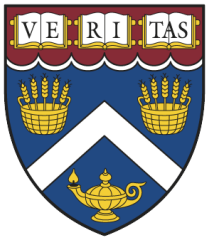
Virtual Machine Overview



Virtualization

- Indirection between application and platform
- We can virtualize at various levels
  - Single machine: virtual box, VMware Fusion
  - Infrastructure suite: AWS, vCloud
- We're interested in the application-level
  - The interface between the application and OS

Good old days

- Write code in C
- Run an optimizing compiler
  - May use cross-compilers to target other architectures
  - Complex make files and build infrastructure
- Link with static libraries
- Distribute the executable
- Link with runtime libraries

Why Virtualize?

- Separate the application from the platform
  - Target a single idealized architecture
  - Implement the architecture once per platform
- Bake in extra language features
  - Memory management
  - Type safety
  - Null and bounds checks
- Sandboxing
  - Don't give the application full access to the platform

Computer Architectures

- Complex Instruction Set Computer
  - Thousands of instructions
- Reduced Instruction Set Computer
  - Hundreds of instructions
- Idealized Bytecode Machine
  - Very small instruction sets
  - VM optimizes to make it run fast
- Direct source code
  - Complete compiler built into the VM

The Java Virtual Machine

- Bytecode-driven virtual machine
  - Based on a language designed for virtualization
- Extremely well-specified
  - Links to the various specs are on Canvas
- Current state of the art
  - Huge amounts of R&D effort over the years
  - Orders of magnitude improvement since early versions

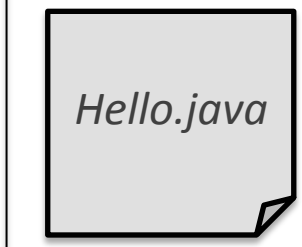
```java
package edu.harvard.cscie98.sample_code;

public class Hello {

  public static void main(final String[] args) {
    System.out.println("Hello World");
  }

}
```

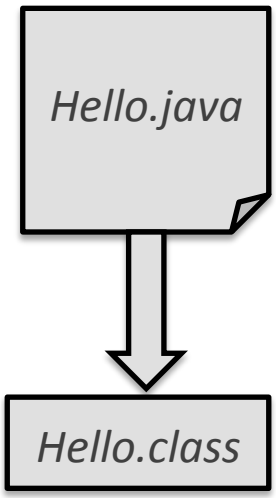
Bytecode Digression

- Compile the Hello.java class
- Inspect the bytecode
  - `javap -v Hello.class`
- See the terminal interaction PDF on Canvas
  - Published in the introduction module

Bytecode Digression

- Examine bytecode
  - Low complexity
    - Compare to i86 asssembly
  - Look at the contents of a single class
    - Constant pool
    - Fields
    - Methods
      - Max stack and locals
      - Bytecode
      - Line numbers
      - Variable table
      - Exception table


Hello.java

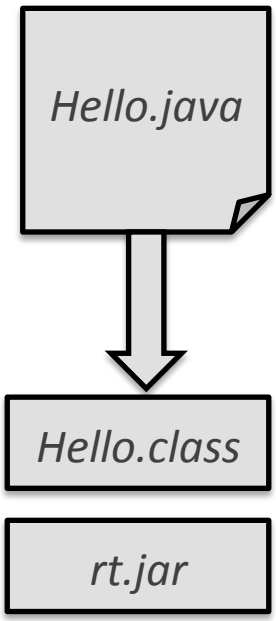

Hello.java
Hello.class

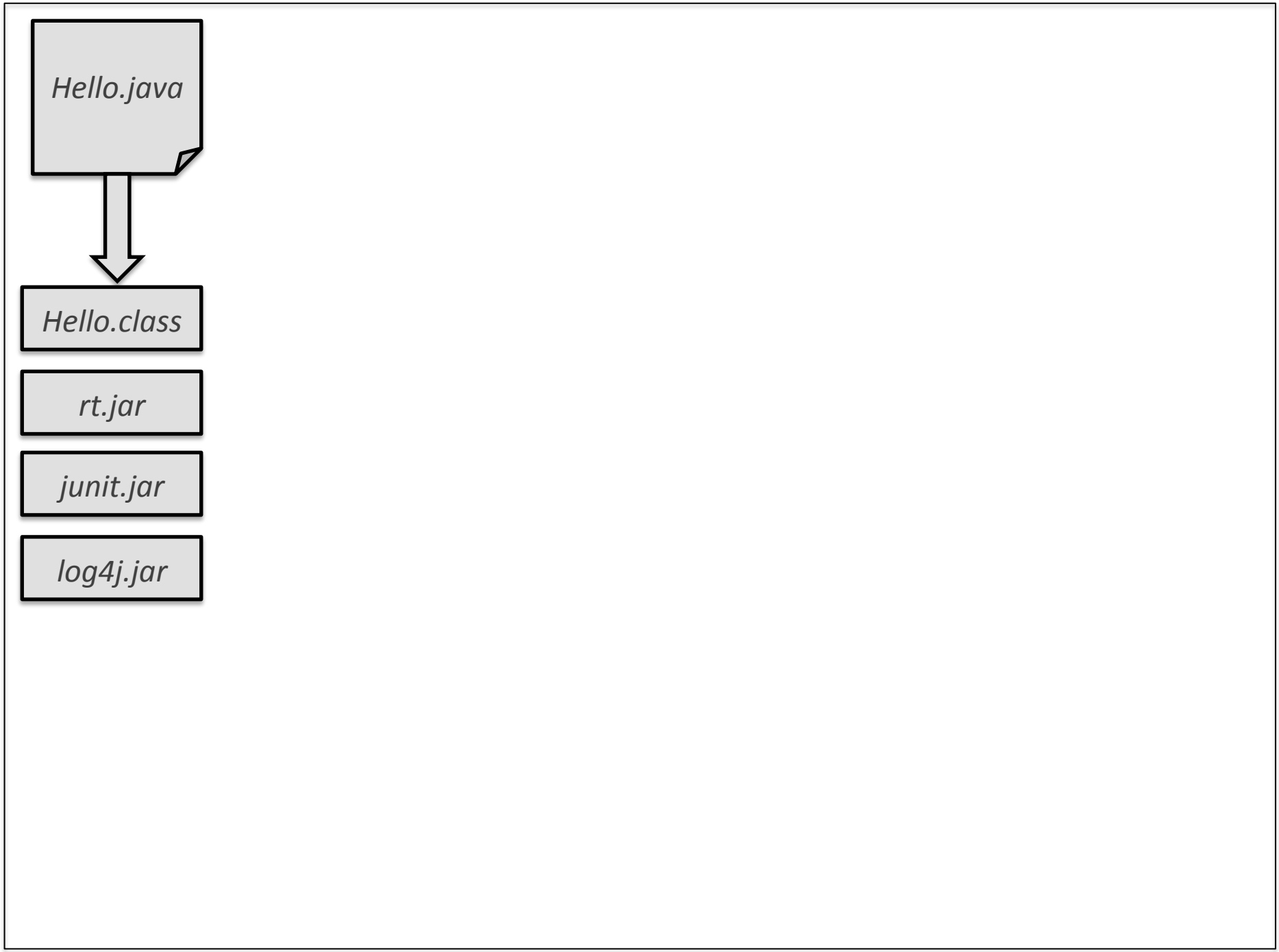
Class Libraries

- The second half of any program
- Written in Java
- Trade-offs of language vs. native libraries

Class Libraries

- The VM is only a part of the runtime system
- Need class libraries to do anything useful
  - Even Hello World uses some complex libraries
    - java.lang.Object
    - java.lang.String
    - java.lang.System
    - java.io.PrintStream


Hello.java
Hello.class
rt.jar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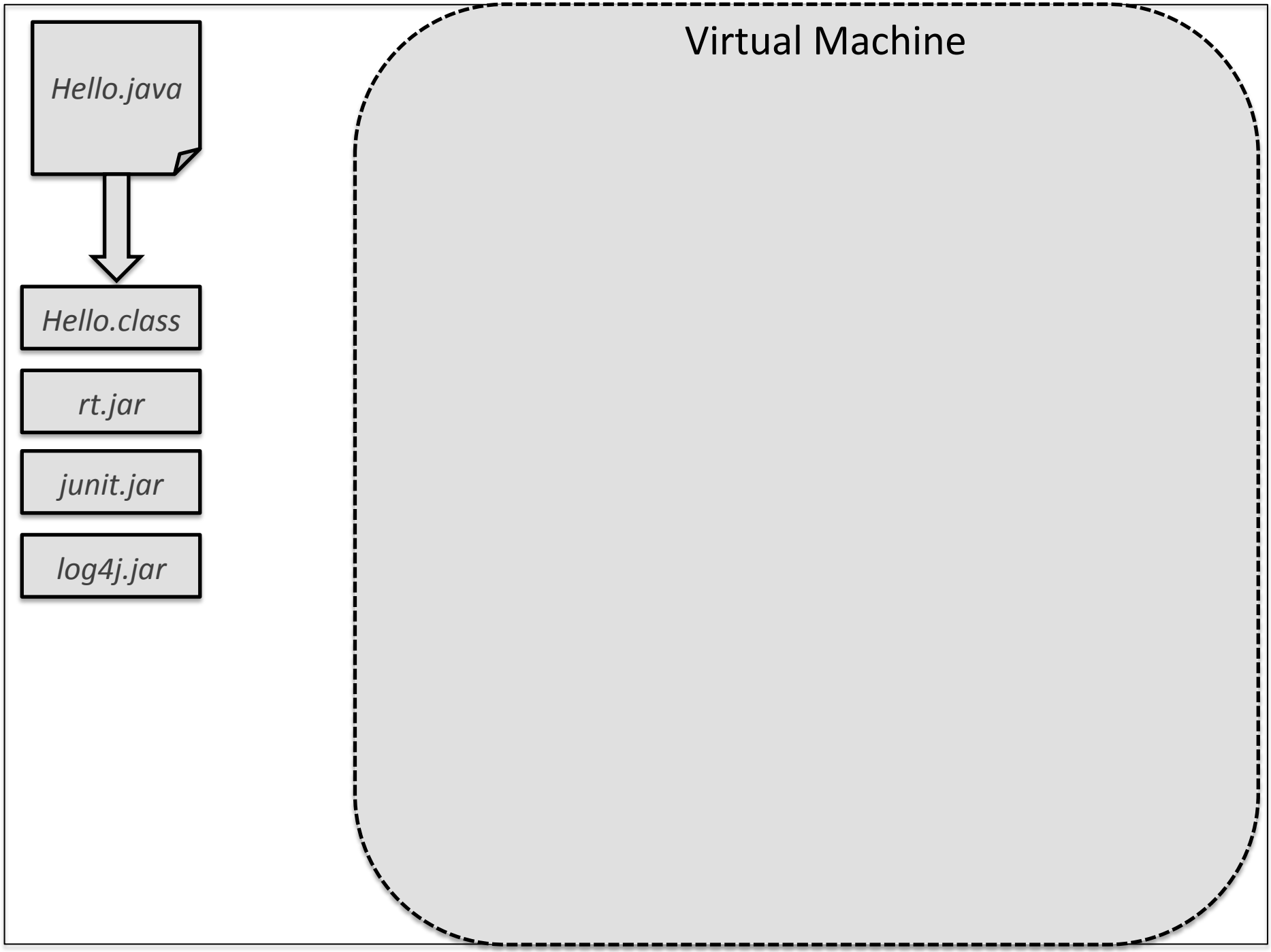
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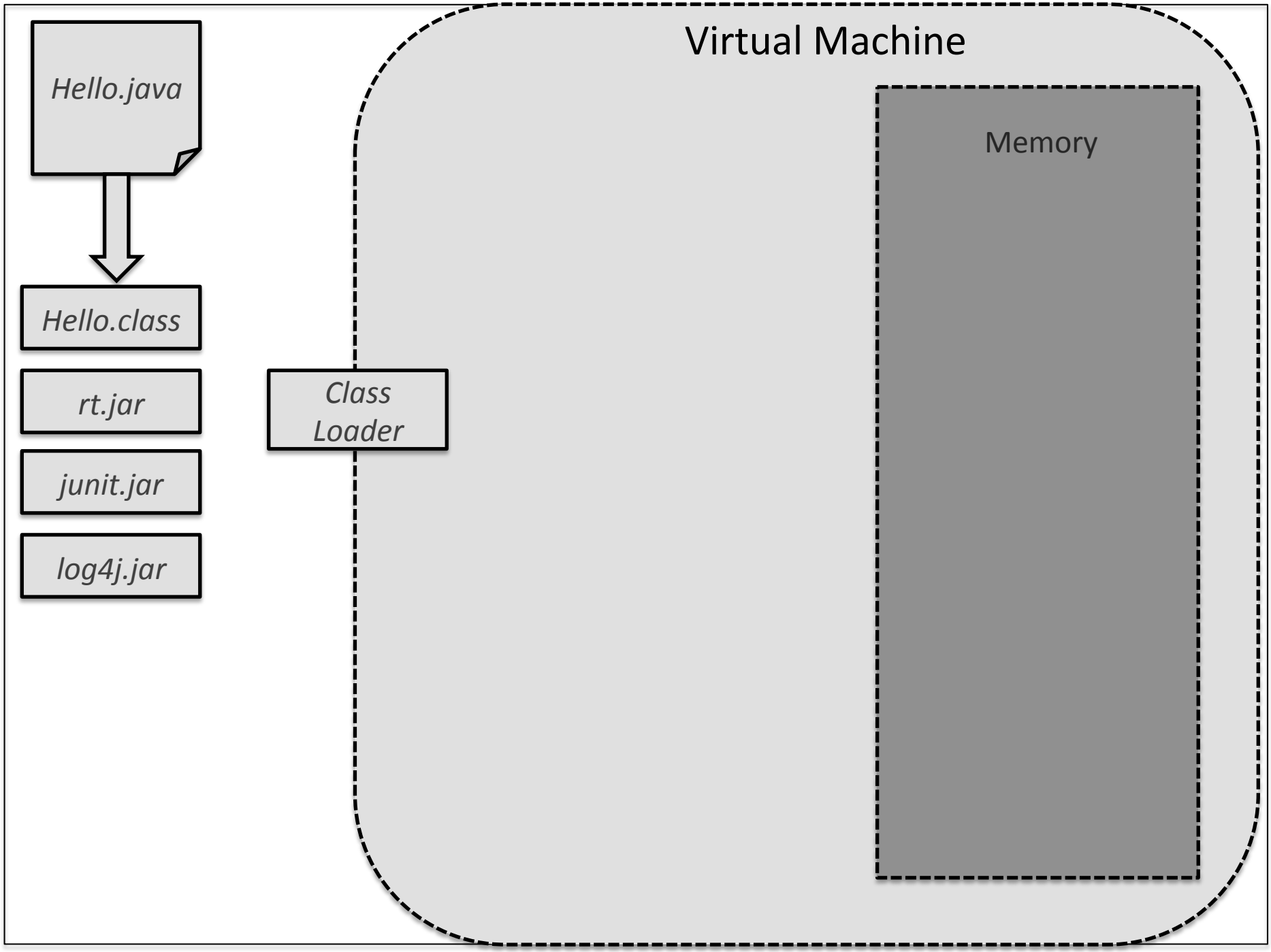
Virtual Machine

Launching the VM

- There's a lot of work to do before `main`
  - Map the heap and other memory
  - Load primordial classes
  - Parse command line arguments
  - Initialize VM components
  - Set up threads and internal structures

- VMs have a longer startup time than native code
  - We'll see more examples of this later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Class Loader
Virtual Machine
Memory

Class Loading

- The process by which code enters the VM
  - Code can come from many sources
    - Read from class files
    - Loaded from JAR files
    - Downloaded from the network
    - Created on the fly
- Classes are loaded lazily
  - Triggered by the first use of a class

Verification

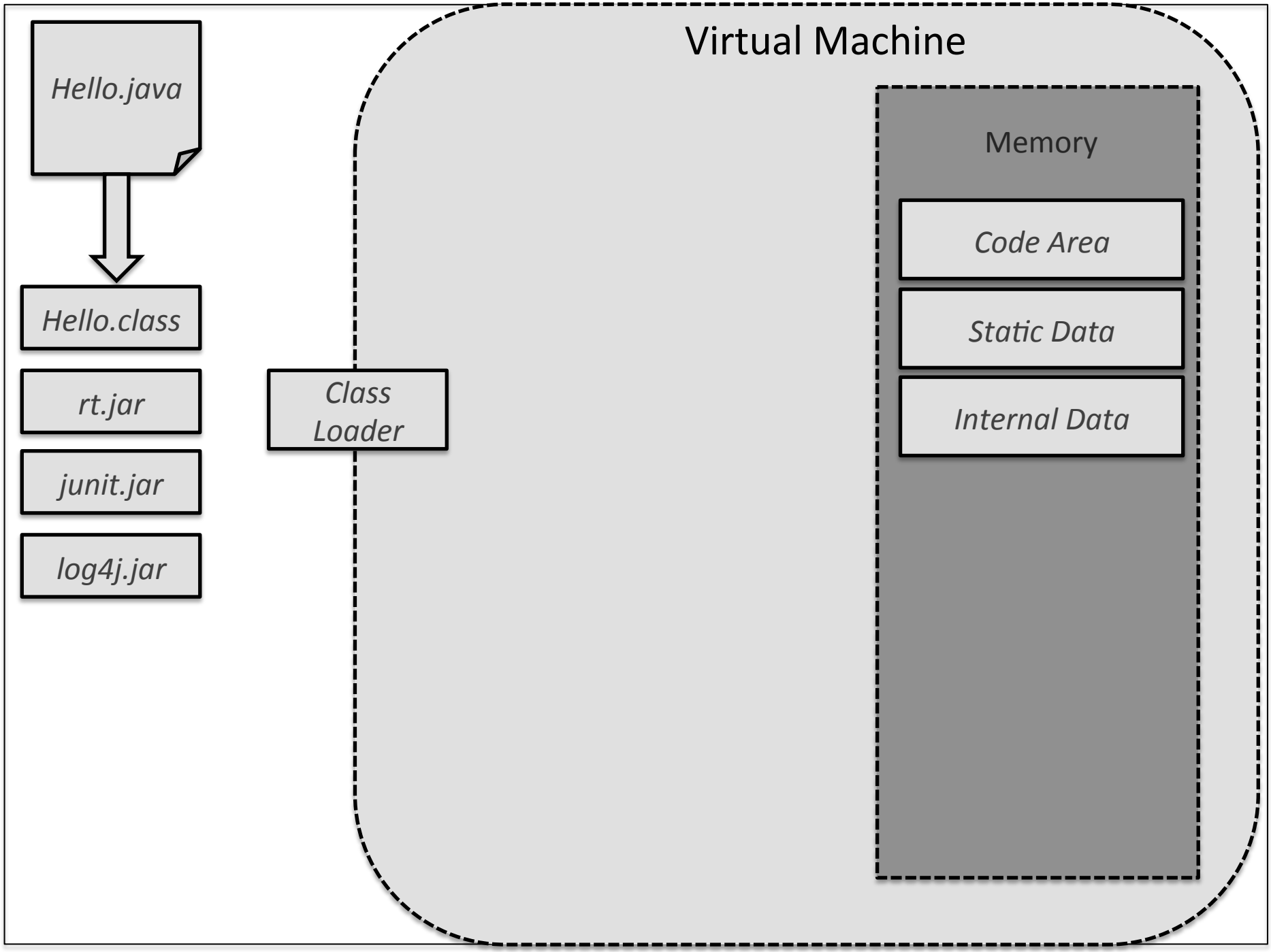
- Bytecode is verified before loading
  - Opcodes and operands must be valid
- Recall the data stored in the bytecode
  - Maximum locals and stack size
  - Exception handler blocks
  - Constant pool types
  - Jump targets

Class Data

- The class file has some internal data structures
  - Constant pool
  - Method bytecodes
  - Mapping tables
- It may also have static initializers
  - `static {}`
  - Static fields

Running the program

- Start with the main class
  - Recall how we identify methods
    - Class: `Hello`
    - Name: `main`
    - Signature: `([Ljava/lang/String;)V`
    - Classloader: `root class loader`
  - Method must also be `static` and `public`
- Program terminates when main exits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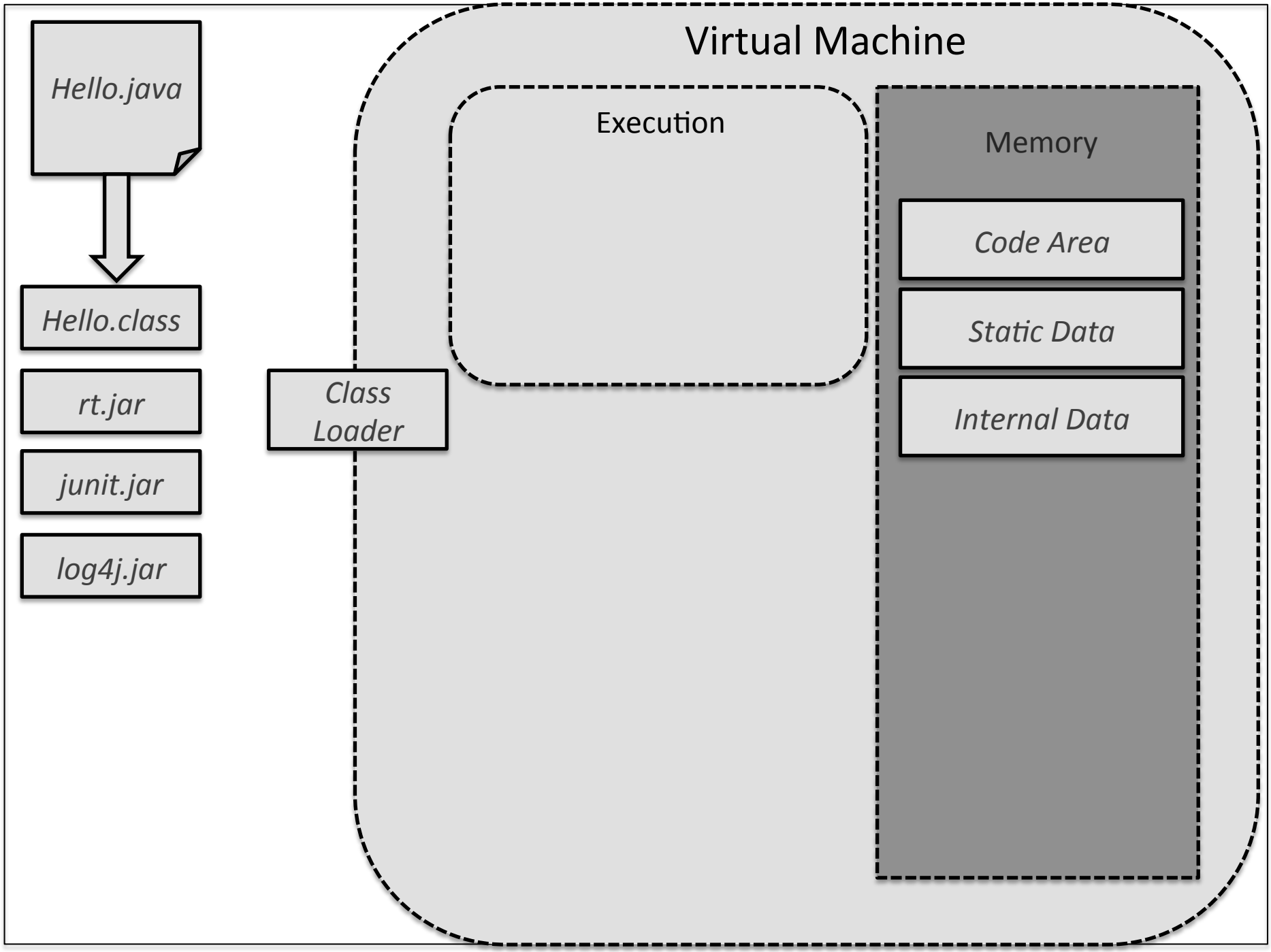
Internal Data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Class Loader

Interpretation

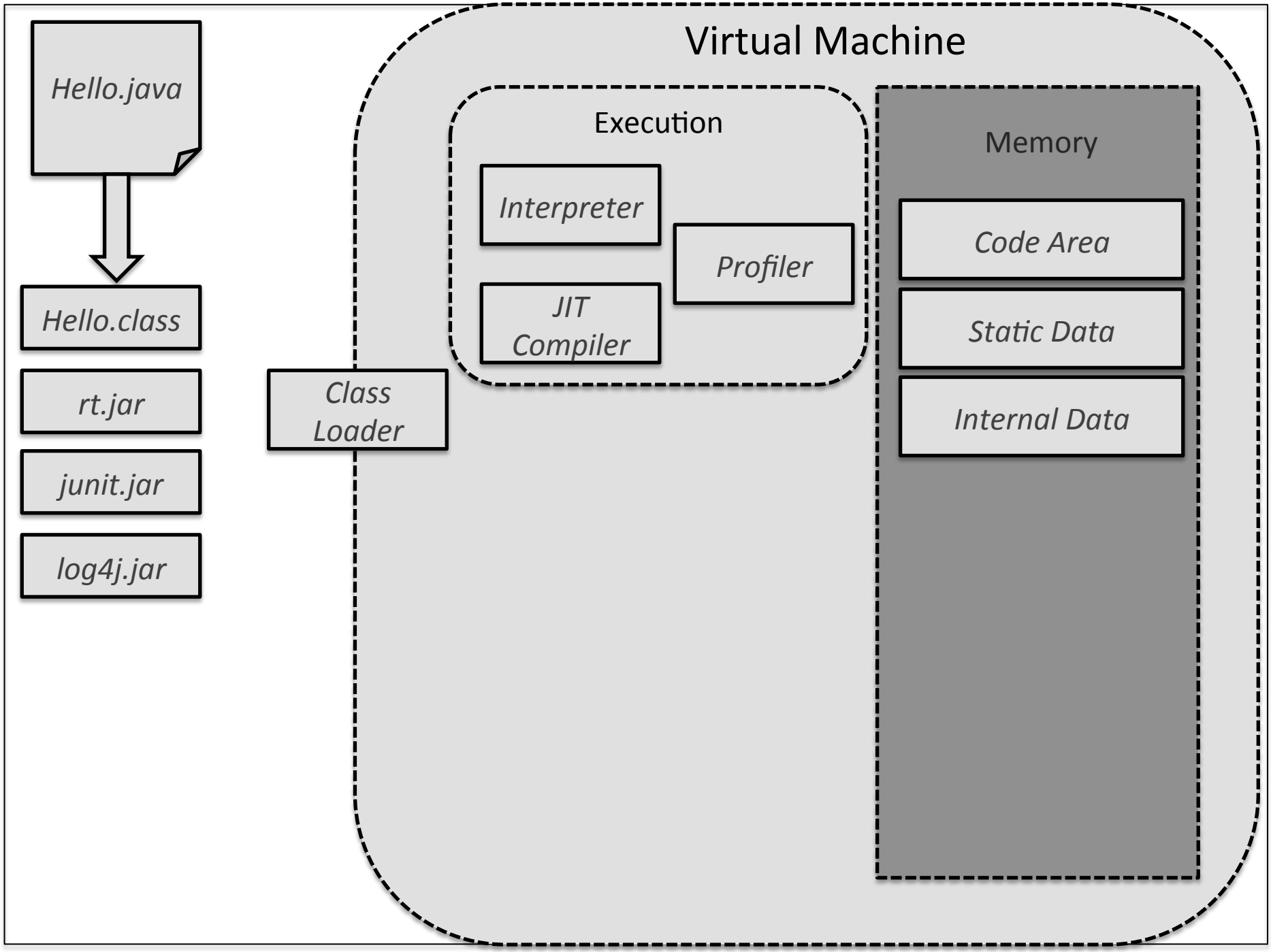
- Take each bytecode and simulate a machine
- Downsides
  - Slow and dumb
- So why bother?
  - Simple
  - Tradeoff speed vs. compilation time
  - Consider how many times `main` is called
    - What would the compilation overhead be?

Profiling

- The interpreter can track program execution
  - Tell what methods are hot
  - Identify loops
  - Identify frequently-used data
  - Phase behavior
- Targeted optimizations
  - Ahmdal's Law
  - Don't bother optimizing code that's not used

JIT Compilation

- Identify what code to optimize
  - Compile that using an optimizing compiler
  - Leave the rest to be interpreted
- JIT knows what optimizations are allowed
  - Depends on the classes that are loaded
  - Can (will) change over time
  - OK to be optimistic, so long as there's a fallback
- Gives the runtime flexibility to add extra features
- Optimize across libraries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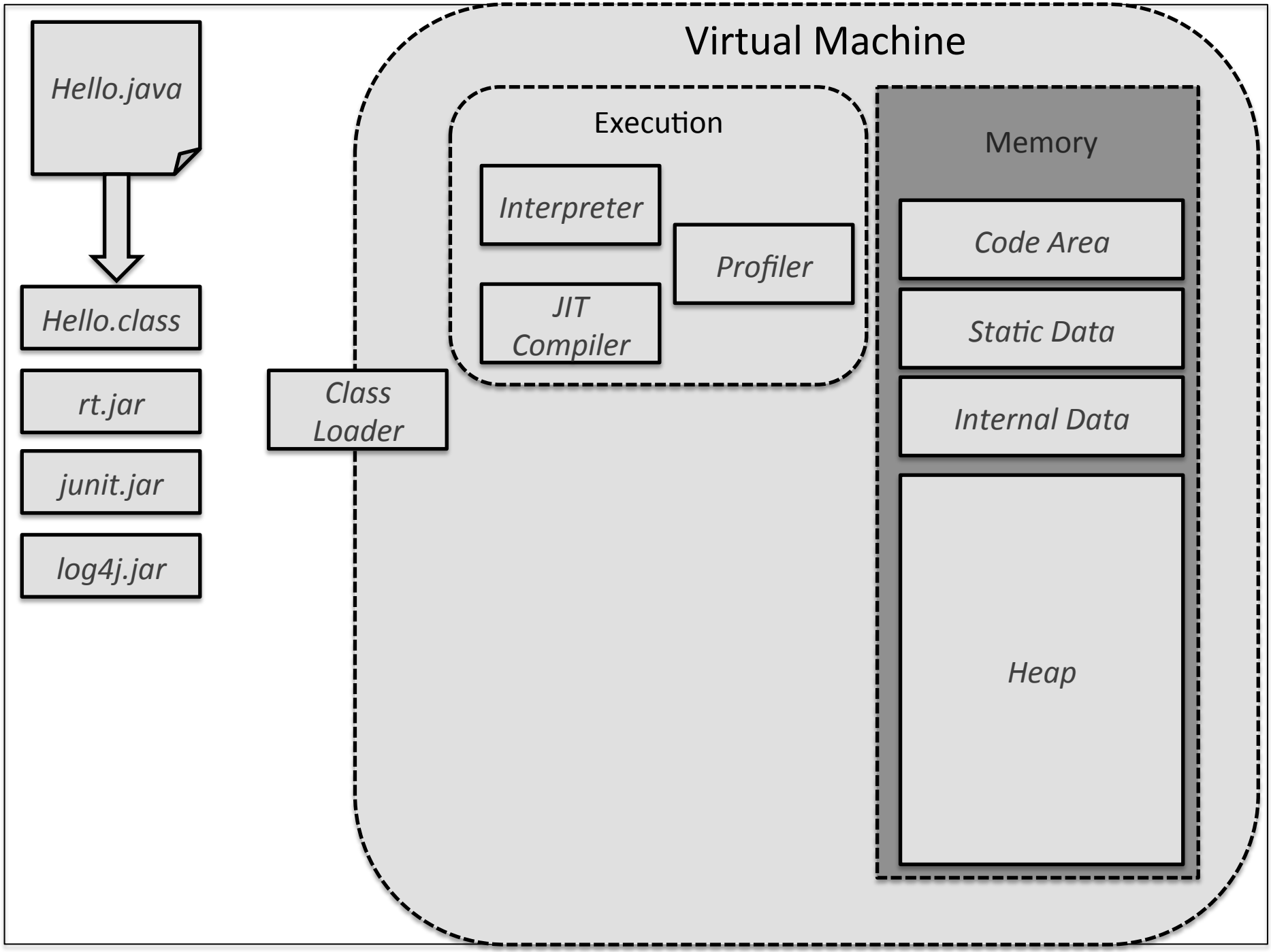
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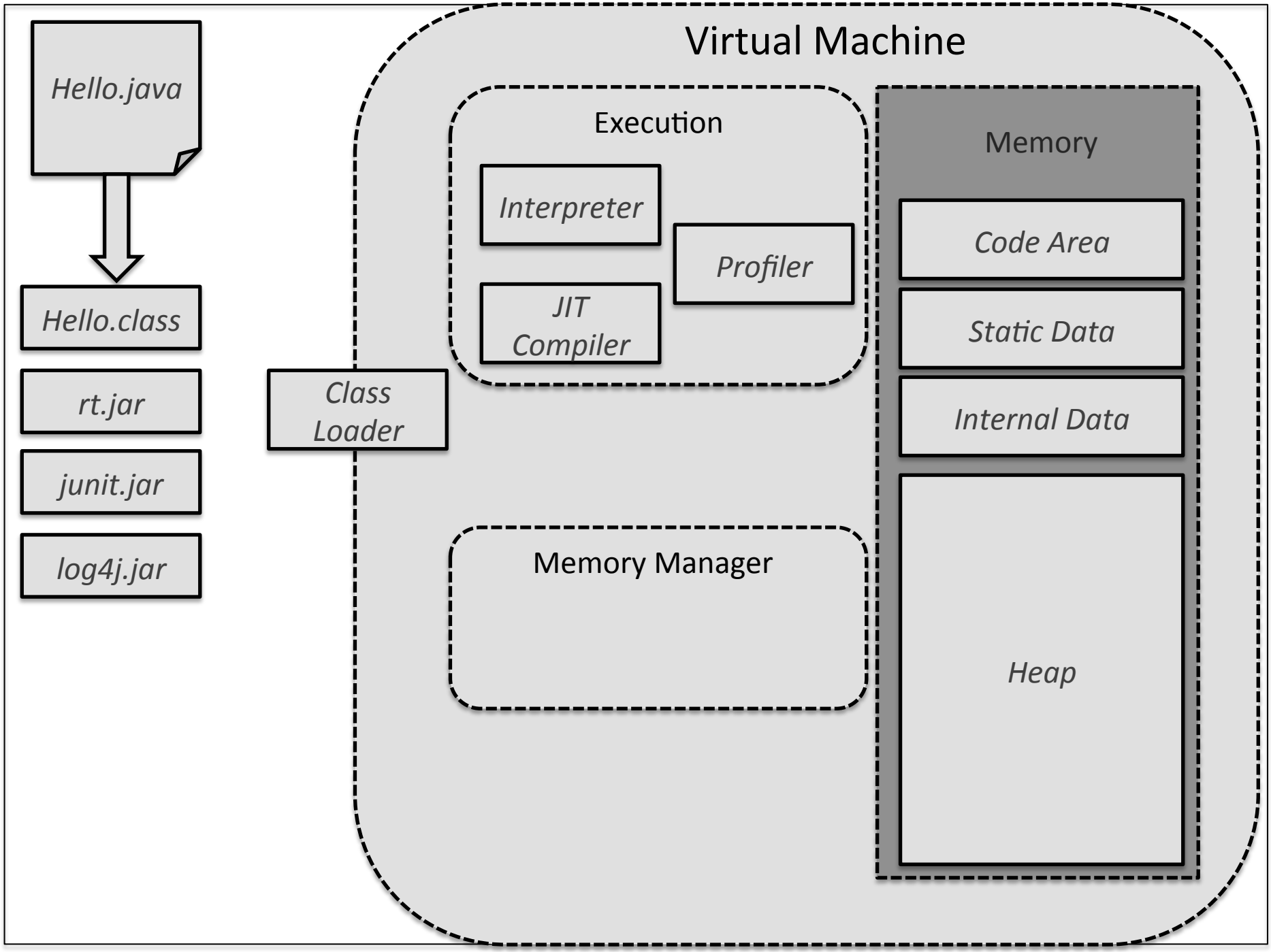
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Memory Management

- In the Good Old Days:
  - Memory could be stack or heap allocated
    - Stack allocation required fixed sizes
    - Heap allocation had to be tracked
  - Lots of bugs came from memory management
    - Memory leaks
    - Double frees
    - Buffer overflows clobbering metadata
- Allocation and Free are always linked.

Allocation

- Lots of possible allocation algorithms
  - Best fit
  - Worst fit
  - First fit
  - Free list
  - Stack or Region allocation
- All have their tradeoffs
  - Performance
  - Fragmentation

Garbage Collection

- Save developers from managing memory
  - Safer, fewer bugs
  - Simplify interfaces
  - Often more efficient (memory freed earlier)
- Present the abstraction of an infinite heap
- A handful of basic approaches
  - With infinite variations on the themes

Reference Counting

- Keep track of references to a memory location
  - When that number hits zero, free the object
- Implemented in C++ as smart pointers
  - Or shared/unique/weak pointers
- Good if nothing else is available
  - Susceptible to circular references
  - Fallback mechanism or new semantics required.

Tracing

- Start with a known set of live references (roots)
  - Static variables
  - Pointers on the execution stack
  - Various others
- Mark the objects that those point to
- Scan the marked objects for more references

Mark Sweep

- Also called scavenging collectors
  - Figure out what objects are alive
  - Delete everything else
- Small conceptual step from reference counting
- Makes use of the full heap
  - But can lead to fragmentation

Copying

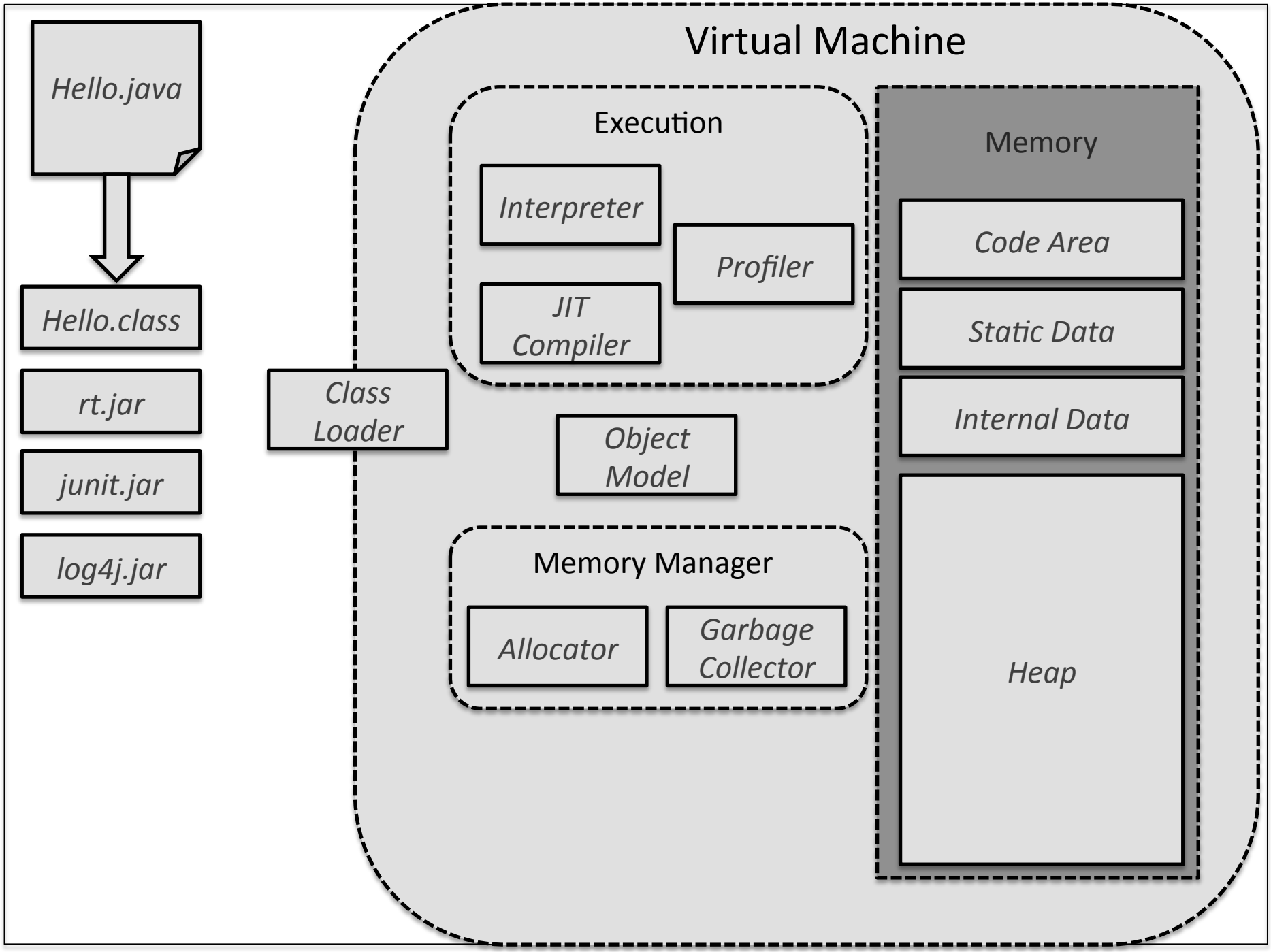
- Takes the opposite approach to Mark Sweep
  - Figure out what objects are alive
  - Copy those objects to some other place
  - Clear the entire allocation area
- Allocation is trivially simple
  - You'll see in Assignment Three
- Adds overhead in time and space
  - Need to set aside an area to copy live objects
  - Although that can be partially mitigated

Conservative GC

- Less common alternative to reference counting
  - Useful when we don't have perfect information
- If it looks like a pointer, assume it is a pointer
  - In case we guess wrong and don't mark a live object
- Can't do copying in case we're wrong
- Lots of complexity for little improvement over RC.

Object Layout

- The runtime system needs information
  - Type of an object on the heap
  - Size of the object or array
  - Location of its references
- May also need to store extra data
  - Garbage collection mark bits
- Every heap object has a standard header
  - Size is important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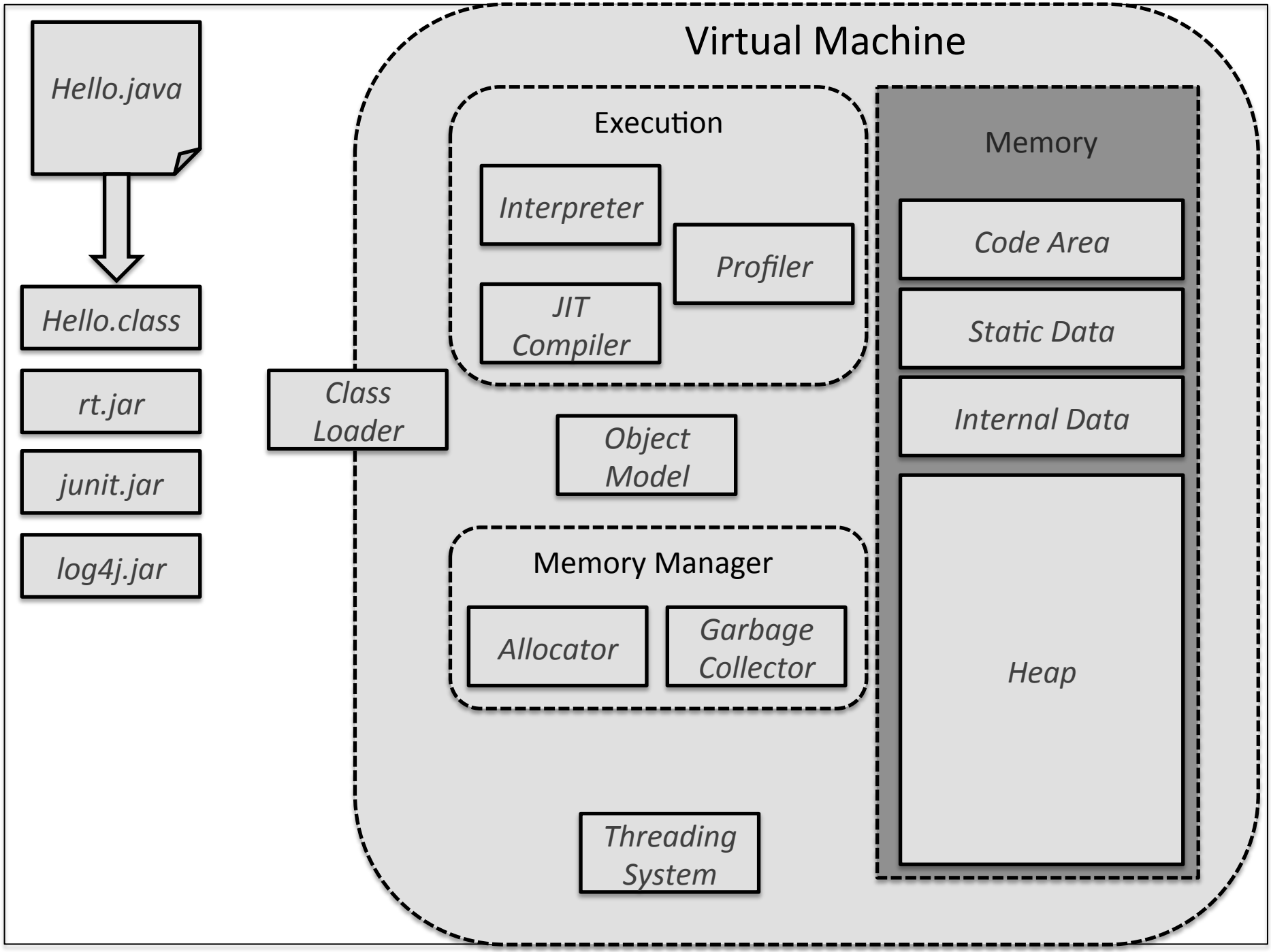
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Threading

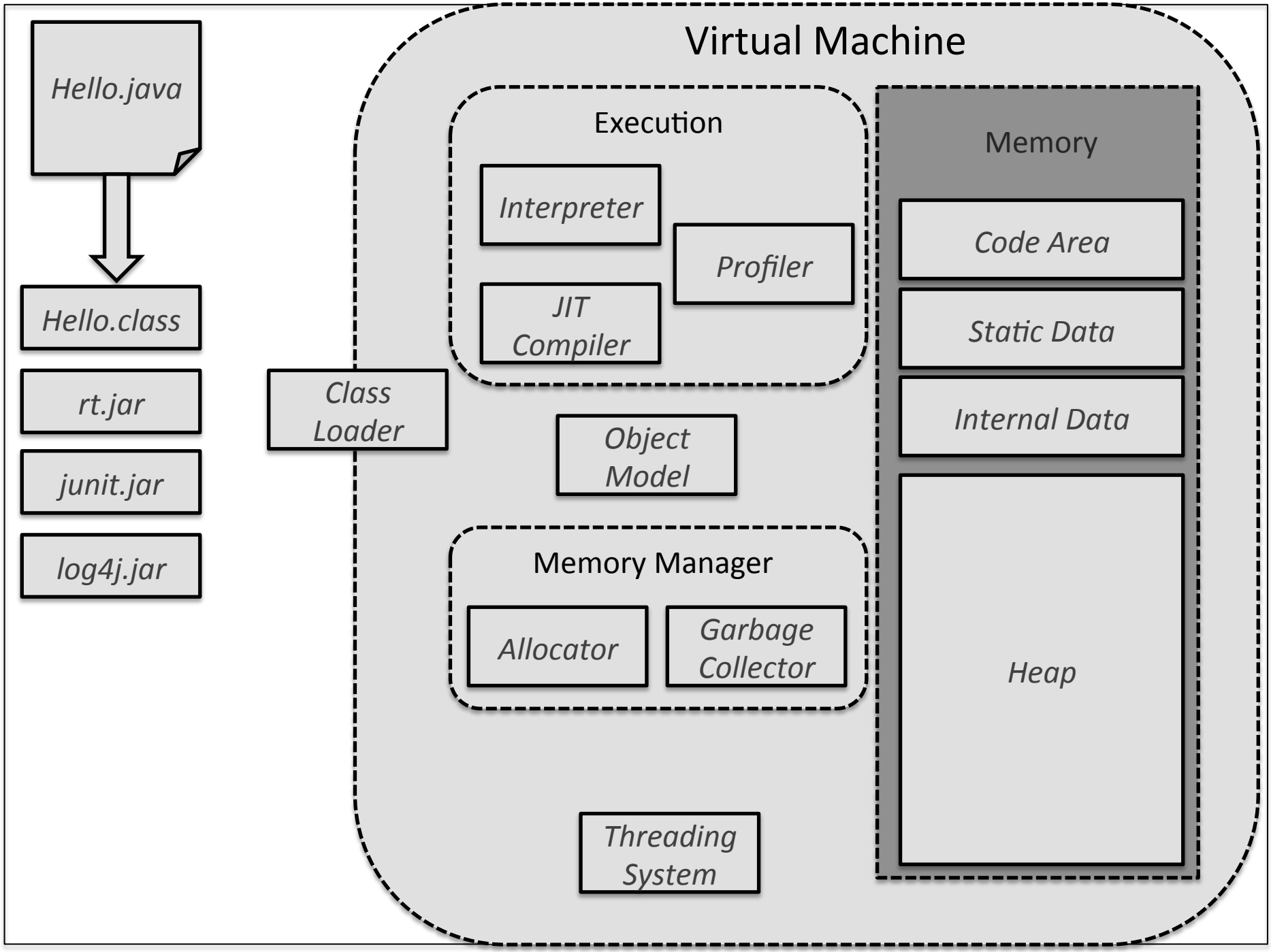
- Threads are vital for performance
- Building a correct concurrent program is hard
  - Building a correct concurrent VM even more so
- Concurrency requires thought in all components

Application Threads

- Threads are available to the developer
  - Require a clear memory model
- Some implementation challenges
  - How to map VM-level threads to OS threads
  - How to implement locks
- Various solutions are available

Background Threads

- Concurrency is not just for applications
  - Garbage collection threads
  - JIT compilation threads
  - Profiling threads
- We can't assume that anything is single-threaded
- Huge potential for performance improvement
  - But at the expense of complexity
  - Consider some of the assumptions in a garbage collector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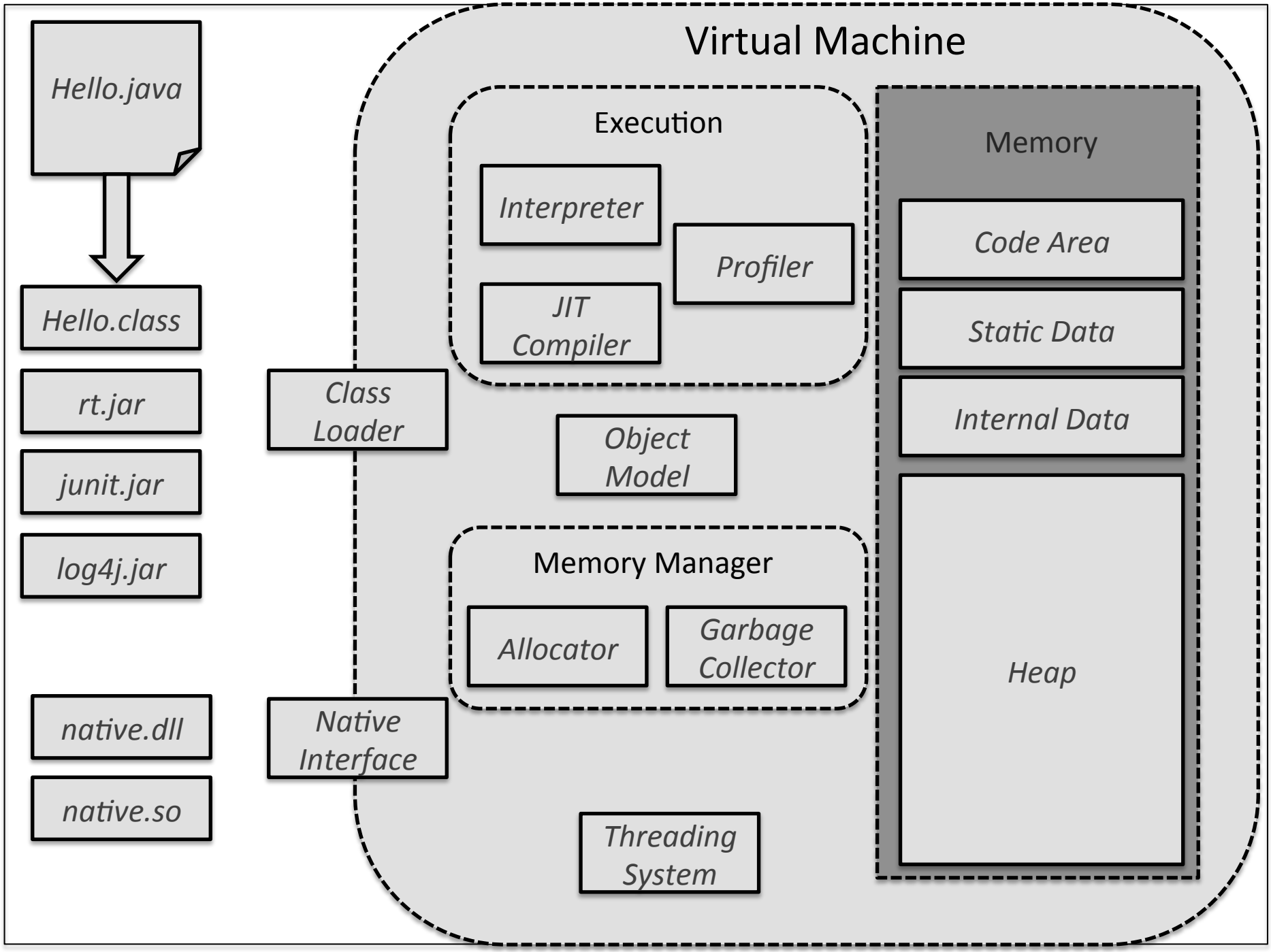
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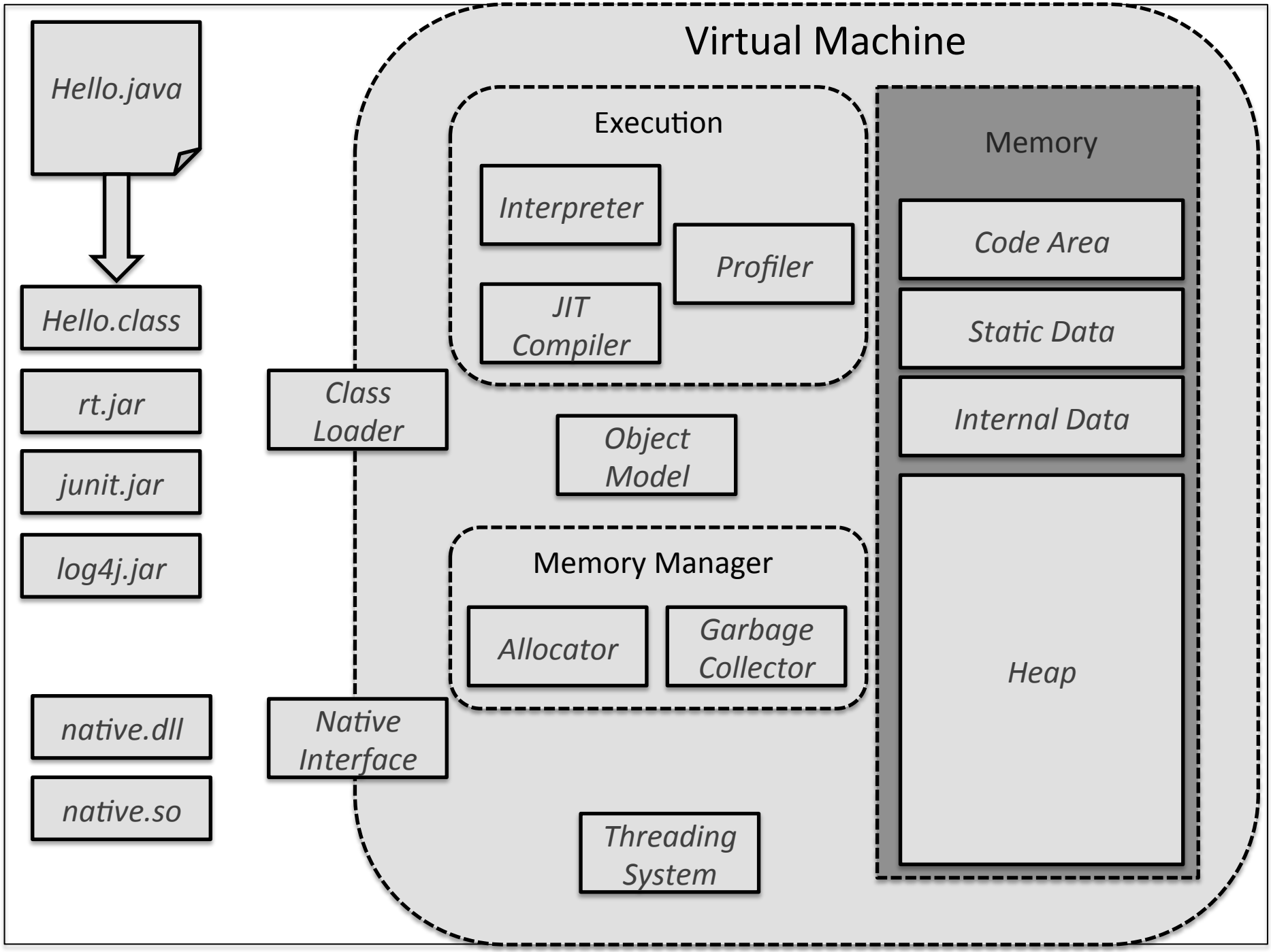
Native Interfaces

- Many VM languages have a native interface
  - An escape hatch for added performance
  - A way to link to legacy code
- Native code has to be a good citizen
  - Consider how that affects other components
    - Memory management
    - Threading and locking
    - Error handling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