Eschatology

- Some people have asked about the final project
  - It will be released in two weeks
  - Students can work alone or in a pair
- You will implement a generational GC algorithm
  - Copying collection in the nursery
  - Mark/Sweep collection in the mature space
  - Those working alone will implement simpler algorithms
- I'd like to get an idea of who's working with who
  - Drop me an e-mail if you're planning on forming a team

Eschatology II

- Final two classes on December 1st and 8th
  - Shorter special topics
  - Current state of the art
  - Review of the semester

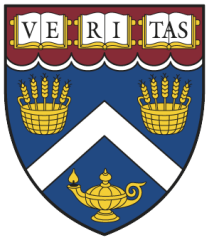
- Suggest topics by e-mail or discussion forum
  - Related areas of interest
  - Things that you'd like to hear more about
  - Anything that wasn't clear during the semester

Eschatology III

- A reminder about the final exam
  - Take-home format
  - Released on the Monday of finals week
  - Due on the Friday

- All material that we've covered is fair game
  - Lecture content
  - Experience when implementing in SimpleJava
  - Assigned readings

Debugging and Profiling



Debugging

- Any mechanism that lets the developer trace code
  - `System.out.println`
  - `new Throwable().printStackTrace()`

- Sometimes stack tracing isn't enough
  - Need deeper insight into code
  - Ability to step through line by line
  - Want to inspect variables or heap objects

Traditional Debugging

- Build application in debug mode
  - Include extra symbol information
  - Turn off optimization
- Use debugger tools to inspect the process
  - Can start with the debugger enabled
  - Or attach the debugger to a running process

Debugging Difficulties

- Debugger can change program characteristics
  - Introduce timing delays
  - Hide race conditions
  - Change cache behavior
- Some bugs don't manifest in debug builds
  - Aggressive optimization changes behavior
  - Operations may have undefined results
  - Developers get away with errors in debug mode

Class File Debug Support

- Java class files ship with debug information
  - File name
  - Line numbers
  - Local variable names
- Bytecode is not optimized
  - Very simple translation from Java to bytecode
  - Makes decompilation simple

Interpreter Debugging

- Well understood process
  - We've run through many examples in class
  - Simple mapping from bytecode to program state
- Breakpoints can be set between bytecodes
  - We've already seen how safepointing works
- Performance is less important
  - Interpreter performance isn't great anyway

Mixed Mode Execution

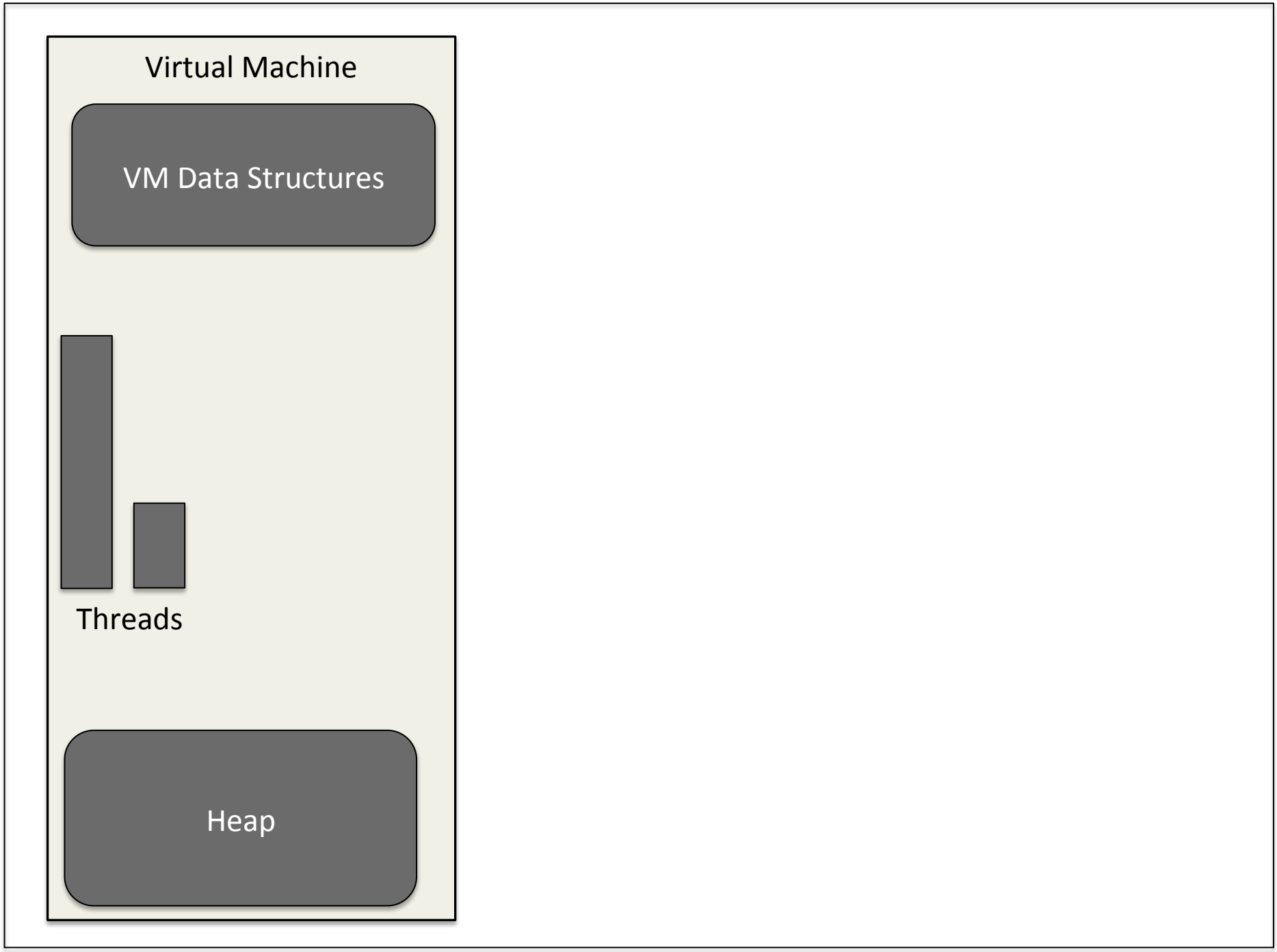
- Stacks can go between JIT and interpreter
  - Both modes need to support debugging
  - Need to transition smoothly
- May want to hot-swap executing code
  - On-stack replacement
- Threads can also enter native code
  - Native debugging is still a research question

Mixed Mode Execution

- Differences can crop up between modes
  - Less common than in native applications
  - Fewer undefined operations
  - Stricter checking of bytecode
- Some things can still be affected
  - Memory layout changes
  - GC behavior
  - Lots of timing changes

Out of Process Debugging

- Running in debug mode can be slow
  - Artificially low optimization level
  - Overhead of debugger operations
- Want to minimize the overhead
  - Particularly when the debugger's not running
- Launch debugger as separate process
  - Debugger's work doesn't interfere with the program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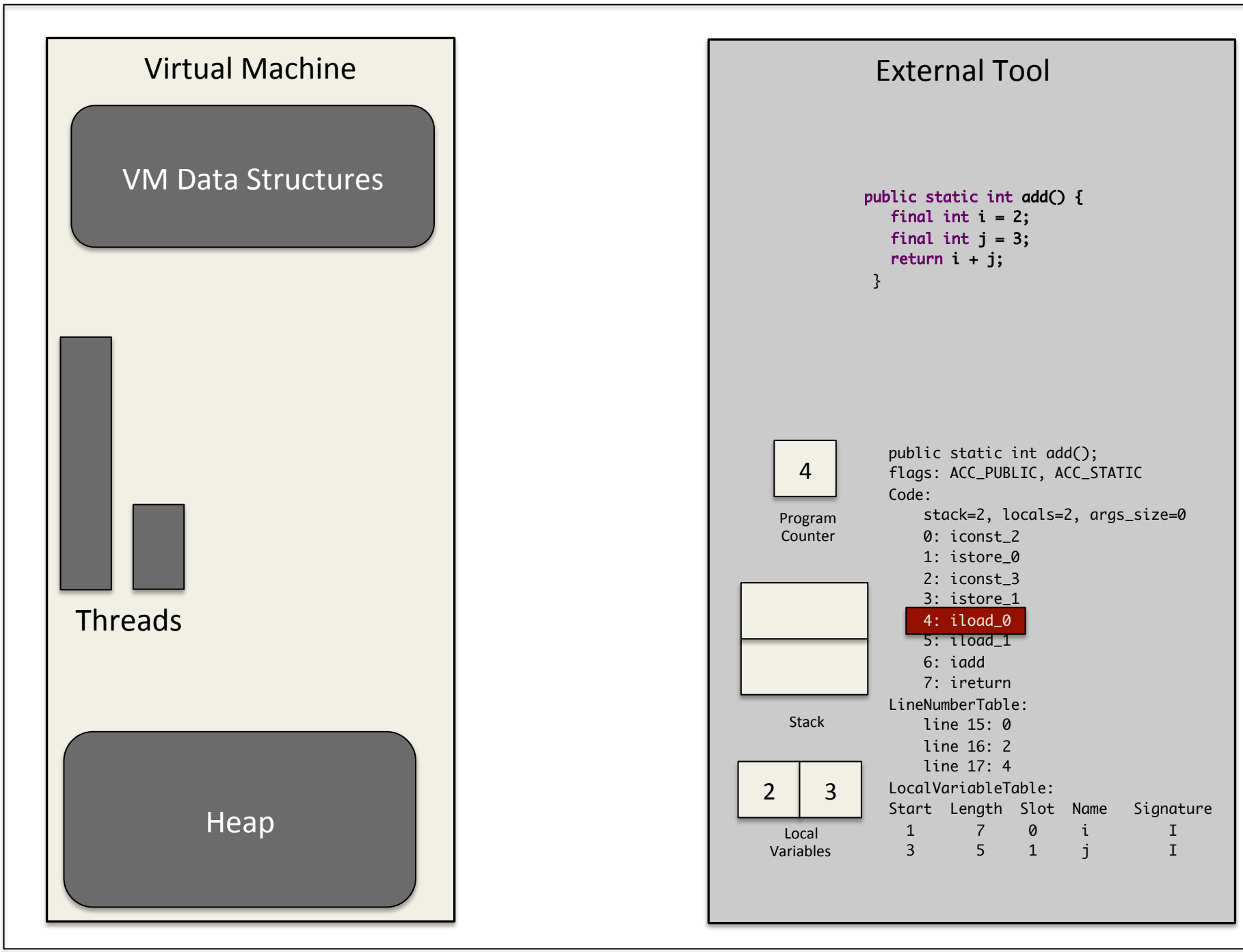
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return i + j;
}
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Program Counter
Stack
2
3
Local Variables
public static int add();
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=2, locals=2, args_size=0
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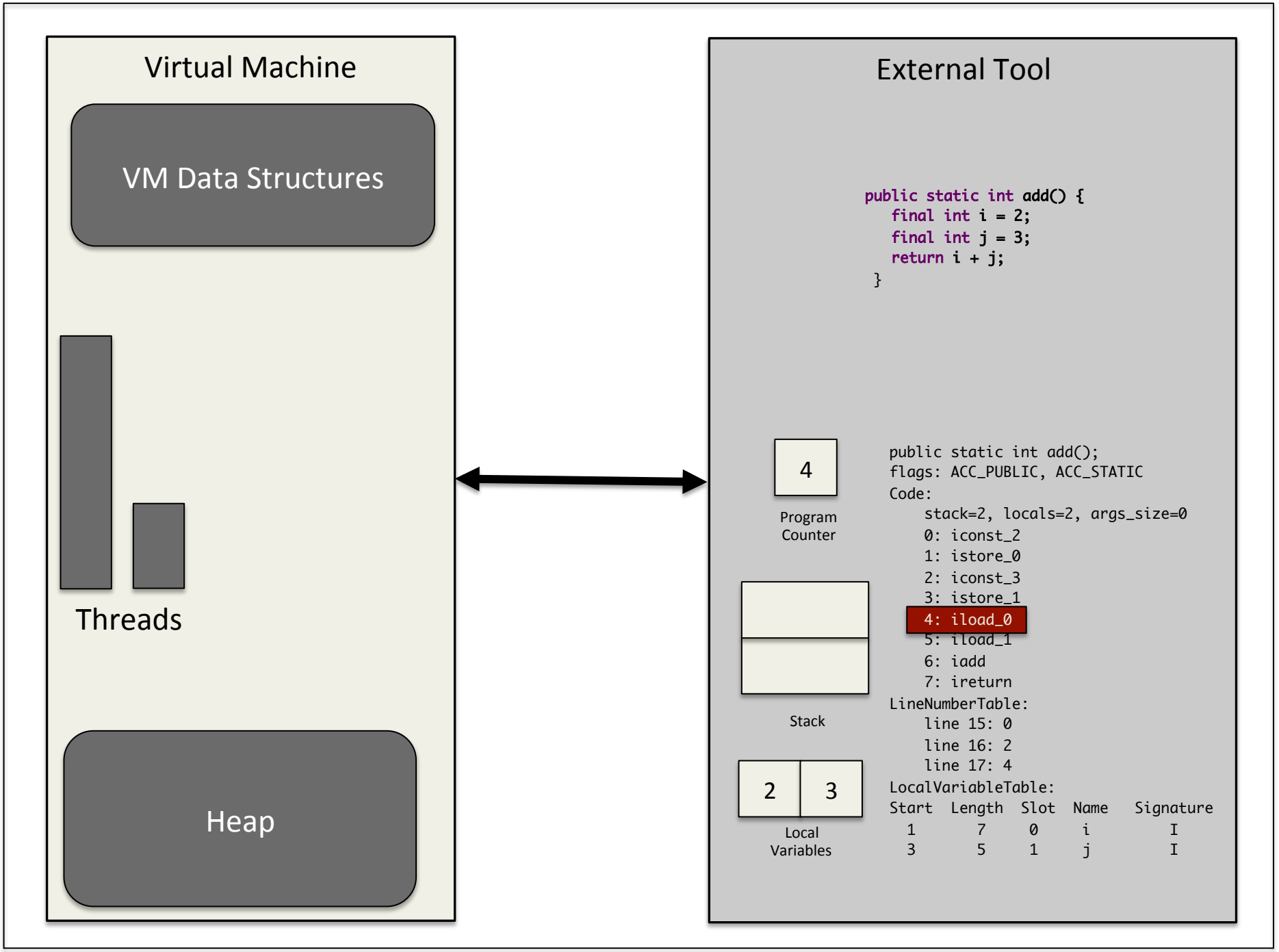
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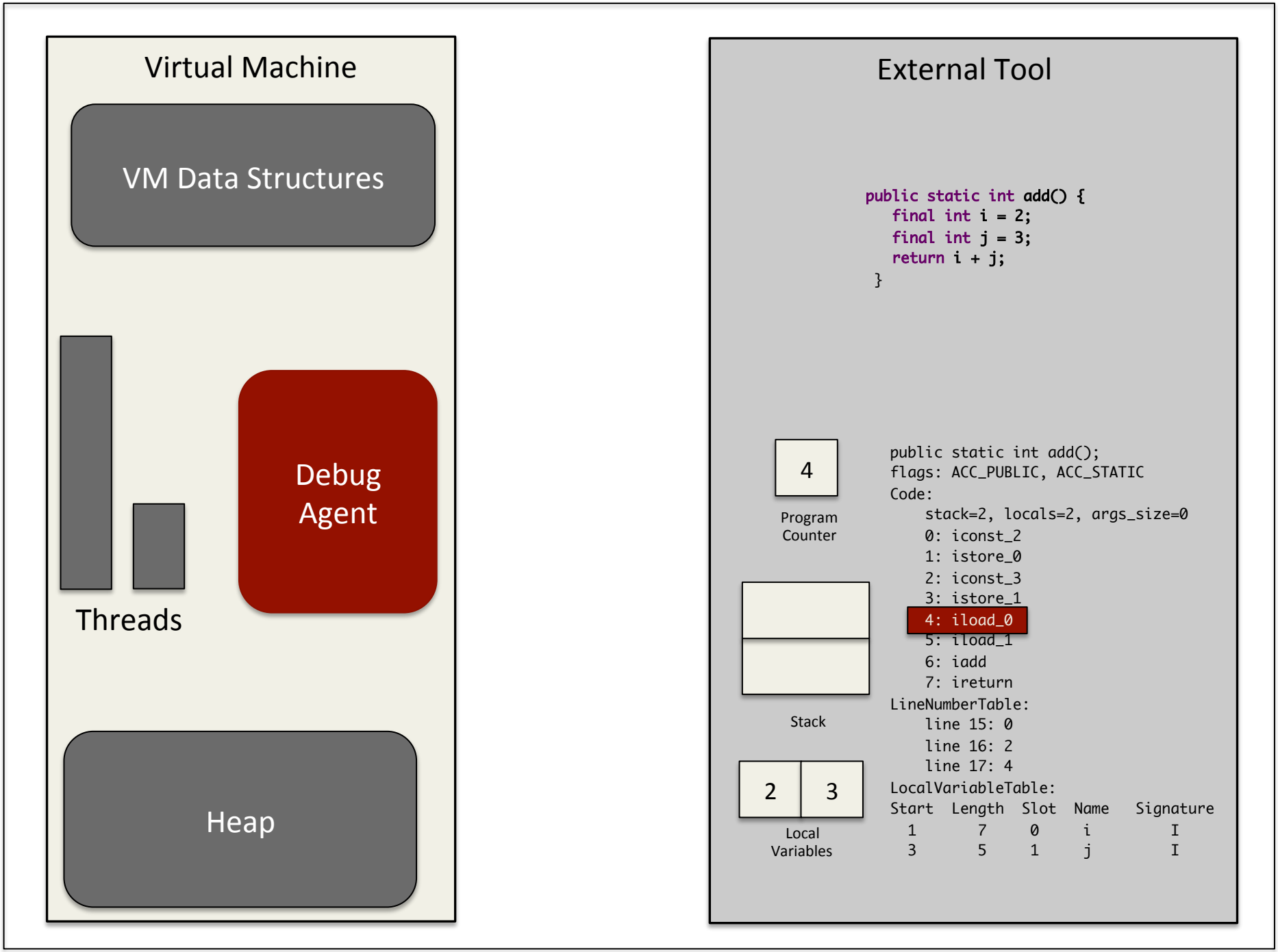
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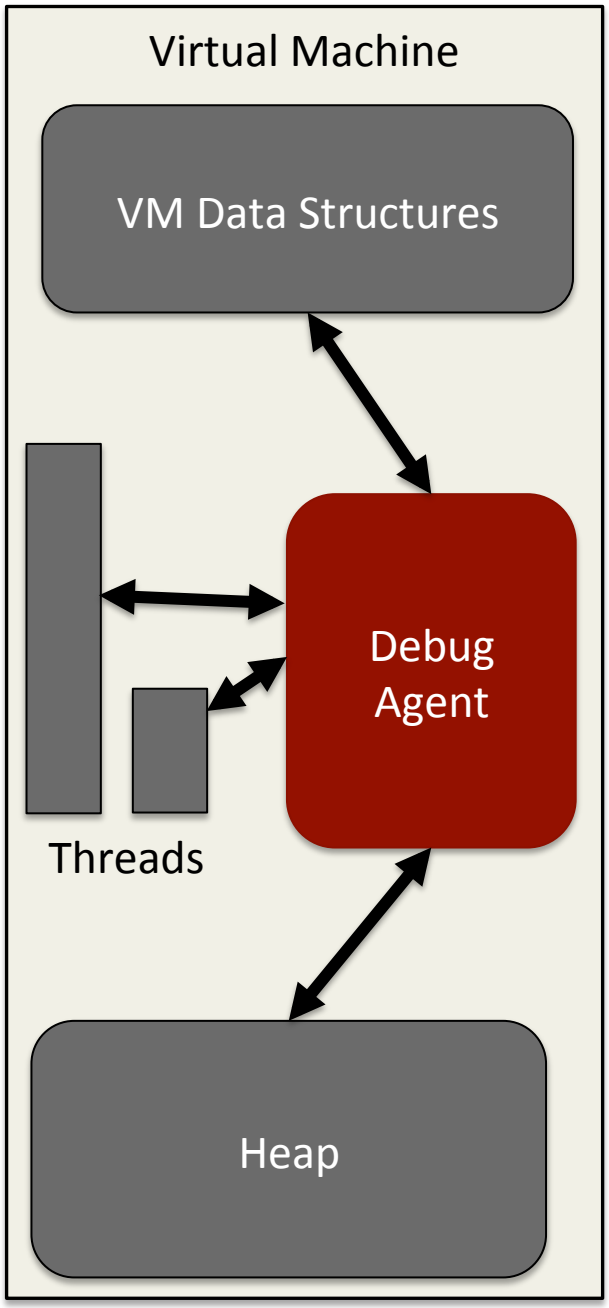

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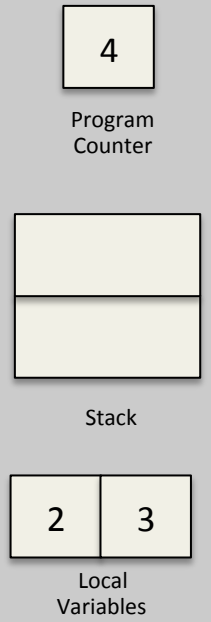


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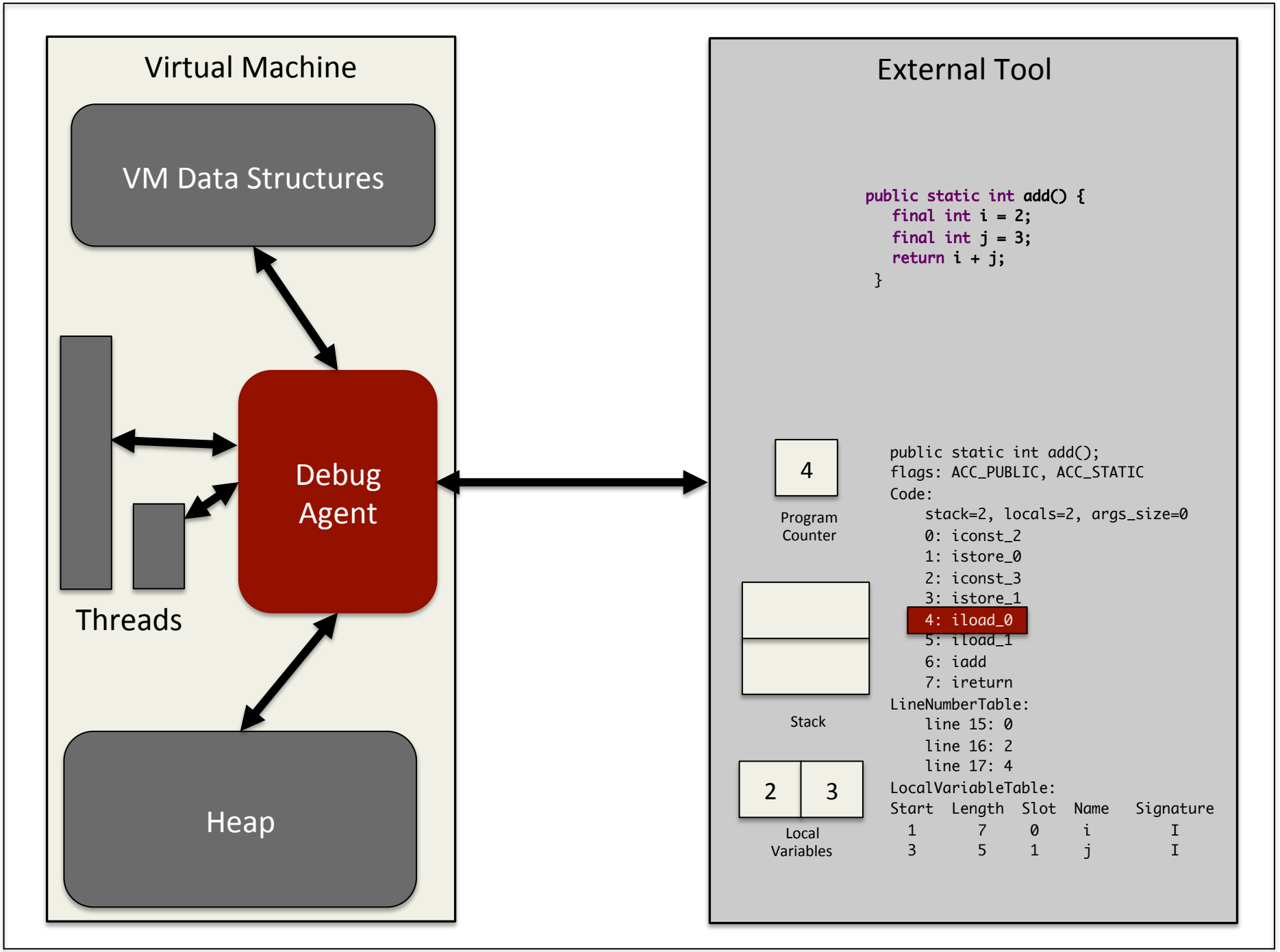
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JVMTI

- The JVM Tools Interface
  - Optional part of the VM specification
  - Introduced with version 1.5 of the JDK
  - Supports external tools that interact with the VM
- Disabled by default
  - Load agent on the command line
- Tool determines which features to turn on

JVMTI Agents

- Written in native language
  - Interface definitions in the JDK include directory
  - Generally a small piece of code
- Agent runs in the VM's address space
- Two-way communication with the VM
  - VM notifies agent of interesting events
  - Agent can control the VM
- Agent relays information to external tool

Loading an Agent

- VM loads the agent and calls startup function
  - `Agent_OnLoad`
- VM only partially created when agent launches
  - System property values have been set
  - No classes loaded
  - No objects created
  - No bytecodes executed
- Failure in agent creation leads to VM shutdown

Attaching an Agent

- Agents can be added once the VM is running
  - Uses `Agent_OnAttach` initialization method
- May have more limited functionality
  - May not be able to instrument running classes
  - Overhead for some features may be higher
- Failure in agent attach ignored by the VM

Timing

- Actions in the `Agent_OnLoad` call restricted
  - Parts of the VM not yet created
- Early loading allows agent to be more powerful
  - Capture VM creation events
  - Instrument system bytecode
  - Influence the newly-created VM

Unloading an Agent

- Agent can create an `Agent_OnUnload` function
  - Free up any resources held by the agent
- Triggers for unloading implementation specific
  - May be manual or automatic
- Called on clean VM shutdown
  - Not called if the VM crashes

Accessing VM Functionality

- The JVMTI agent uses a set of VM functions
  - Environment pointer to thread data and functions
  - Double indirection to allow function replacement
  - Allowable methods limited in some cases
- Control is inverted from JNI
  - Most agent threads not created by Java method call
  - Can't assume that they will eventually return
  - Complicates object reference management

Capabilities

- Set of events and permissions for the agent
  - Specified in `Agent_OnLoad`
- Capabilities are implementation dependent
  - Not all VMs will support all capabilities
  - Capabilities determine agent portability
  - Not all capabilities available after startup
- VM need only provide requested capabilities
  - Can tailor configuration for performance

Event Handling Capabilities

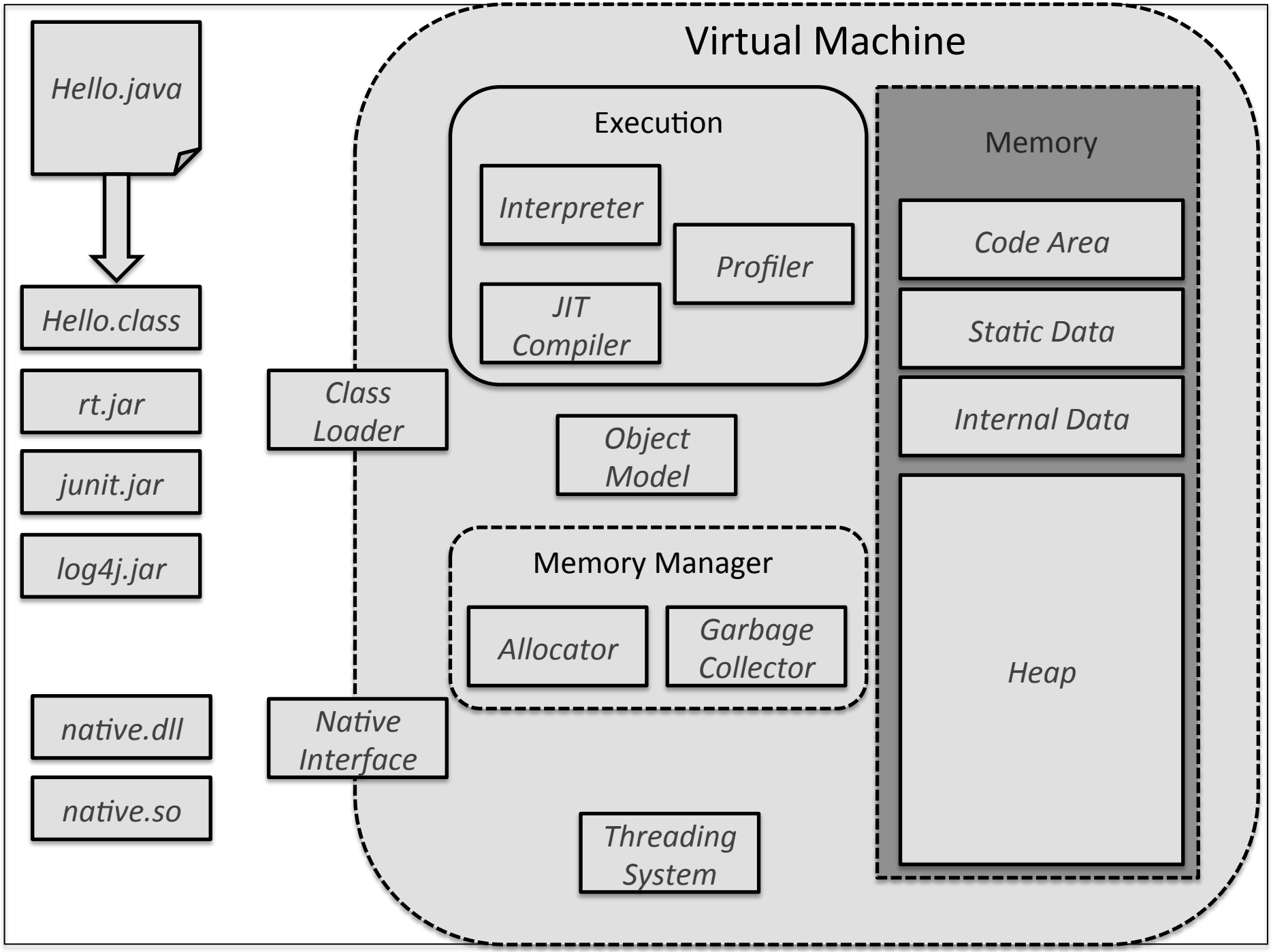
- Some capabilities cause callbacks to event handlers
  - Field modification
  - Field access
  - Method entry/exit
  - Class loading
  - JIT Compilation
  - Native method binding
  - Some allocation
  - Garbage collection
  - Resource exhaustion

System Monitoring Capabilities

- Others allow tools to access system information
  - Get monitor states
  - Get bytecodes for a method
  - Get source file and line numbers
  - Get class constant pool
  - Get CPU time for a given thread

Agent Functionality Capabilities

- Other capabilities let the agent perform actions
  - Tag objects on the heap
  - Pop frames from the stack or force method return
  - Redefine or re-transform classes
  - Stop, suspend or interrupt threads
  - Set breakpoints
  - Single-step through code
  - Generate events for other agents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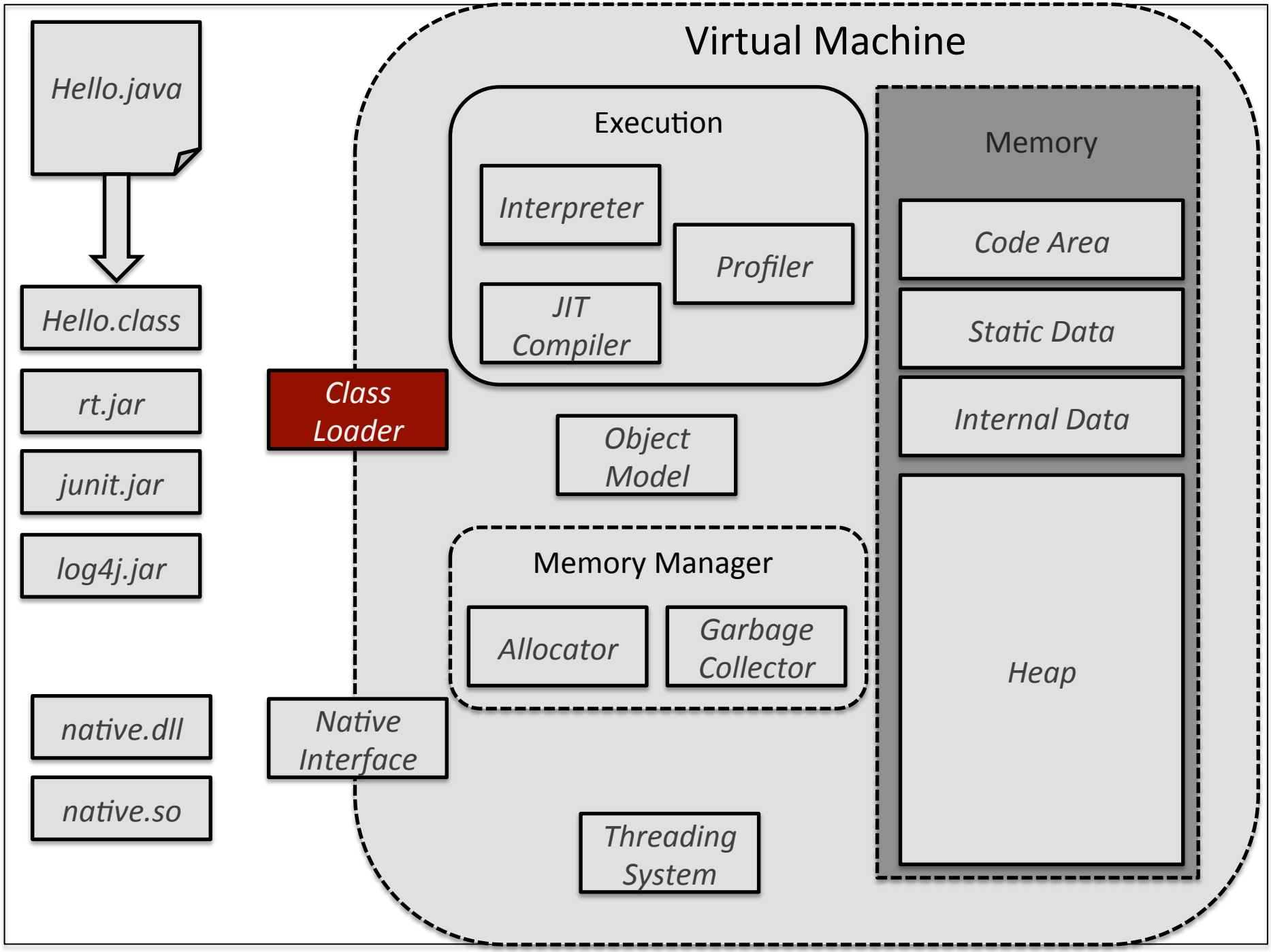
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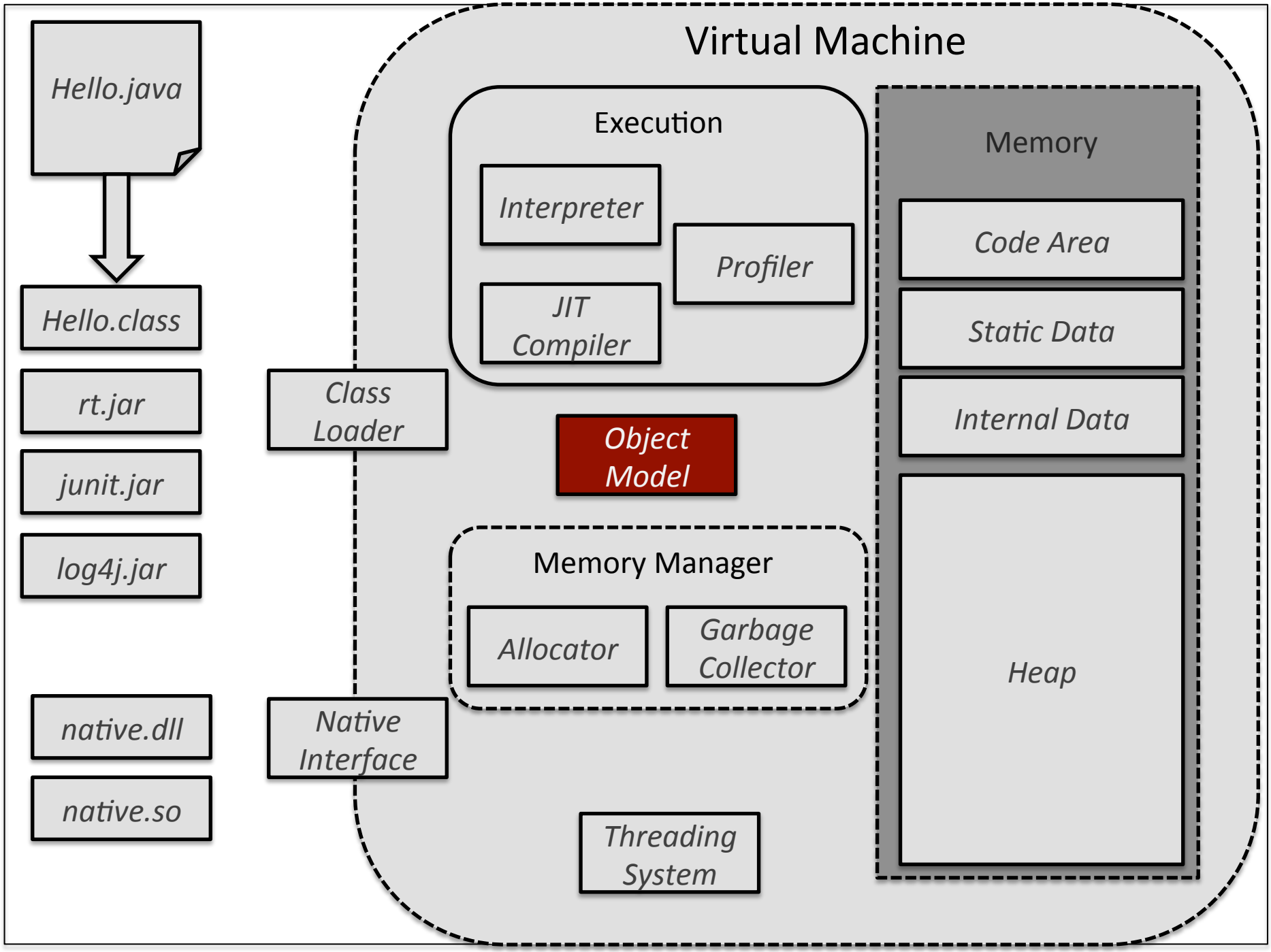
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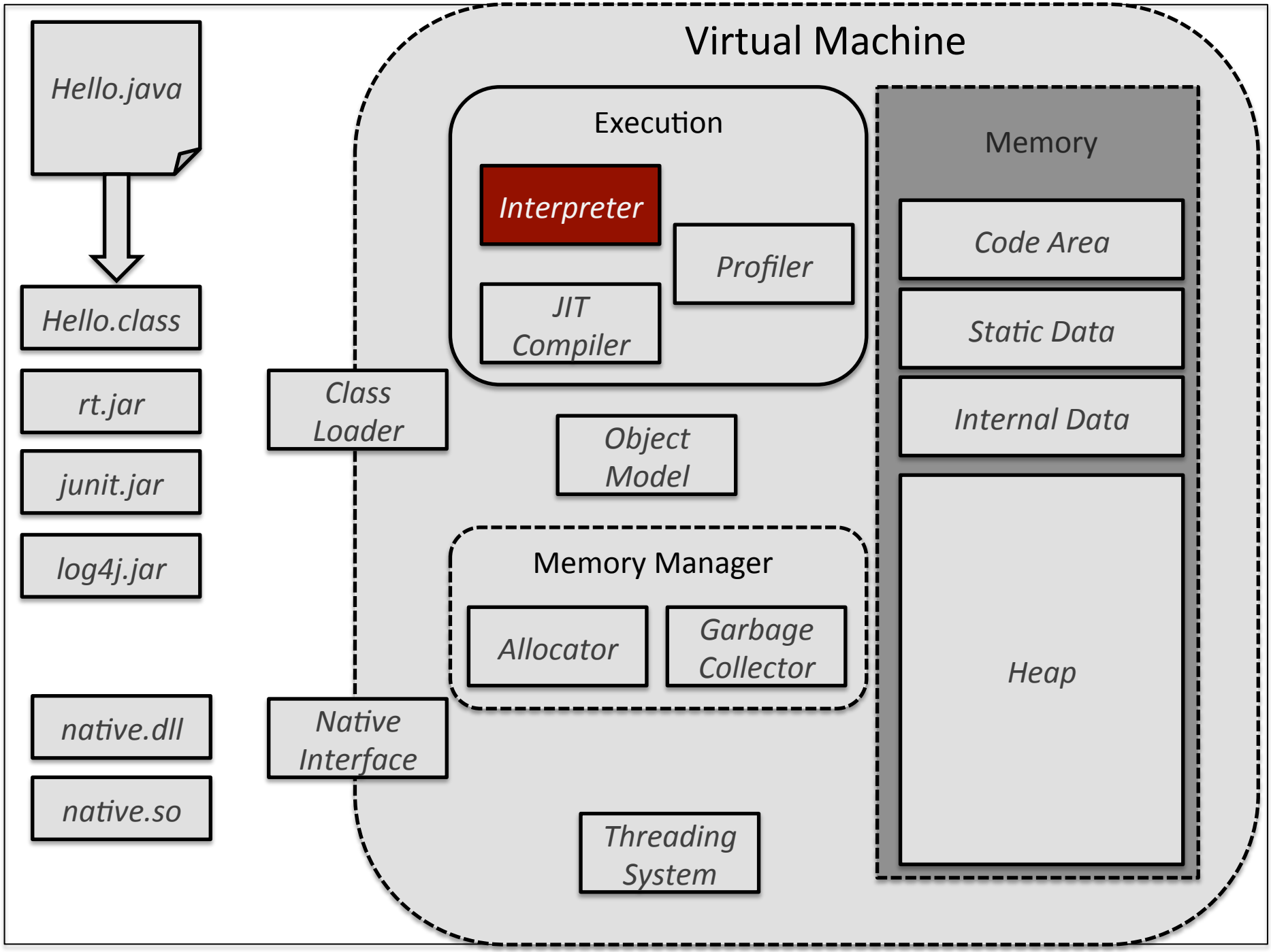
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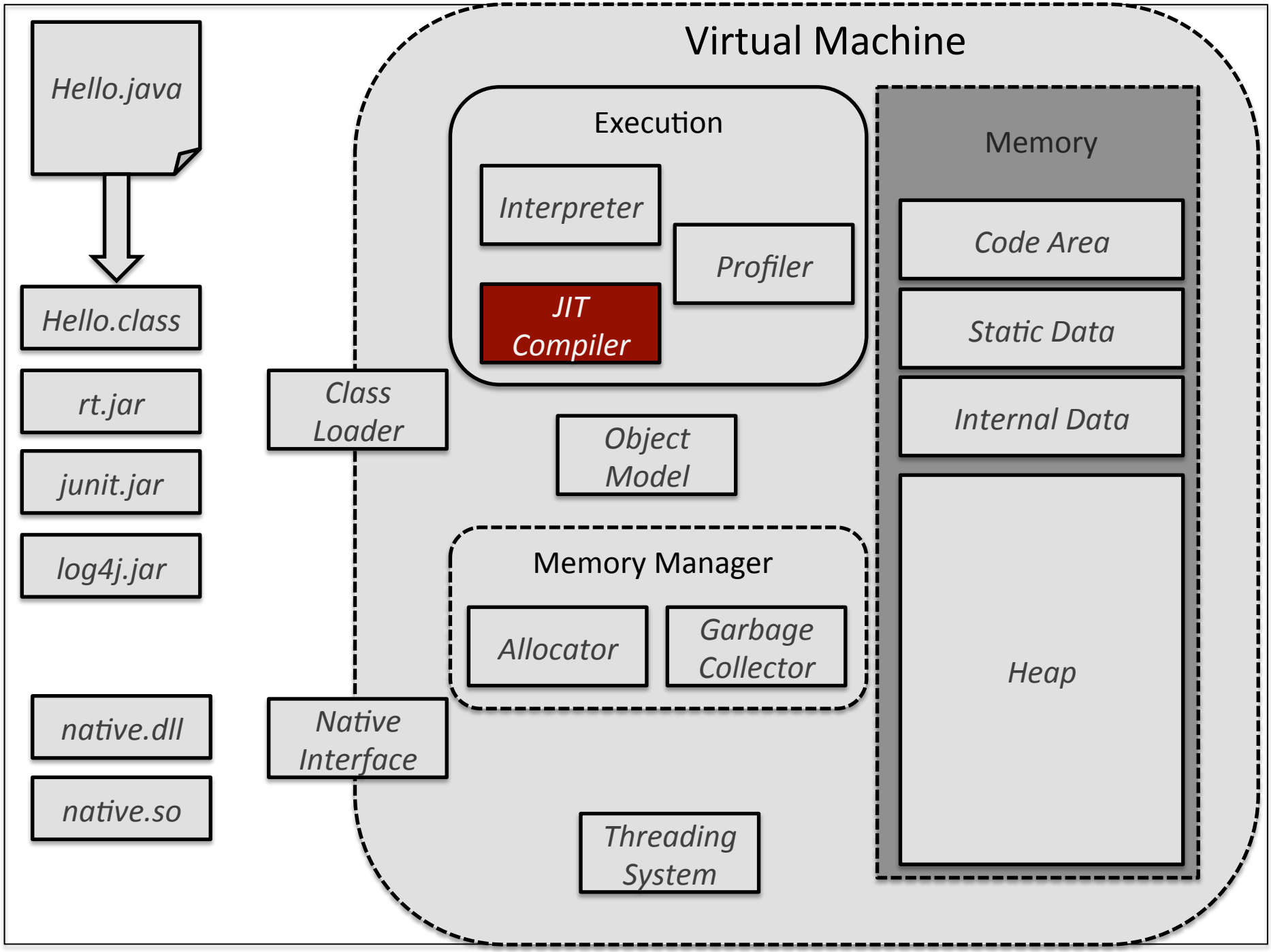
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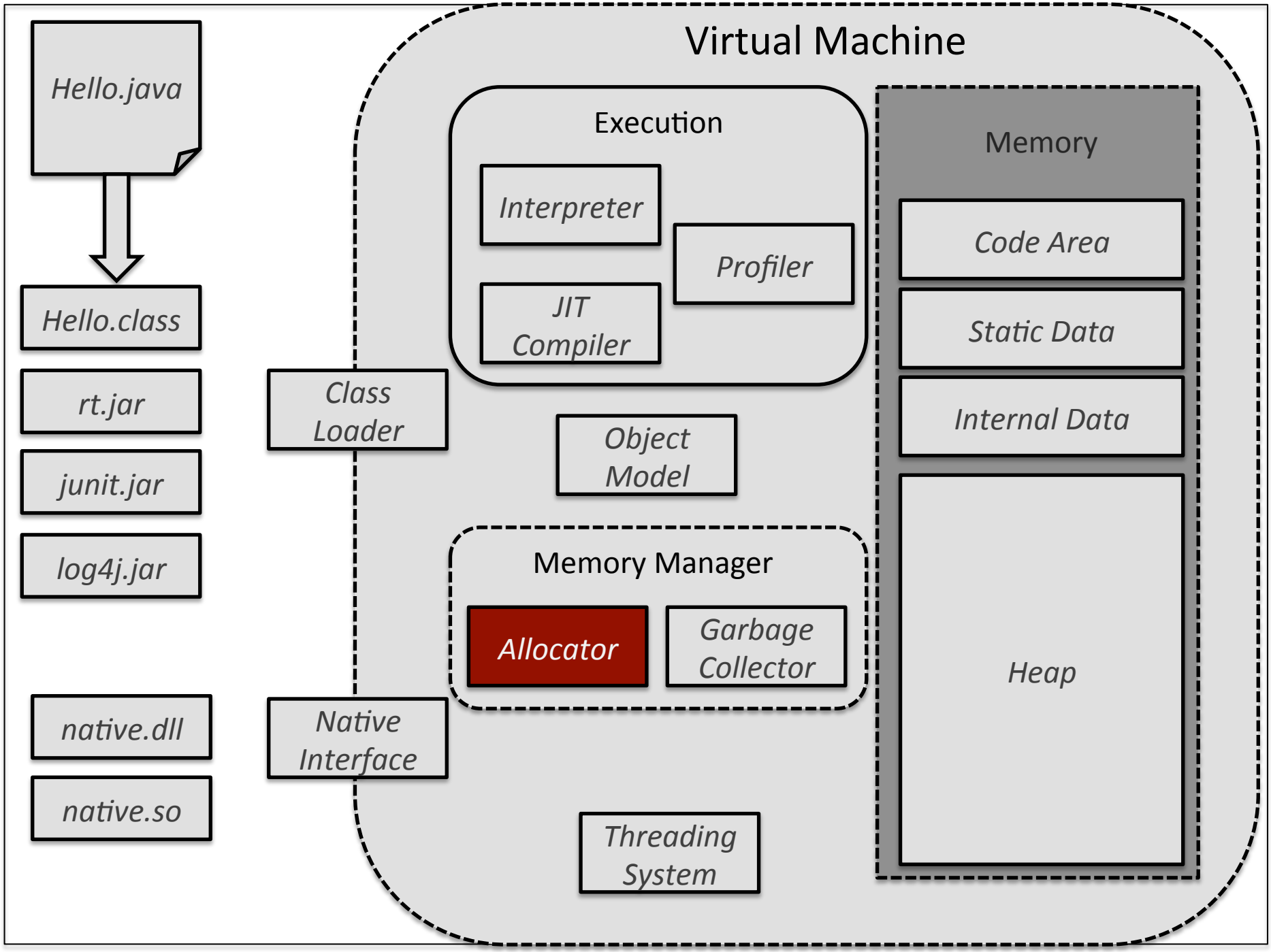
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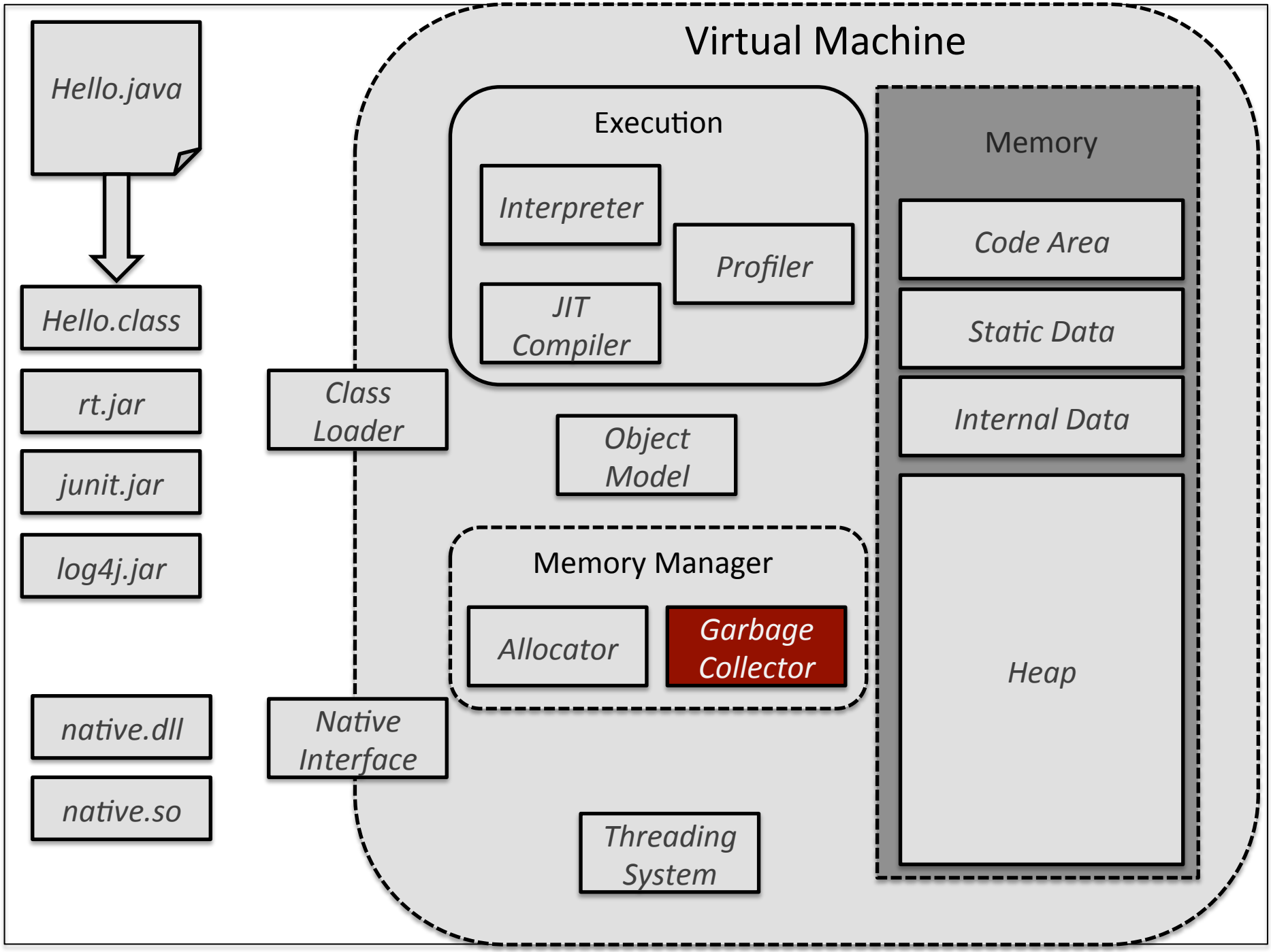
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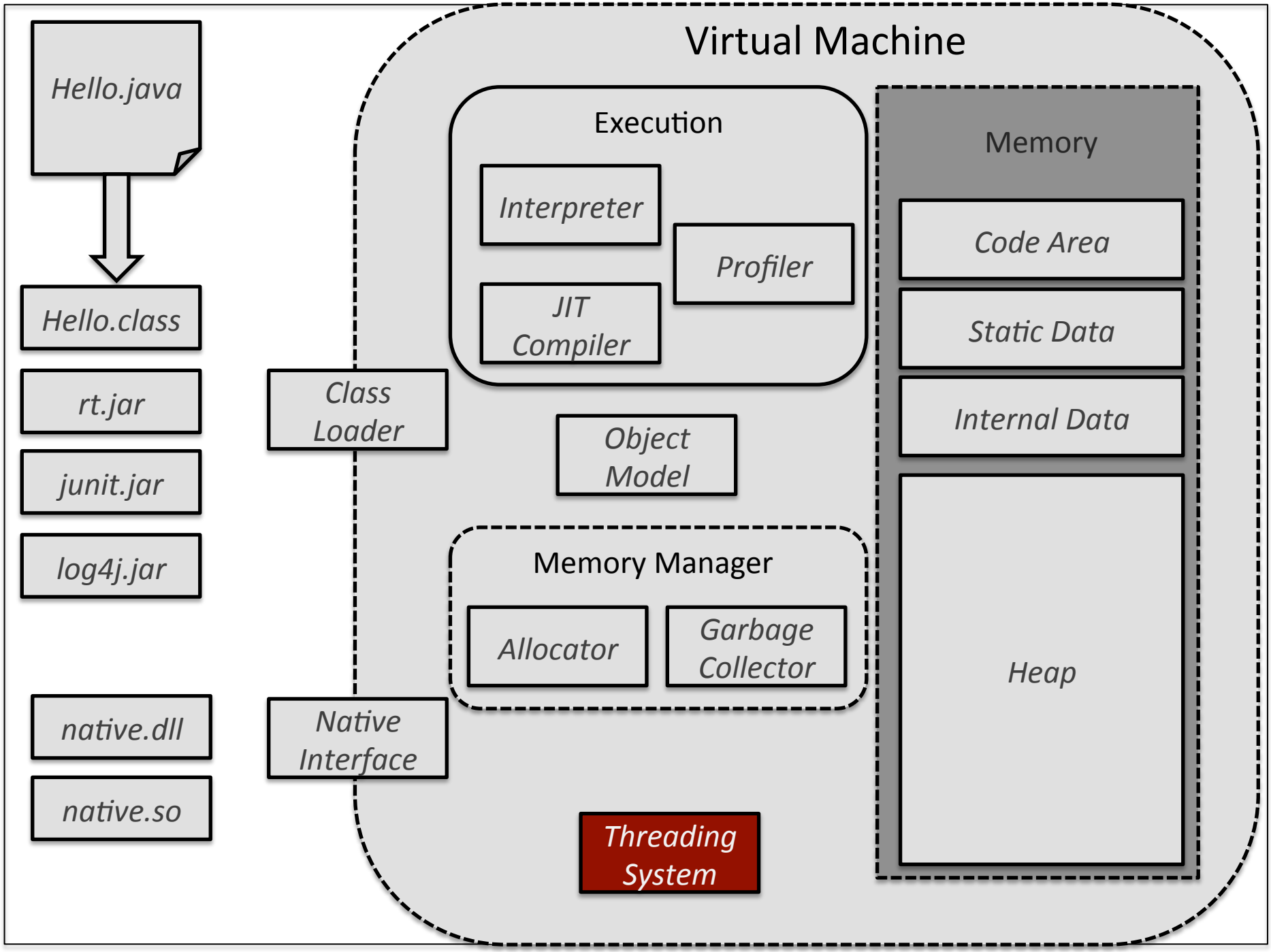
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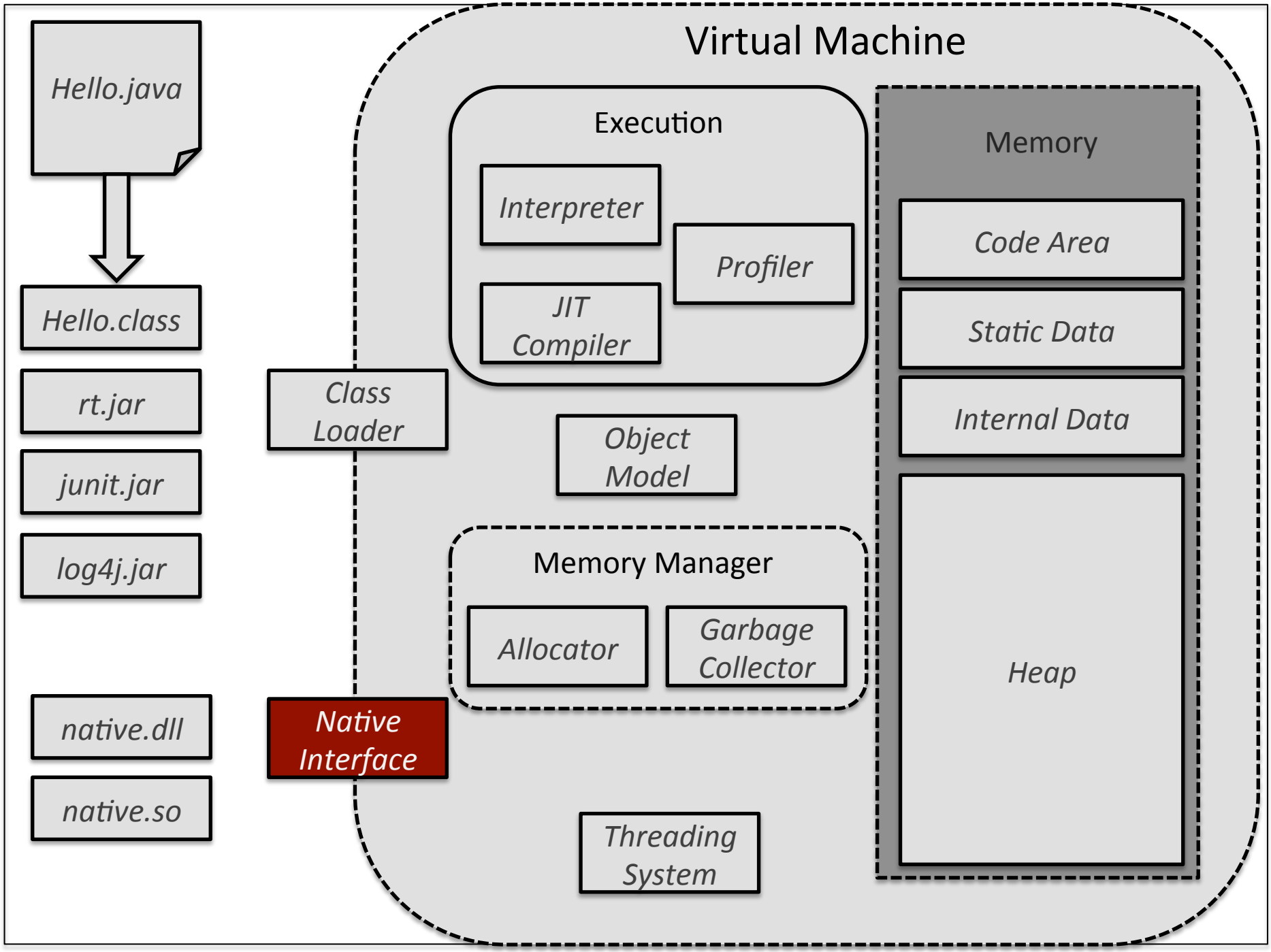
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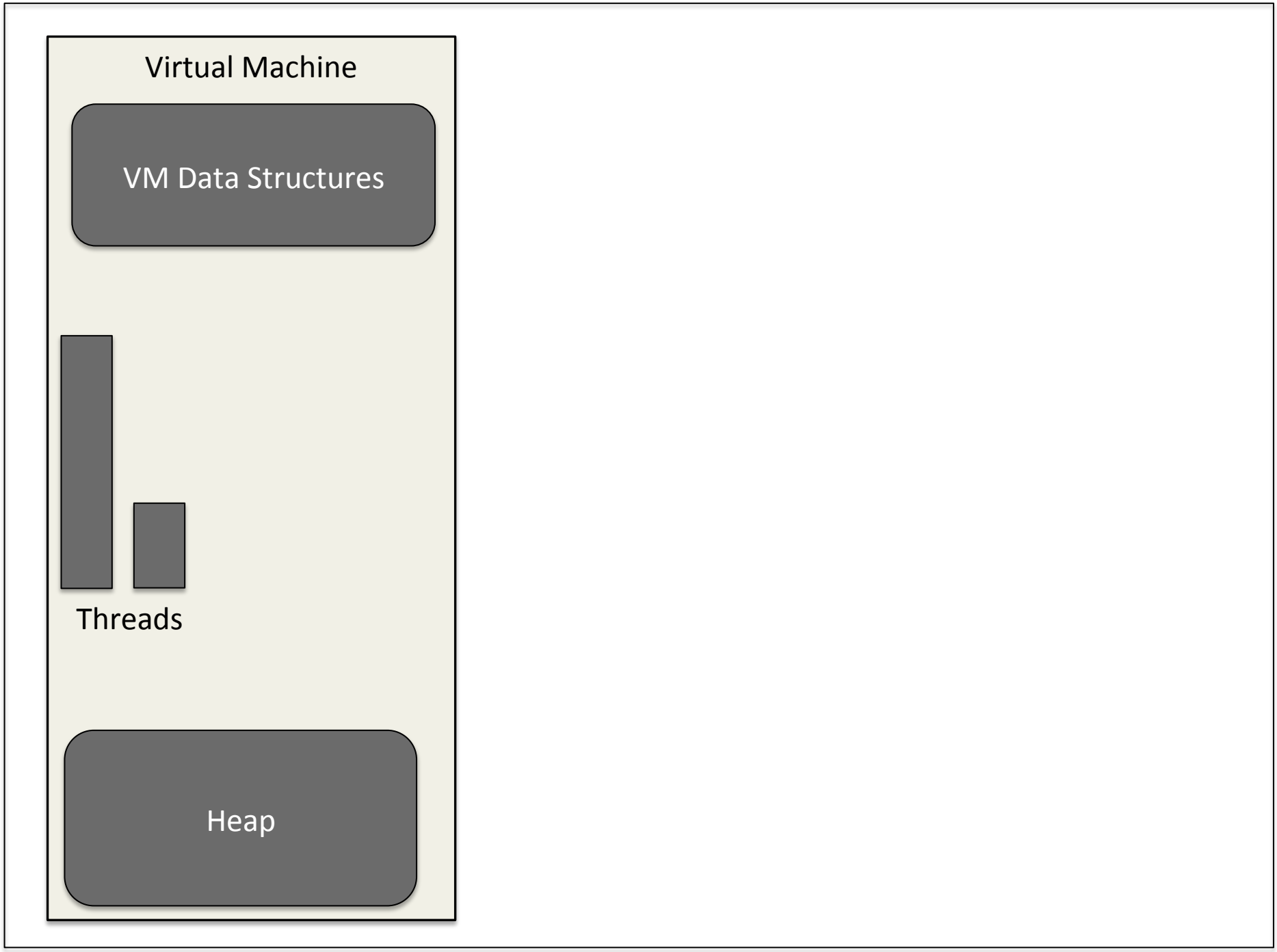
Case Study: Debugging

- Build the external debug tool
- Build the JVMTI agent
  - May need a separate implementation per platform
- Register the agent for relevant capabilities
- Relay events to the external tool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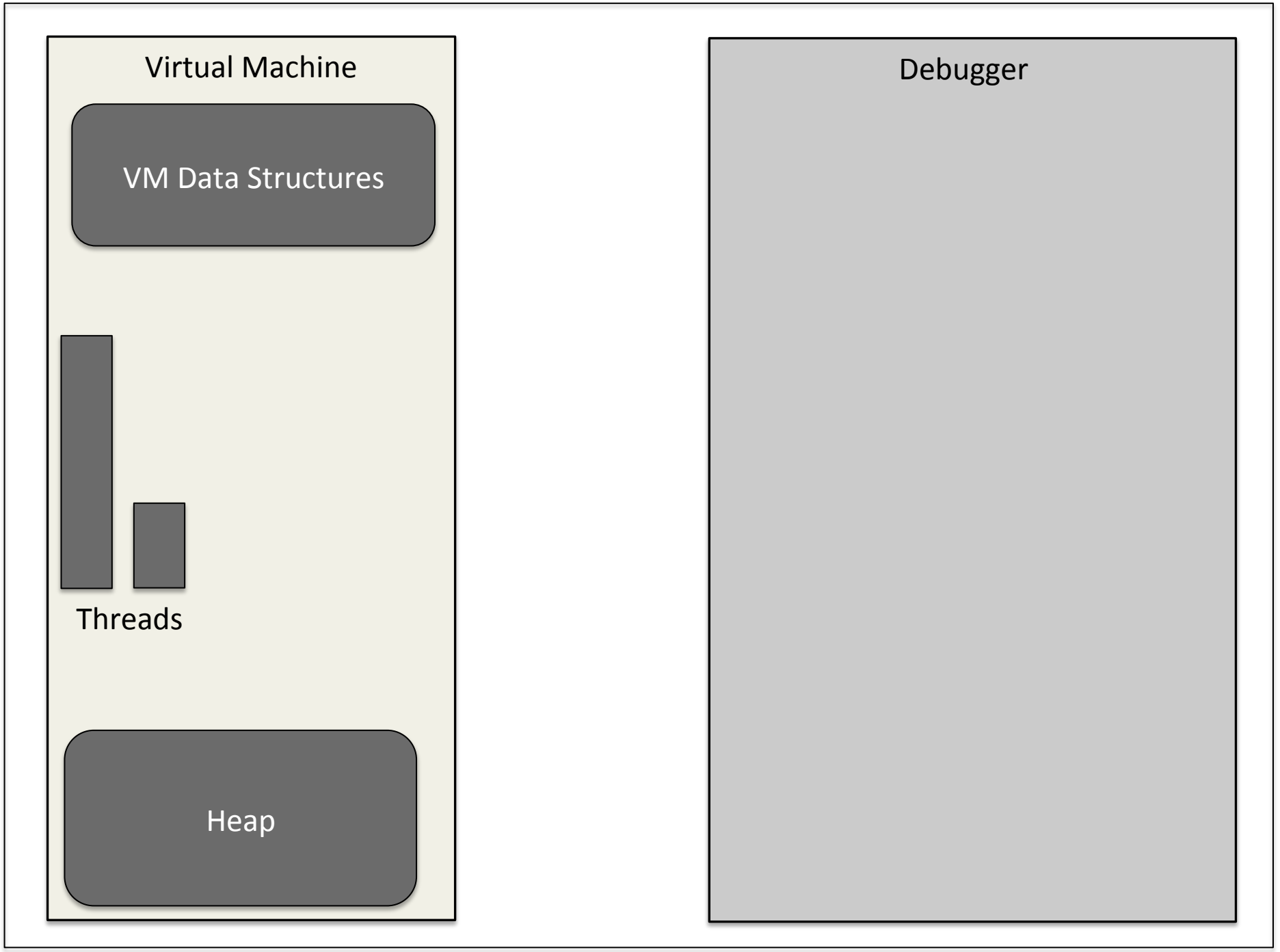
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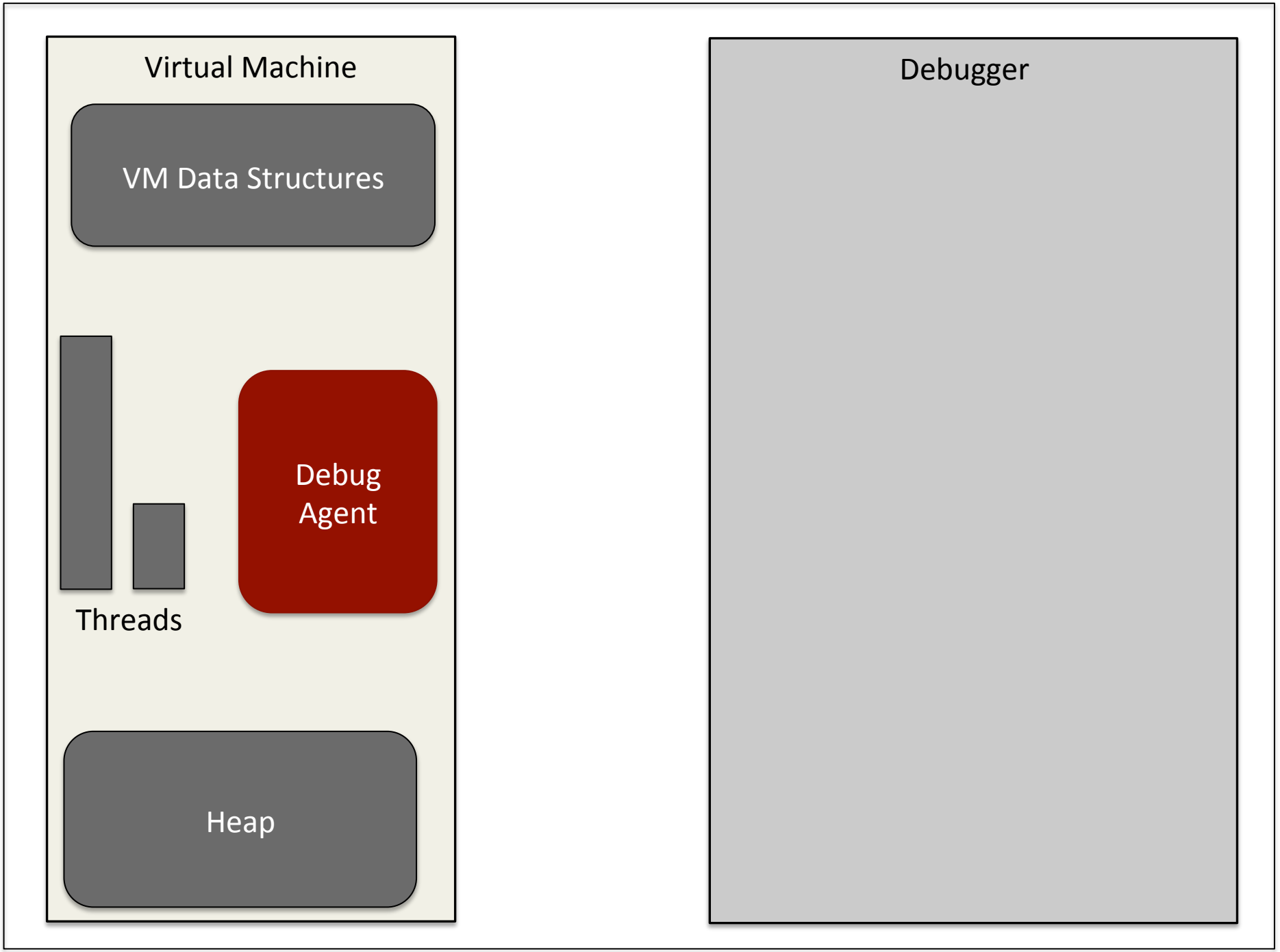
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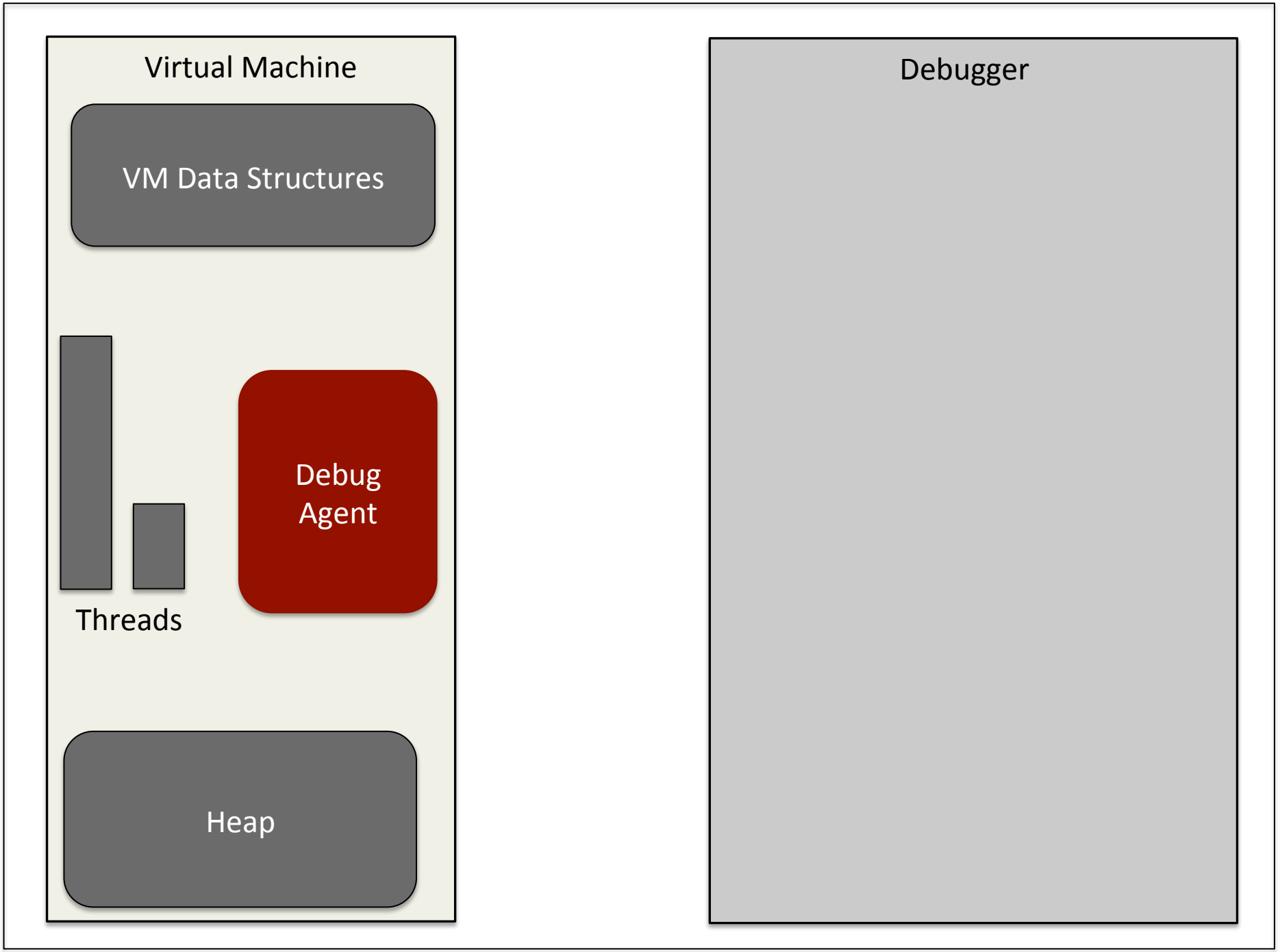
Capabilities

- Select the capabilities for the debugger
  - Receive exception events
  - Ability to tag objects
  - Ability to set breakpoints
  - Ability to signal threads
  - Ability to single-step through code
- Register the capabilities and callbacks at startup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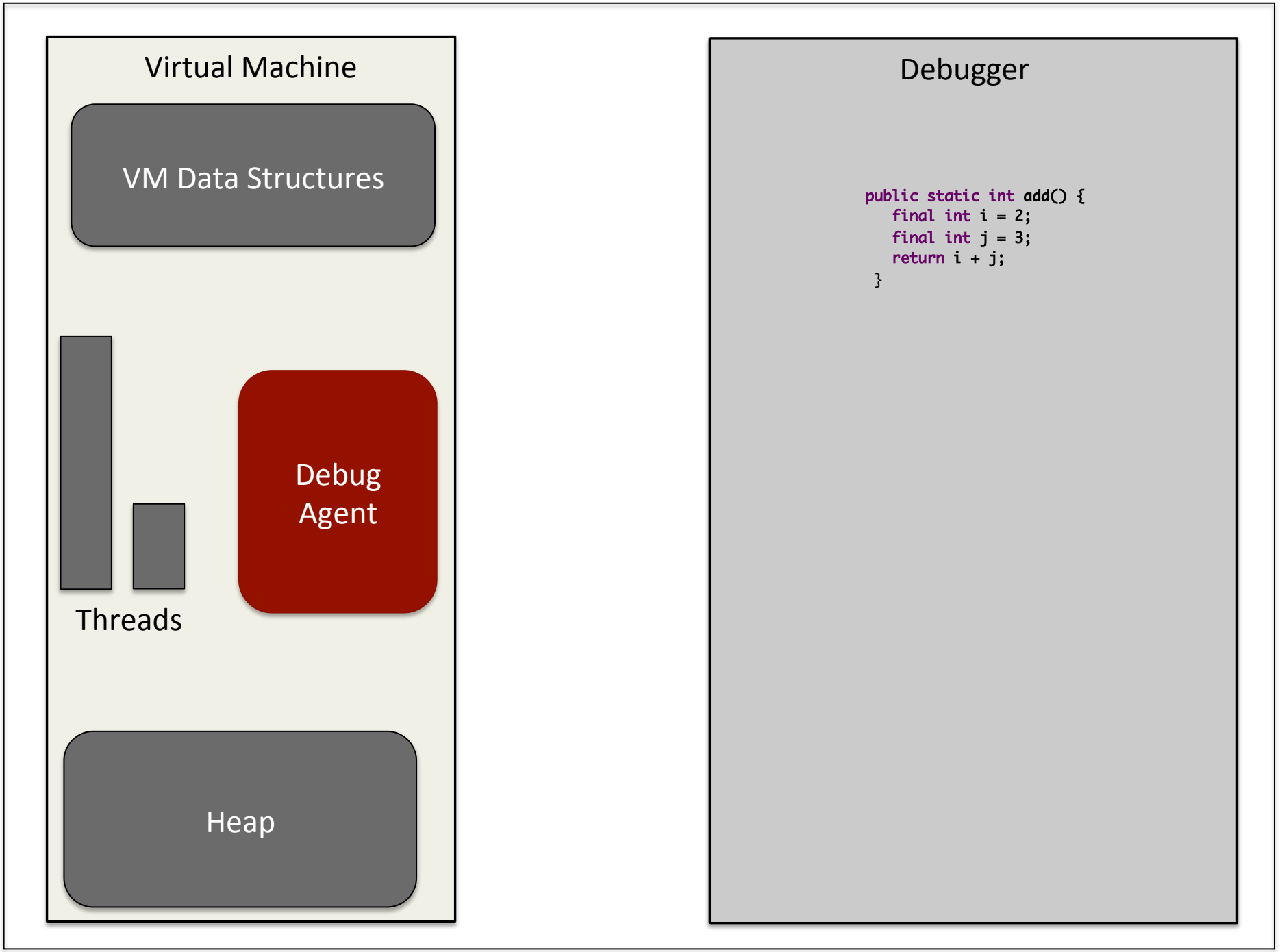
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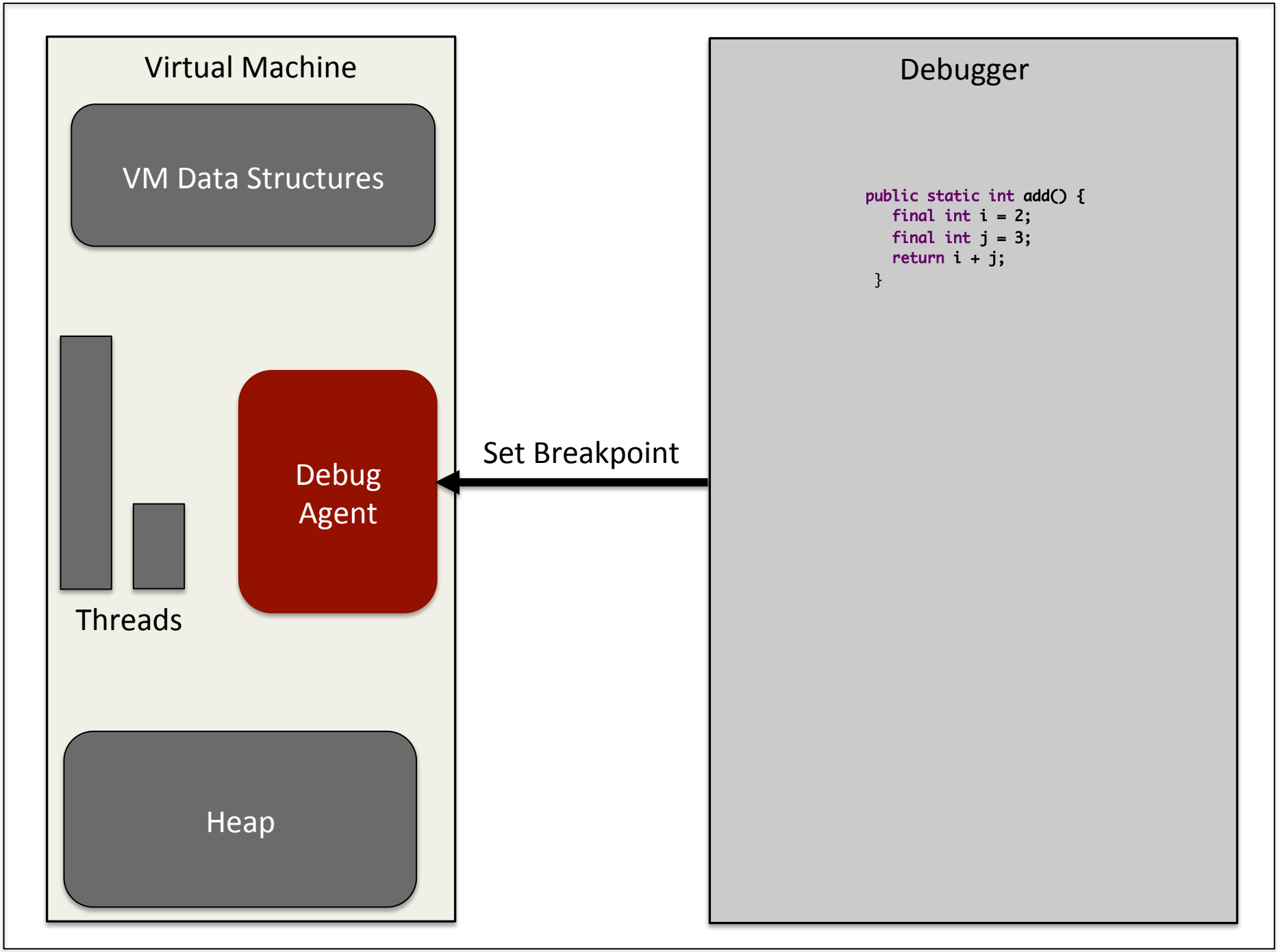
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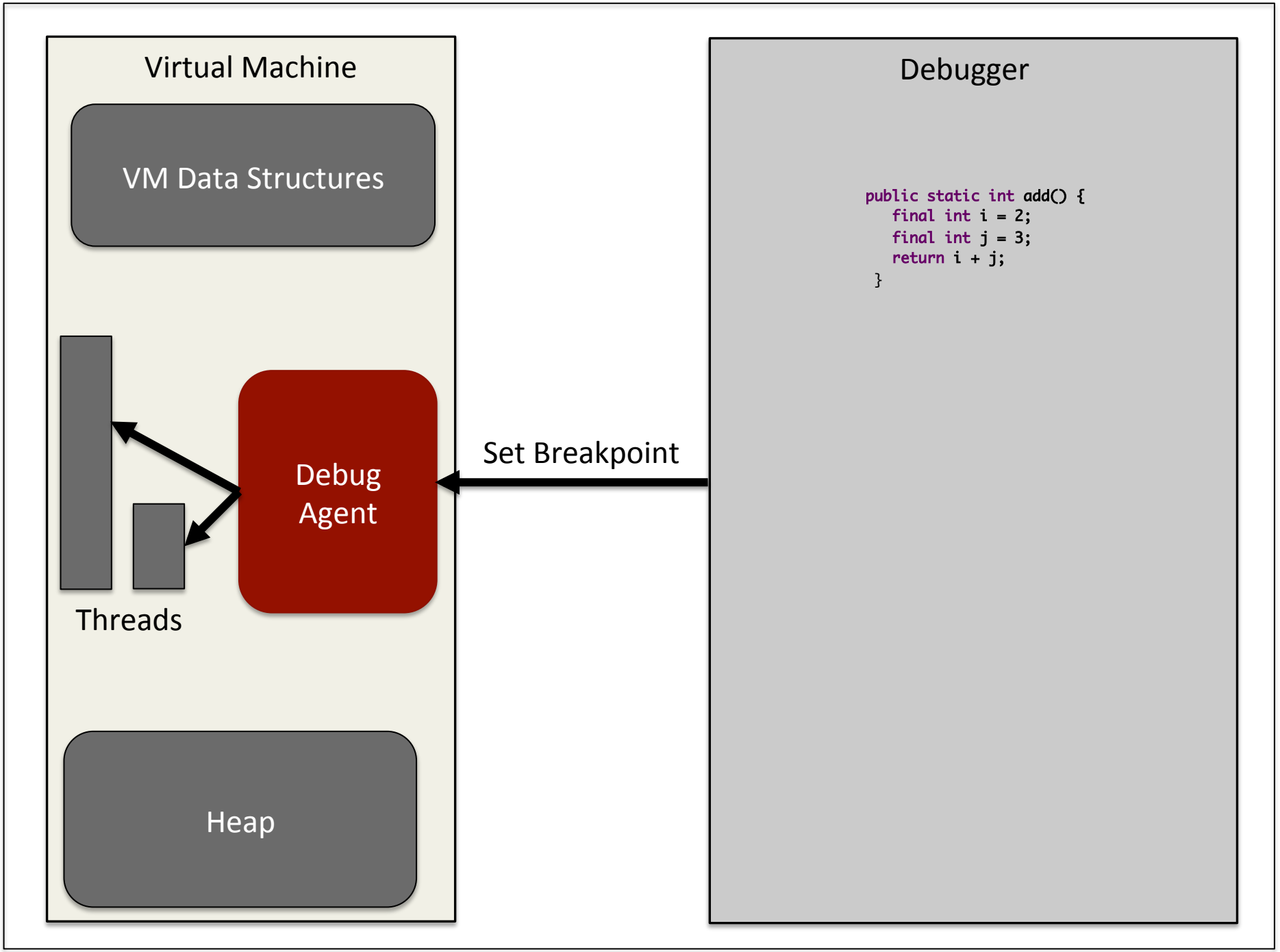
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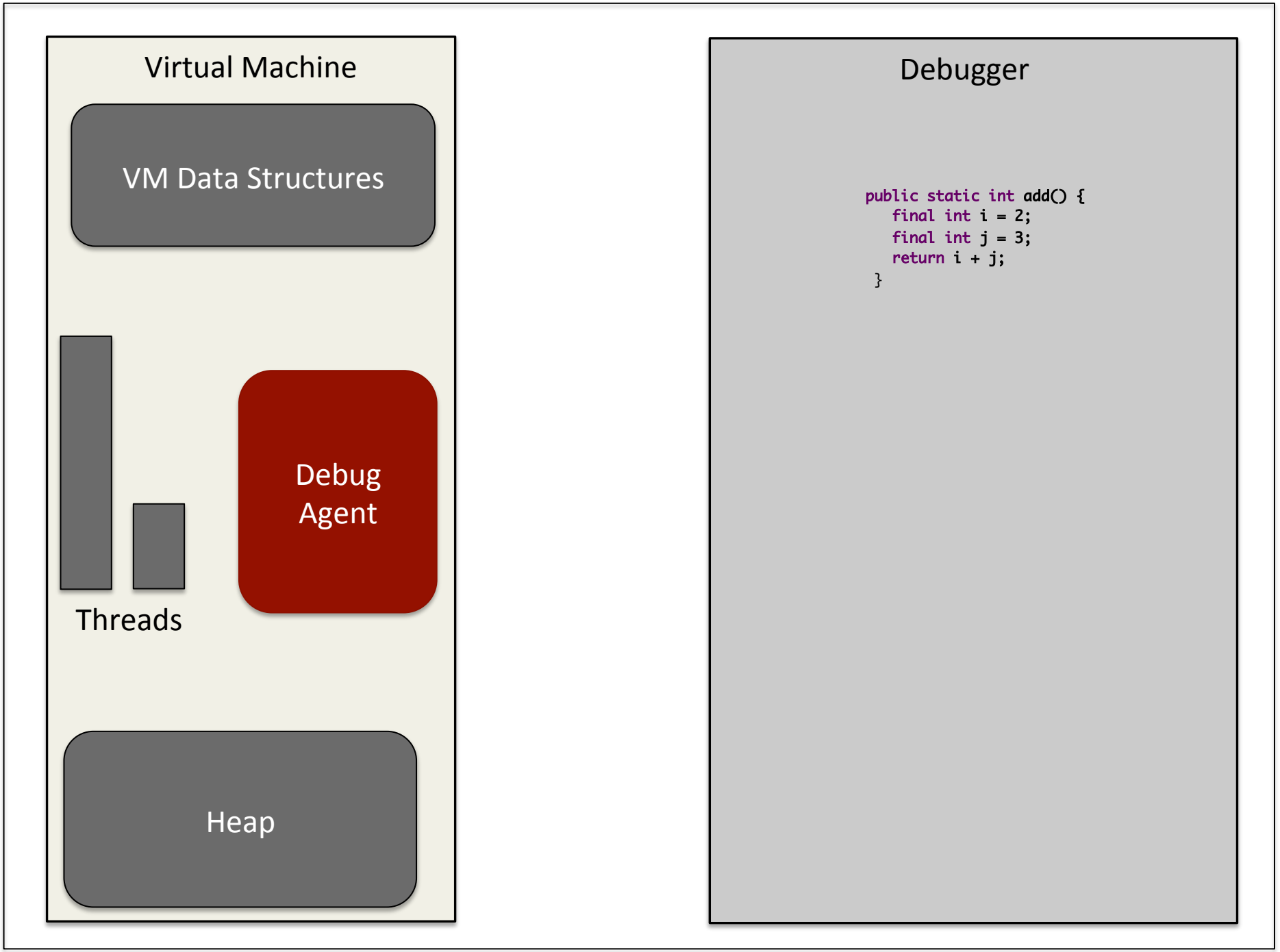
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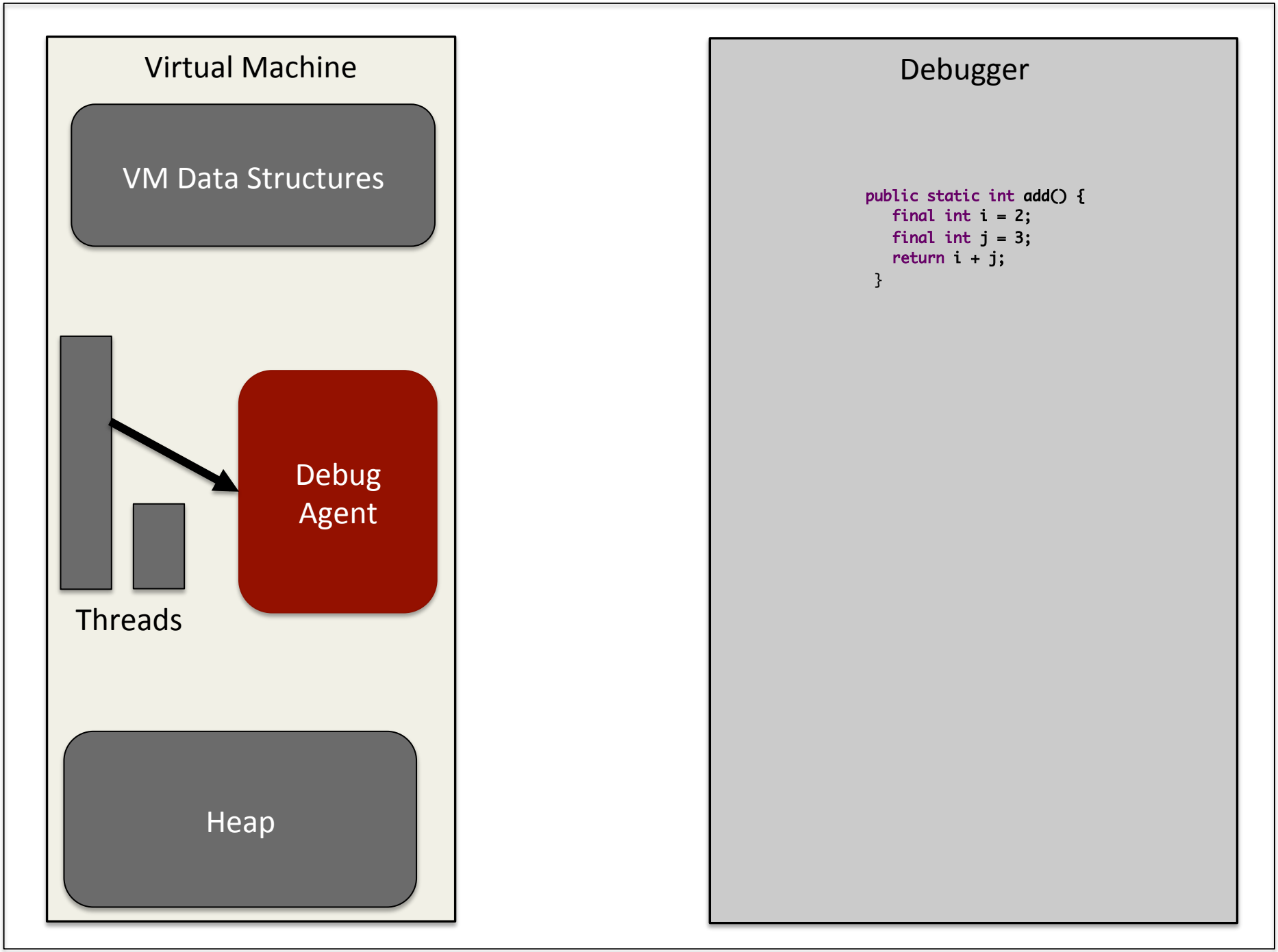
Virtual Machine
VM Data Structures
Debug Agent
Threads
Heap
Debugger
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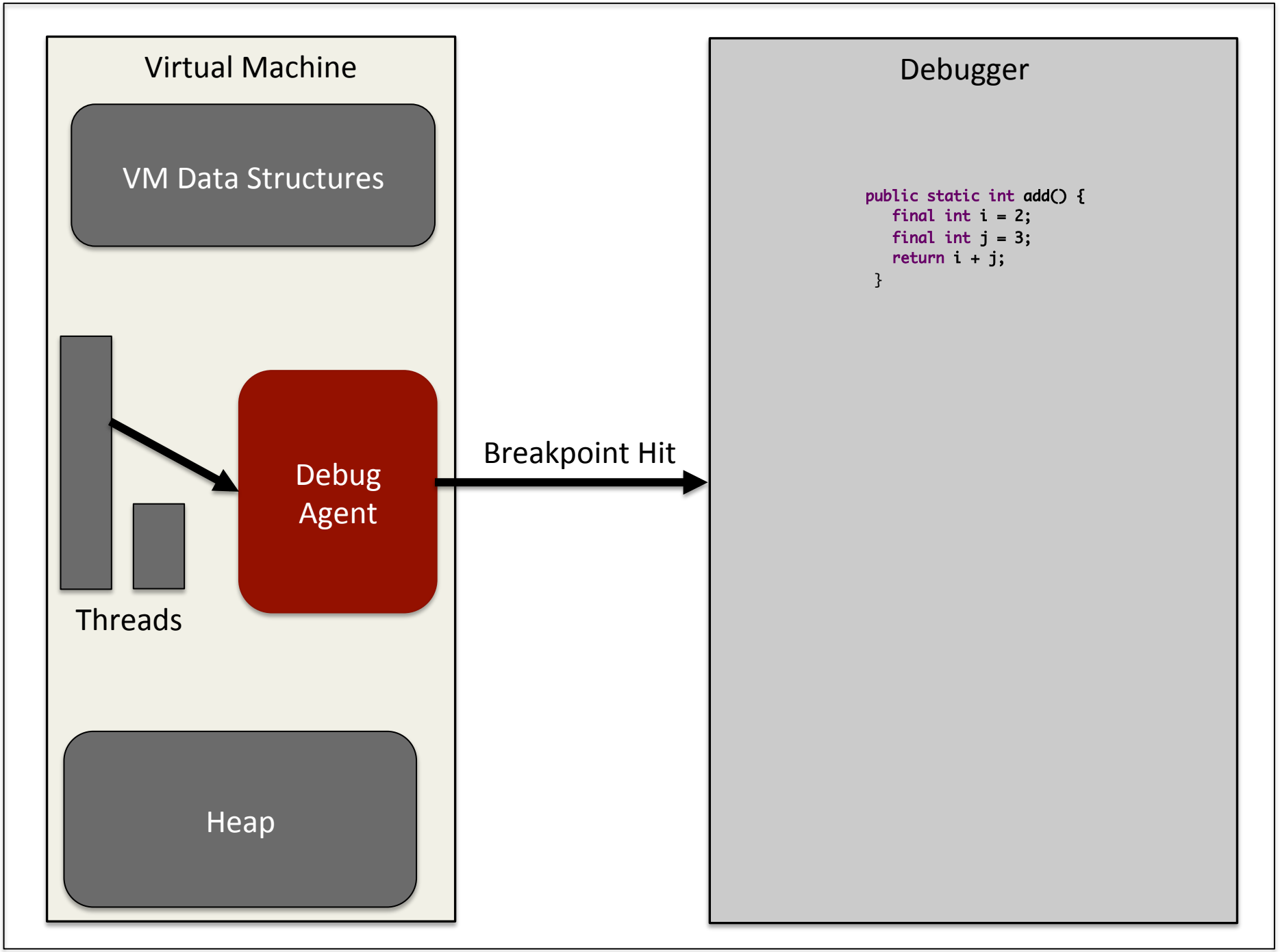
Virtual Machine
VM Data Structures
Threads
Debug Agent
Heap
Breakpoint Hit
Debugger
public static int add() {
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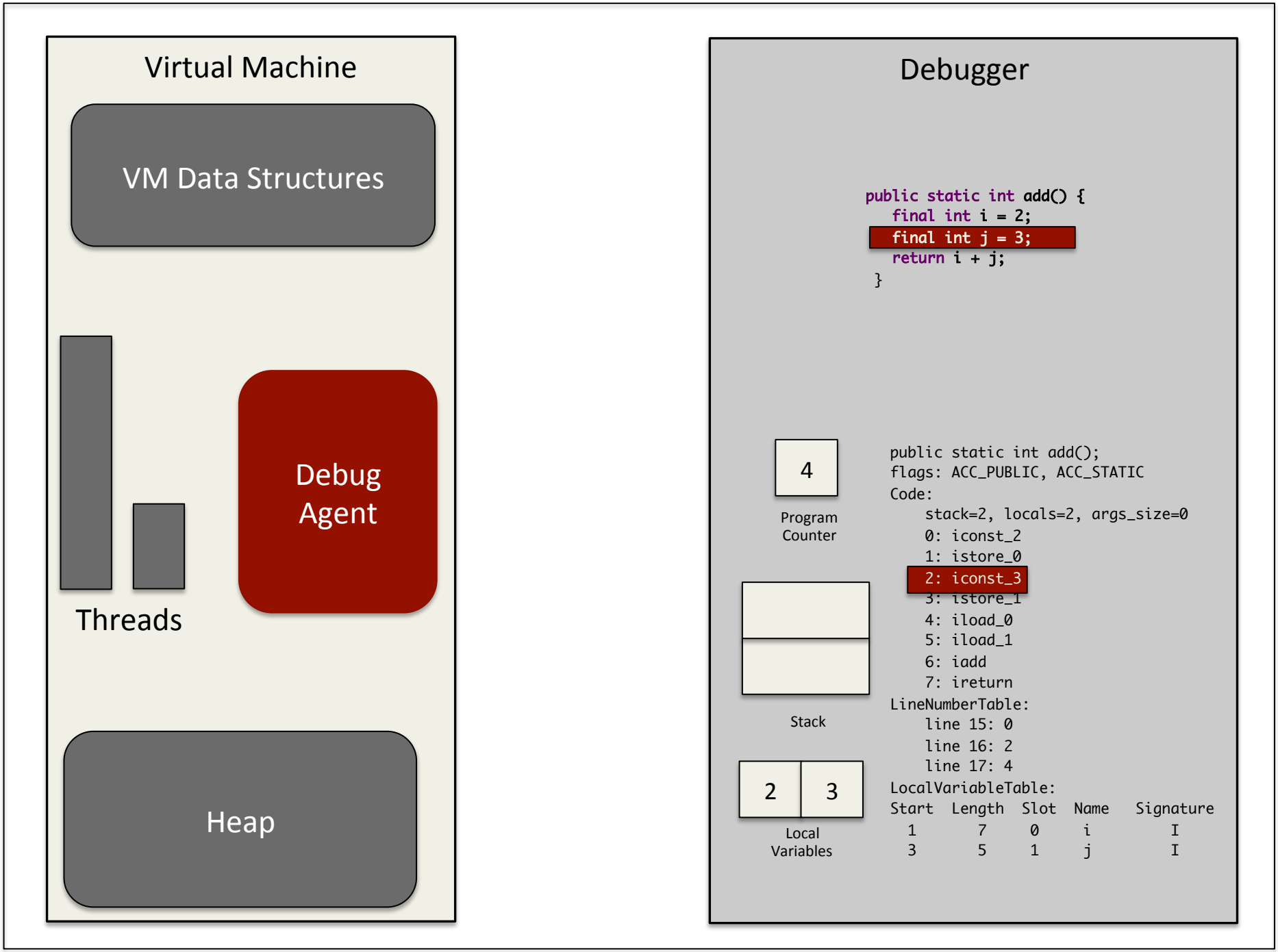
Virtual Machine
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4
Program Counter
Stack
2
3
Local Variables
public static int add();
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=2, locals=2, args_size=0
0: iconst_2
1: istore_0
2: iconst_3
3: istore_1
4: iload_0
5: iload_1
6: iadd
7: ireturn
LineNumberTable:
line 15: 0
line 16: 2
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LocalVariableTable:
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1 7 0 i I
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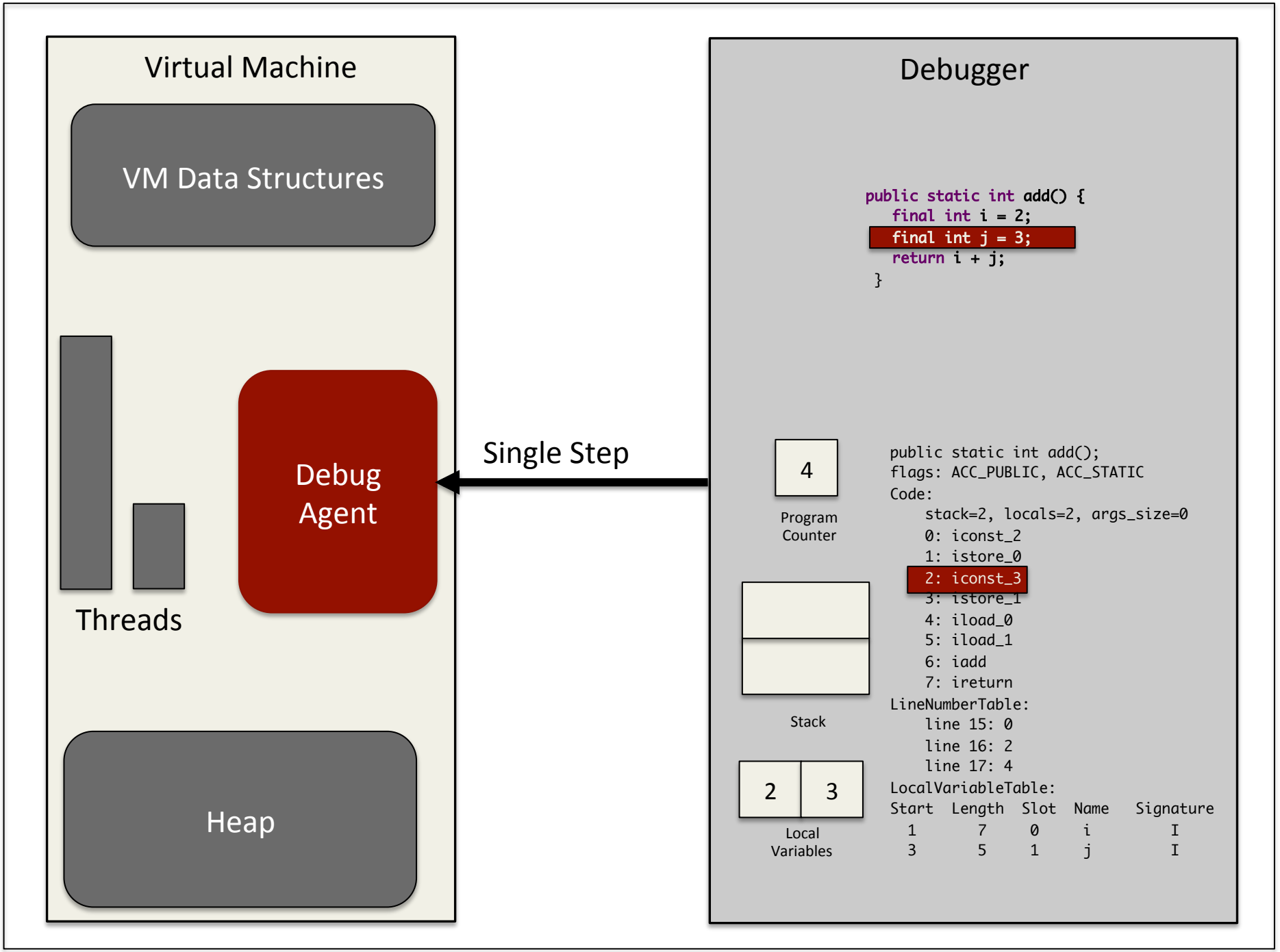
Virtual Machine
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Single Step
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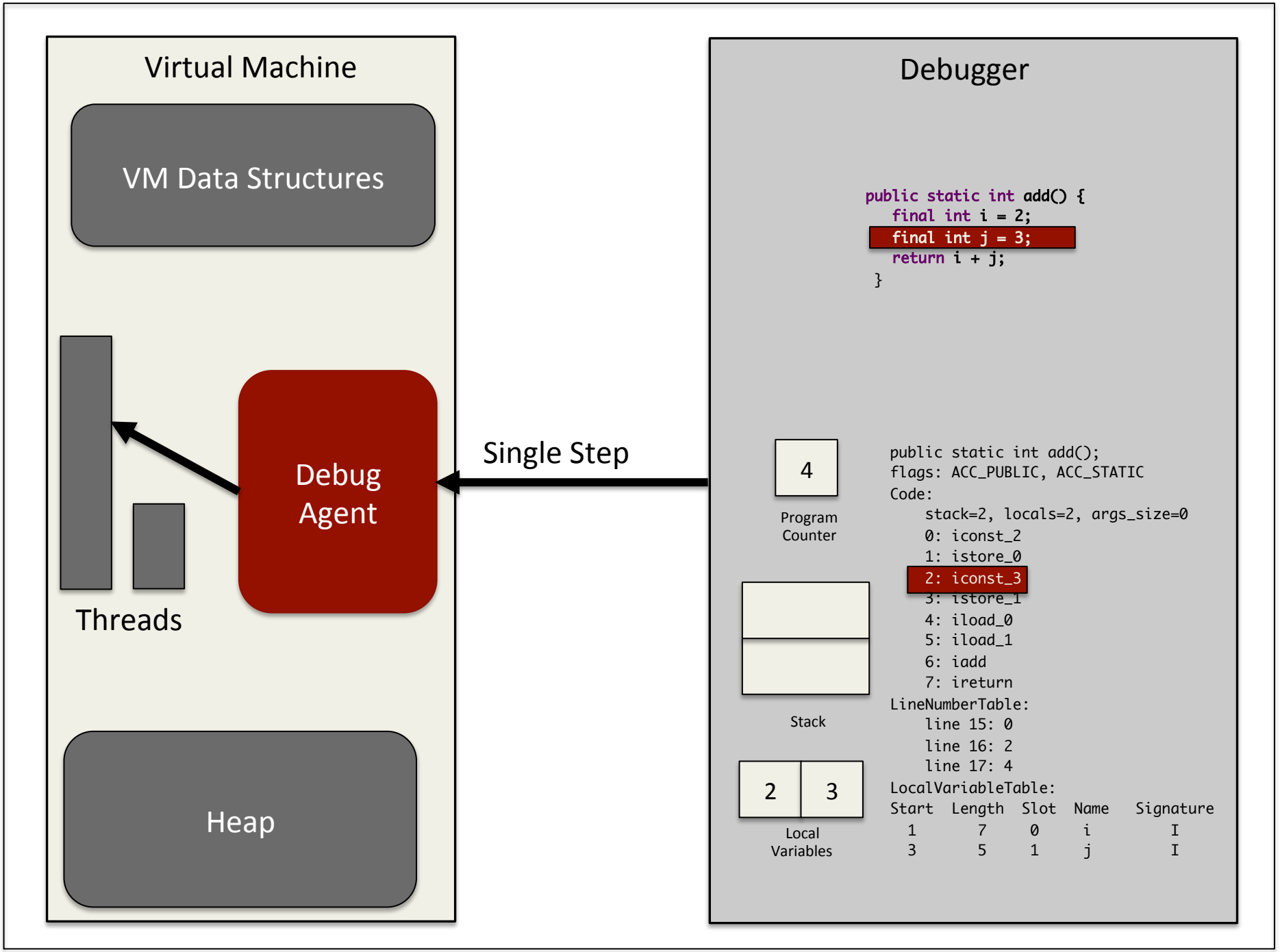
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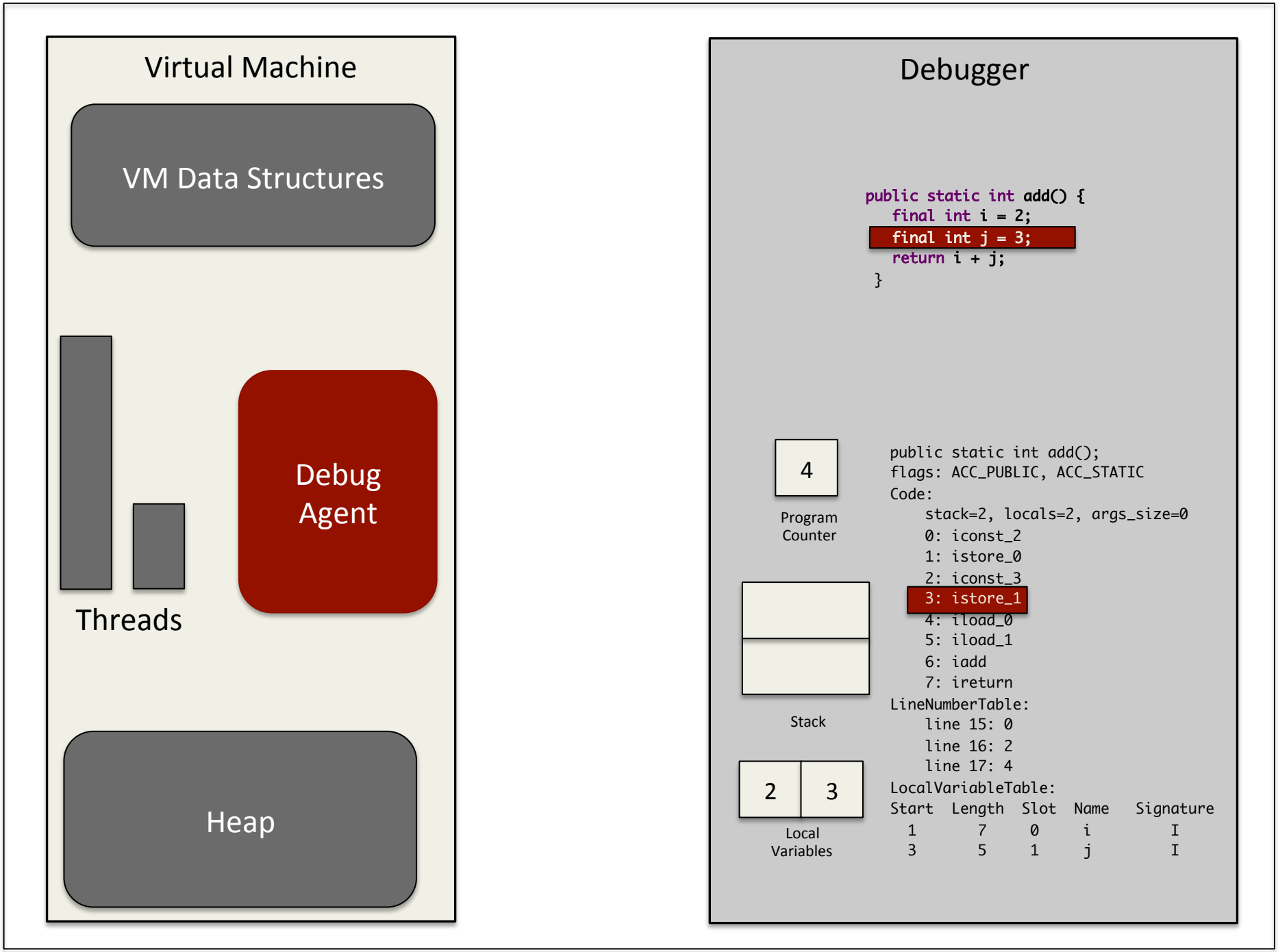
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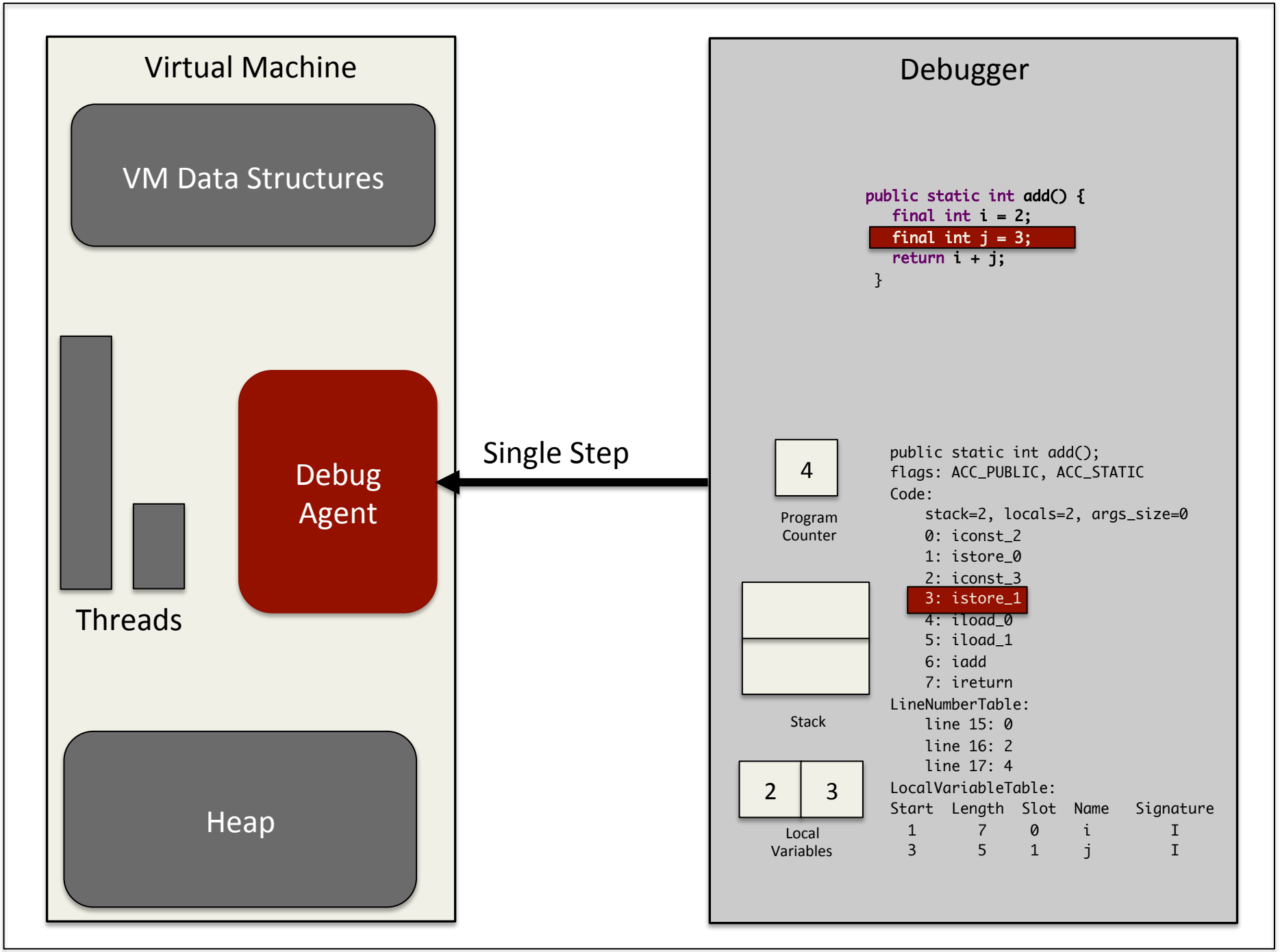
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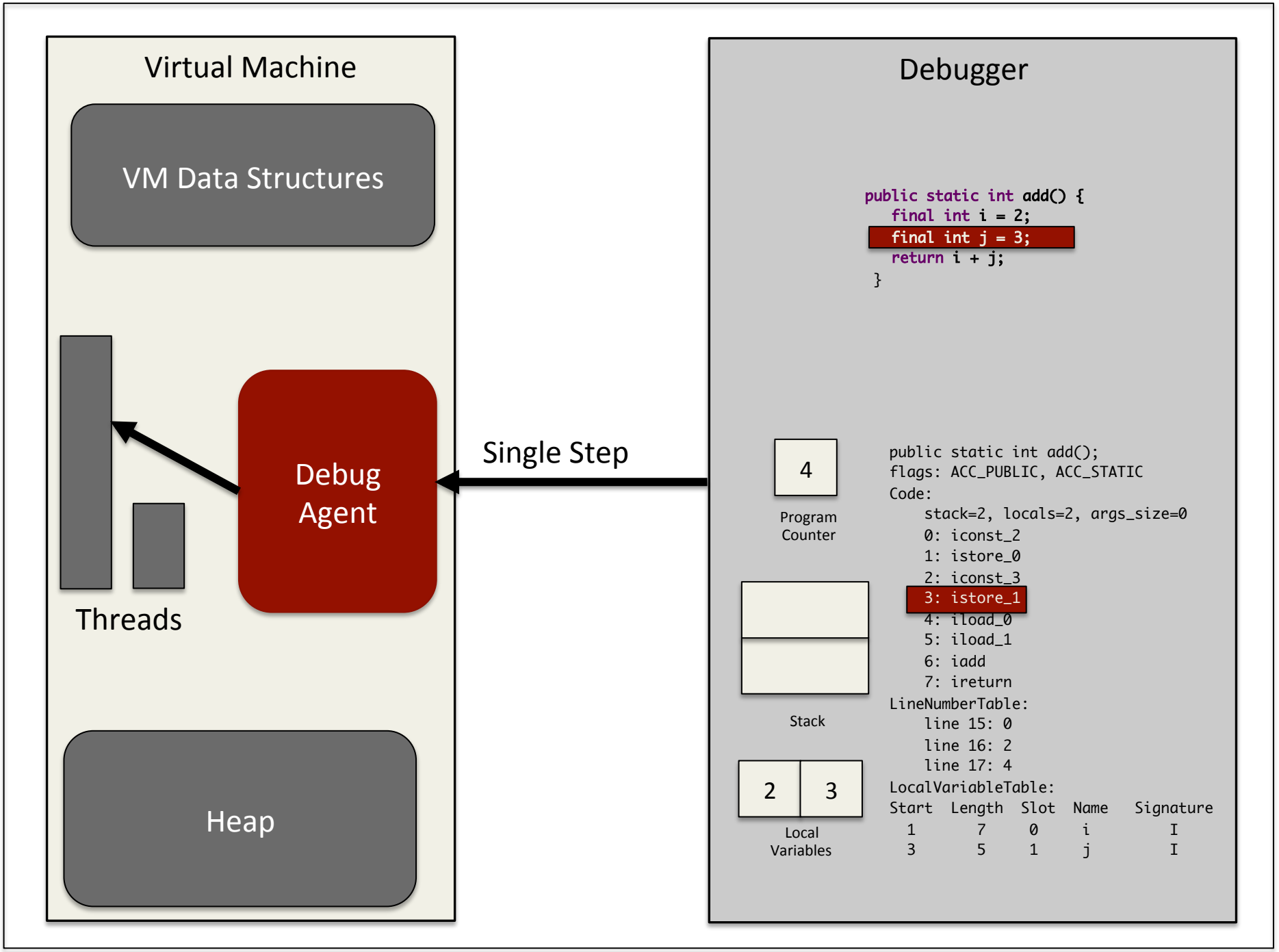
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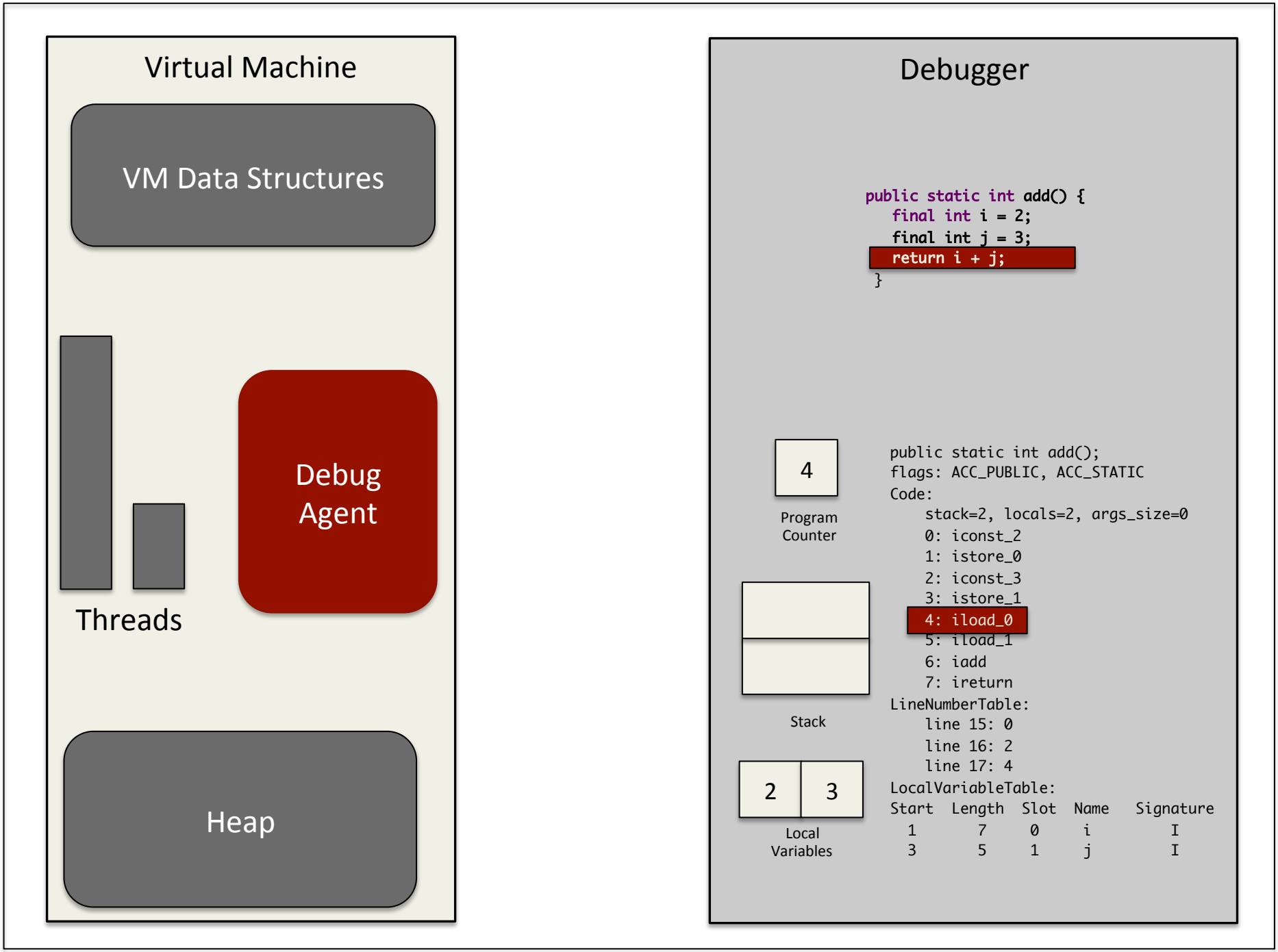
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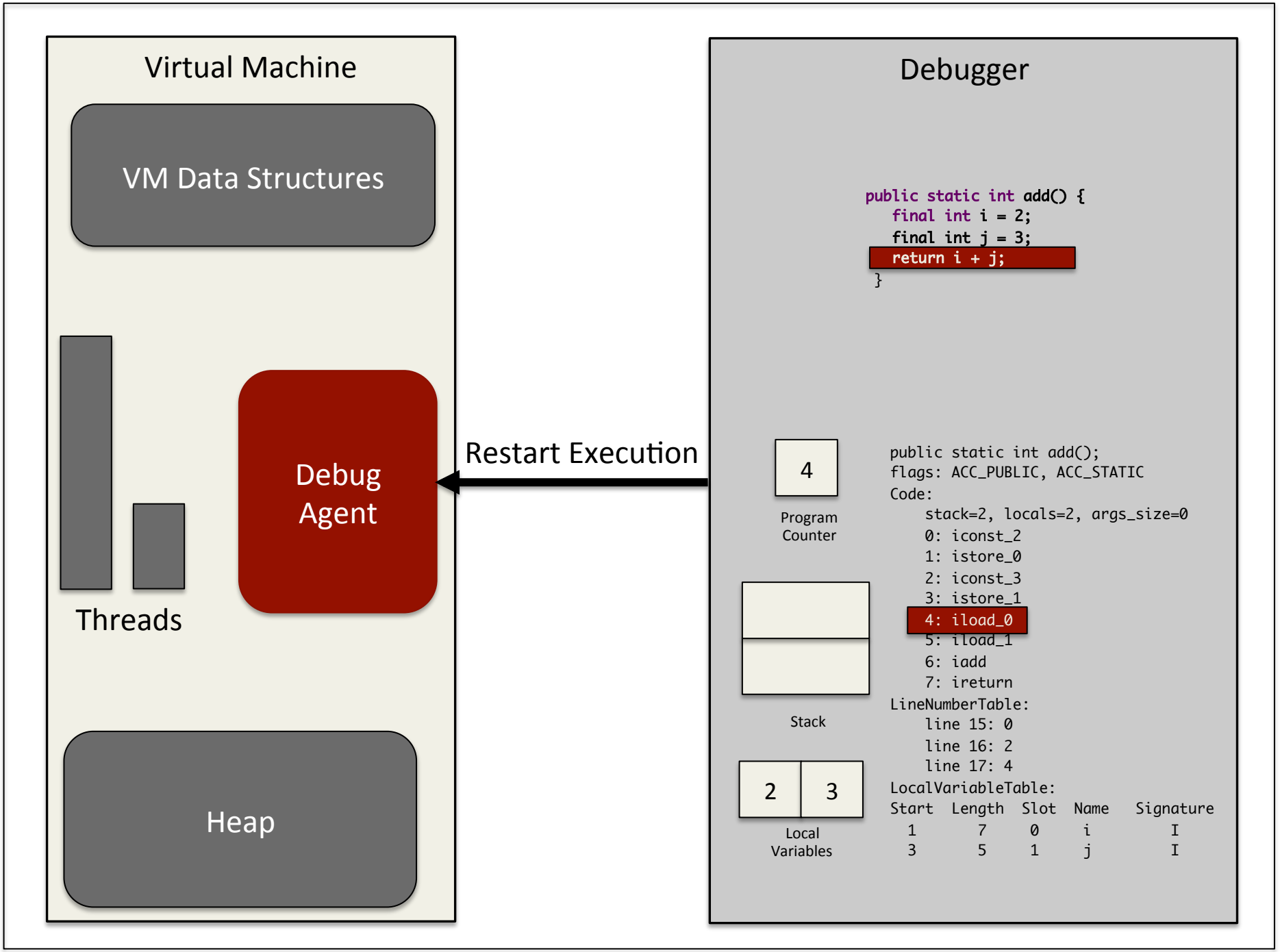
Virtual Machine
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Debug Agent
Heap
Restart Execution
Debugger
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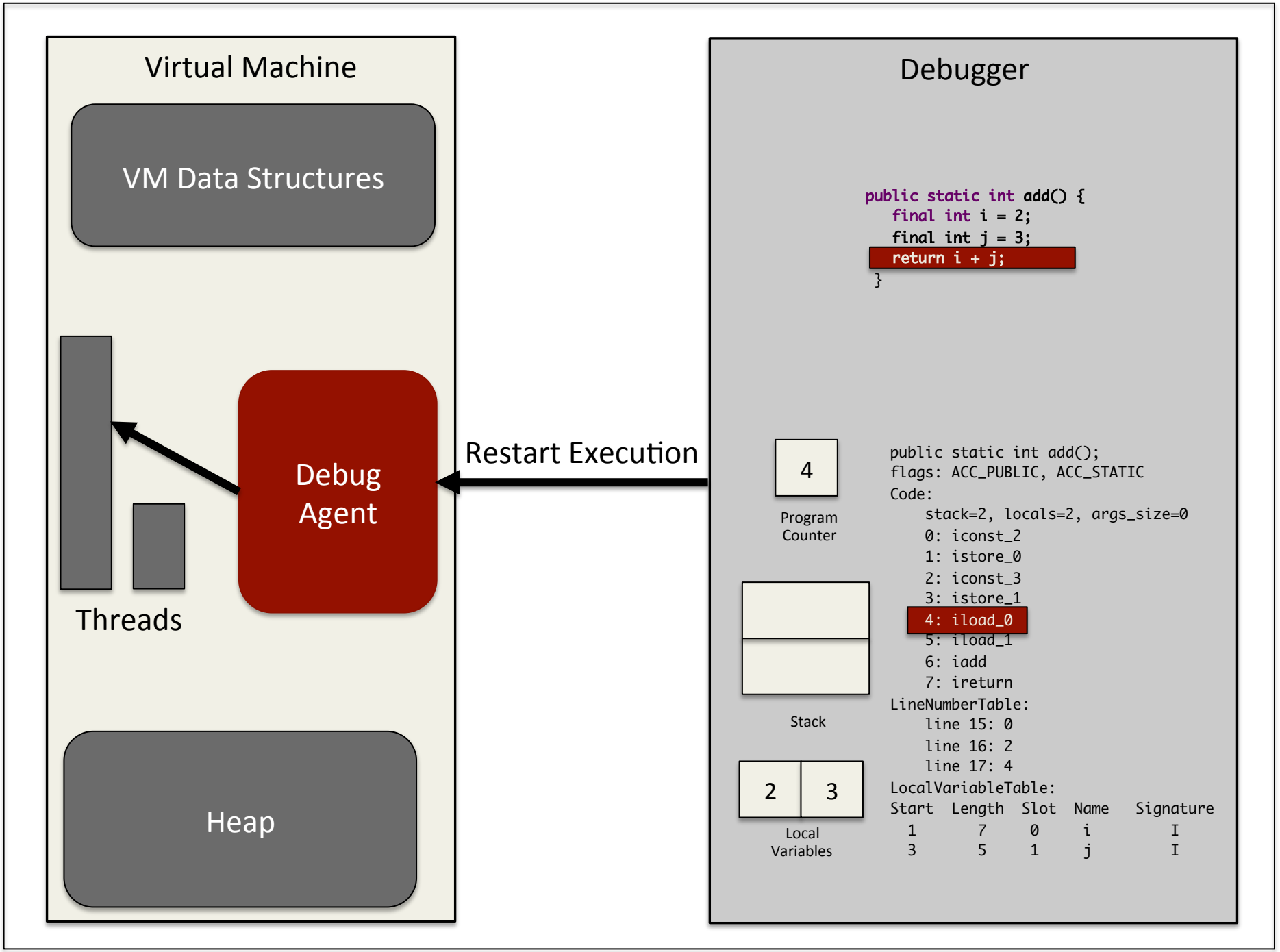
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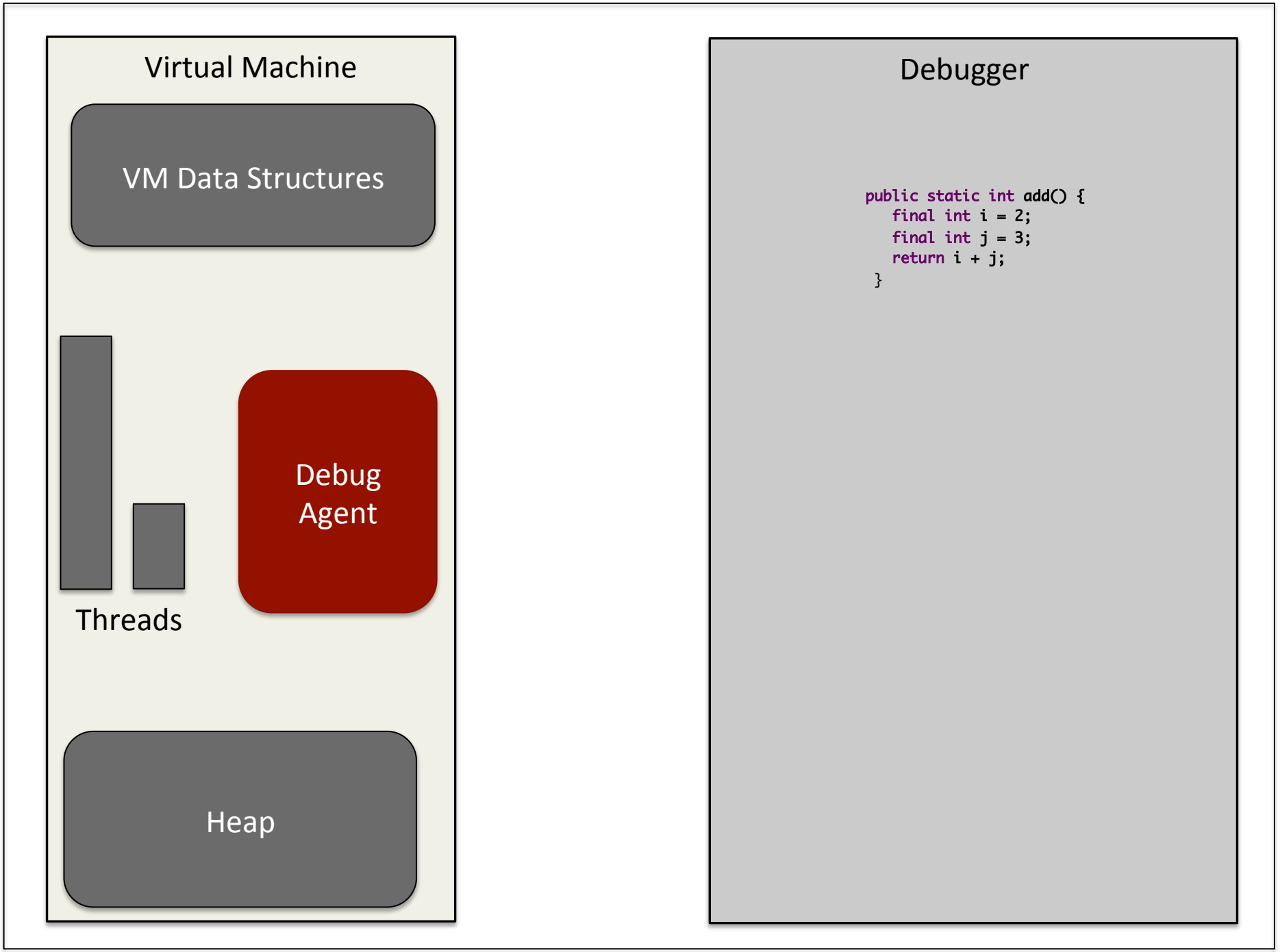
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Missing Events

- Not all interesting operations have events
  - Object allocation
  - Operand stack or local variable activity
- Interface allows for bytecode modification
  - Rewrite the class file before the VM loads it
  - Reload a class to insert new code
- Instrumentation happens during class loading
  - After loading but before linking
  - Rewritten bytecode is verified

Bytecode Instrumentation

- Can insert very specific data gathering
  - Generate conditionally events
  - May rely on static analysis
- Profiling code is pure Java bytecode
  - New bytecode becomes part of the program
  - JIT compiler optimizes profiling code
- No native code involved in runtime profiling

Java-Level Agent Data

- May now have two methods of profiling
  - Instrumented bytecode at the Java level
  - JVMTI agent works in native code
- May need communication between the two
  - Can use JNI to access Java-level data
- May output two streams to external tool
  - Less communication inside the VM
  - More complexity in the tool interface

Instrumentation Limitations

- Bytecode instrumentation best for small changes
  - Add a static call to profiling code
  - Log program state at key points during execution
- Hard to make more elaborate changes
  - Can only modify classes, not create them
  - Cross-class dependencies hard to manage
  - Instrumentation code normally written in C
- Custom classloaders are much more flexible

Bytecode Rewriting

- Modifying bytecode is trickier than it seems
  - Need to pass verification
  - Gets harder when changes are not local
- Bytecode indices are important
  - Jump instructions
  - Local variable, line number, exception tables
- Adding local variables can cause unexpected issues
  - Some bytecodes have indices built in

Object Allocation

- Normally access by bytecode instrumentation
  - Instrument new, newarray, anewarray instructions
- Some allocations not captured this way
  - Constant interning
  - Reflection
  - Native allocations
- Special event signaled in these cases

Method Entry and Exit

- Capability exists for tracking method calls
  - Method entry and exit events can be generated
  - Callback method determines if they are interesting
- Tracking all method calls can be expensive
  - Well-factored code should consist of small methods
  - Need to generate events on inlined code
- Can use bytecode instrumentation instead
  - Much more selective about what to track

Heap Monitoring

- Interface provides some heap traversal calls
  - Can opt to find only reachable objects
  - Traversal order is not guaranteed
- Heap objects can be tagged on creation
  - Associate a `jlong` value with an object
  - Lets the agent keep track of that object later

Profiling

- Design of the tool similar to the debugger

- Use a different set of capabilities
  - Get monitor status
  - Access heap data
  - Receive object allocation events
  - Receive method enter and exit events
  - Ability to tag objects
  - Ability to instrument bytecode

Profiler Performance

- Some of the capabilities are heavyweight
  - Tracing the heap
  - Tracking allocations
  - Tracing method enter and exit
- Profilers should minimize disruption
- Can decide up-front what to monitor
  - Separate runs to track heap and execution time
  - Tailor the capabilities that the agent requests

Other uses for Tool Interface

- Code coverage
  - Instrument all paths through a method
- Deadlock or livelock analysis
  - Pause threads and check monitor status
- VM monitoring
  - Correlate VM events to OS or hardware counters
- Extreme bytecode rewriting
  - Modify classes that otherwise can't be rewritten