301AA - Advanced Programming

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***AP-04**:* *Runtime Systems and intro to JVM*

Overview

- Runtime Systems
- The Java Runtime Environment
- The JVM as an abstract machine
- JVM Data Types
- JVM Runtime Data Areas
- Multithreading
- Per-thread Data Areas
- Dynamic Linking
- JIT compilation
- Method Area

Runtime system

- Every programming language defines an **execution model**
- A **runtime system** implements (part of) such execution model, providing support during the execution of corresponding programs
- **Runtime support** is needed both by *interpreted* and by *compiled* programs, even if typically less by the latter

Runtime system (2)

- The runtime system can be made of
  - Code in the executing program generated by the compiler
  - Code running in other threads/processes during program execution
  - Language libraries
  - Operating systems functionalities
  - The interpreter / virtual machine itself

Runtime Support needed for…

- Memory management
  - Stack management: Push/pop of activation records
  - Heap management: allocation, garbage collection

  ➔ **Chapter 7 of "Dragon Book"**
- Input/Output
  - Interface to file system / network sockets / I/O devices
- Interaction with the **runtime environment**,
  - state values accessible during execution (eg. environment variables)
  - active entities like disk drivers and people via keyboards.

Runtime Support needed for… (2)

- Parallel execution via threads/tasks/processes
- Dynamic type checking and dynamic binding
- Dynamic loading and linking of modules
- Debugging
- Code generation (for JIT compilation) and Optimization
- Verification and monitoring

Java Runtime Enviroment - JRE

- Includes all what is needed to run compiled Java programs
  - JVM – Java Virtual Machine
  - JCL – Java Class Library (Java API)
- We shall focus on the JVM as a real runtime system covering most of the functionalities just listed
- Reference documentation:
  - The Java^{TM} Virtual Machine Specification
  - The Java Language Specification
  - https://docs.oracle.com/javase/specs/index.html

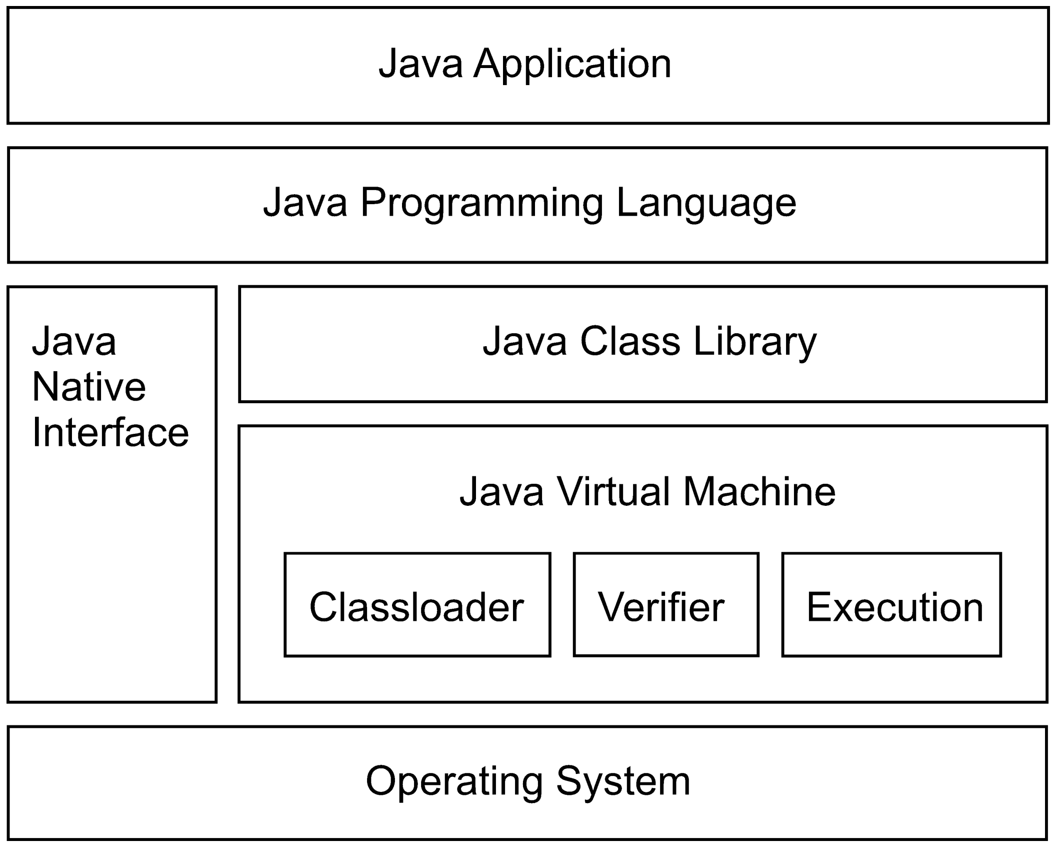
What is the JVM?

- The **JVM** is an **abstract** machine in the true sense of the word.
- The JVM specification does *not* give implementation details like memory layout of run-time data area, garbage-collection algorithm, internal optimization (can be dependent on target OS/platform, performance requirements, etc.)
- The JVM specification defines a machine independent “**class file format**” that all JVM implementations must support
- The JVM imposes **strong syntactic** and **structural constraints** on the code in a class file. Any language with functionality that can be expressed in terms of a valid class file can be hosted by the JVM

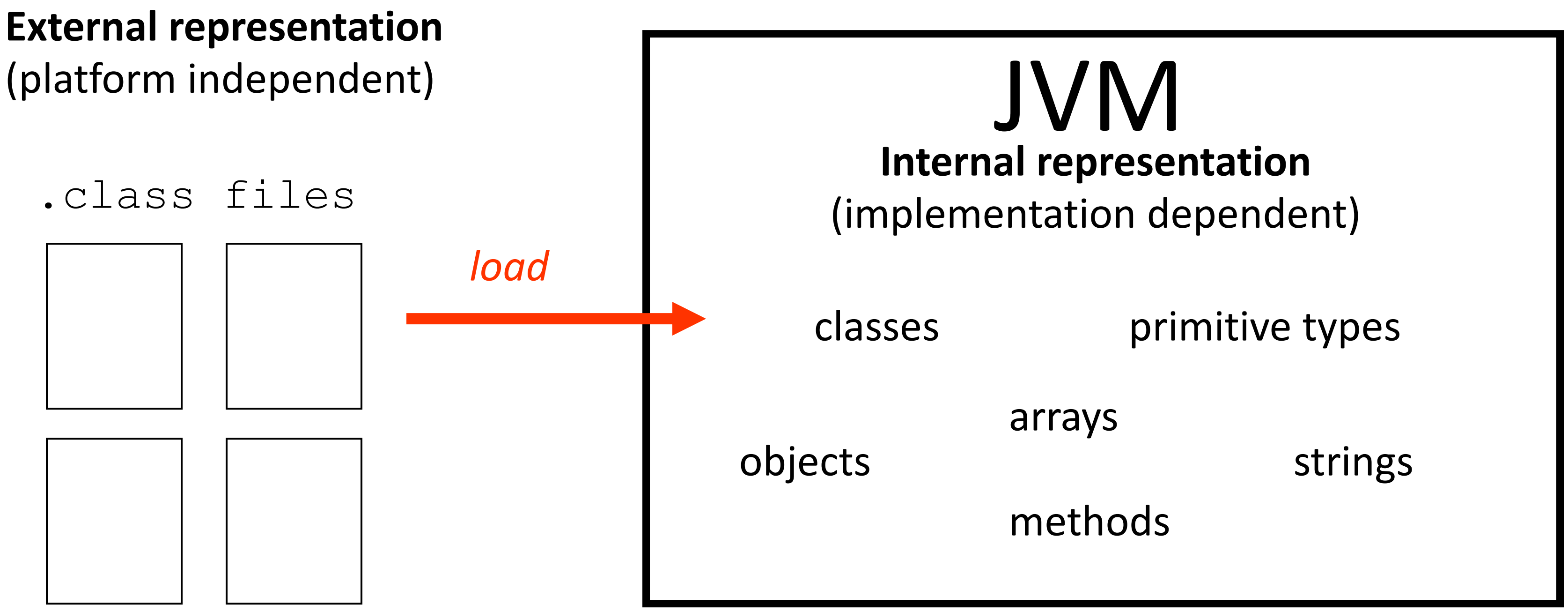
Execution model

- JVM is a ***multi-threaded stack based machine***
- JVM instructions
  - implicitly take arguments from the top of the **operand stack** of the current frame
  - put their result on the top of the operand stack
- The operand stack is used to
  - pass arguments to methods
  - return a result from a method
  - store intermediate results while evaluating expressions
  - store local variables

Java Abstact Machine Hierarchy



Class Files and Class File Format



JVM Data Types

Primitive types:

- numeric integral: `byte`, `short`, `int`, `long`, `char`
- numeric floating point: `float`, `double`
- boolean: `boolean` (support only for arrays)
- internal, for exception handling: `returnAddress`

Reference types:

- class types
- array types
- interface types

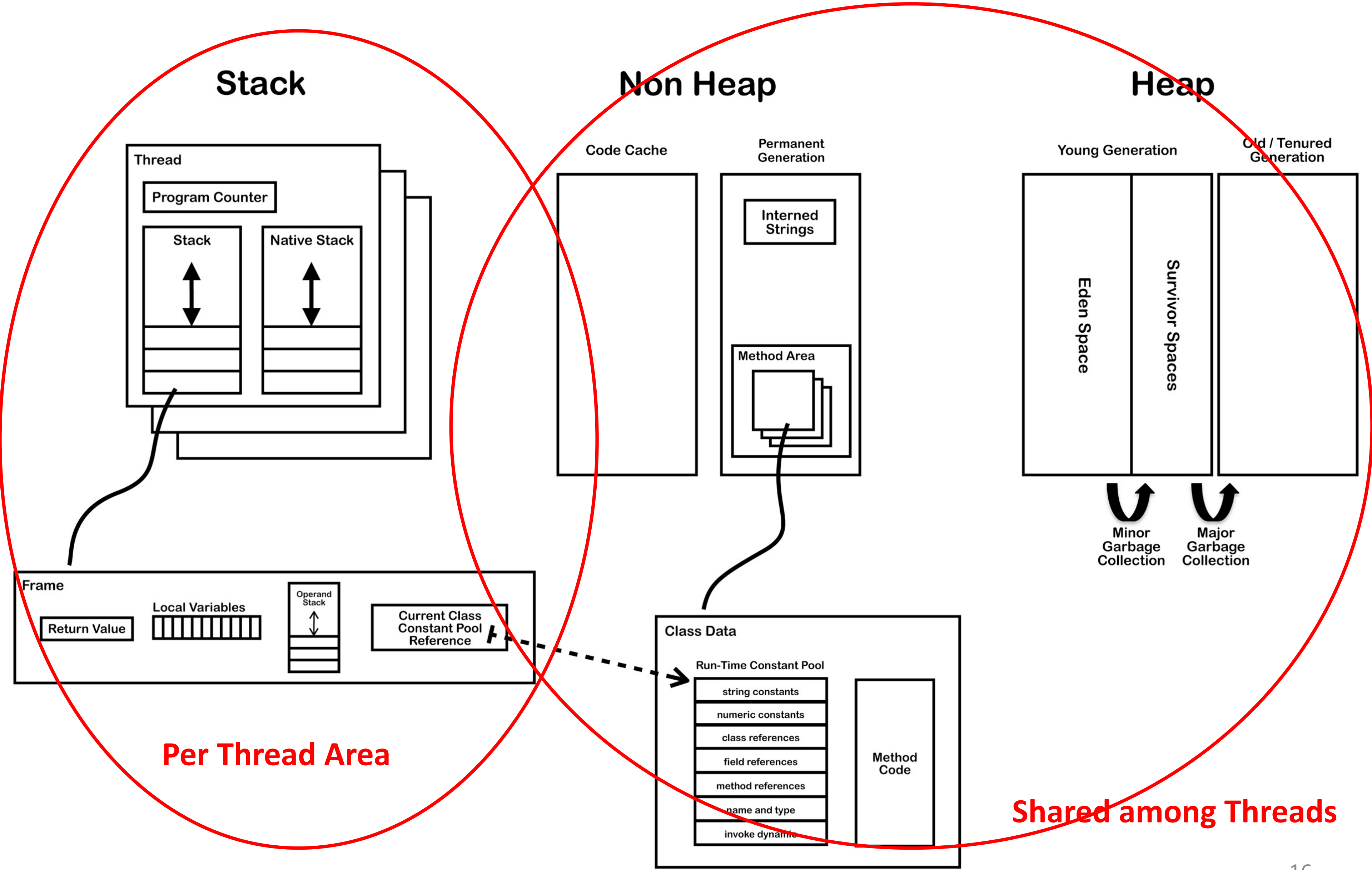
Note:

- No type information on local variables at runtime
- Types of operands specified by **opcodes** (eg: `iadd`, `fadd`, ….)

Object Representation

- Left to the implementation
  - Including concrete value of `null`
- Extra level of indirection
  - need pointers to instance data and class data
  - make garbage collection easier
- Object representation must include
  - mutex lock
  - GC state (flags)

JVM Runtime Data Areas



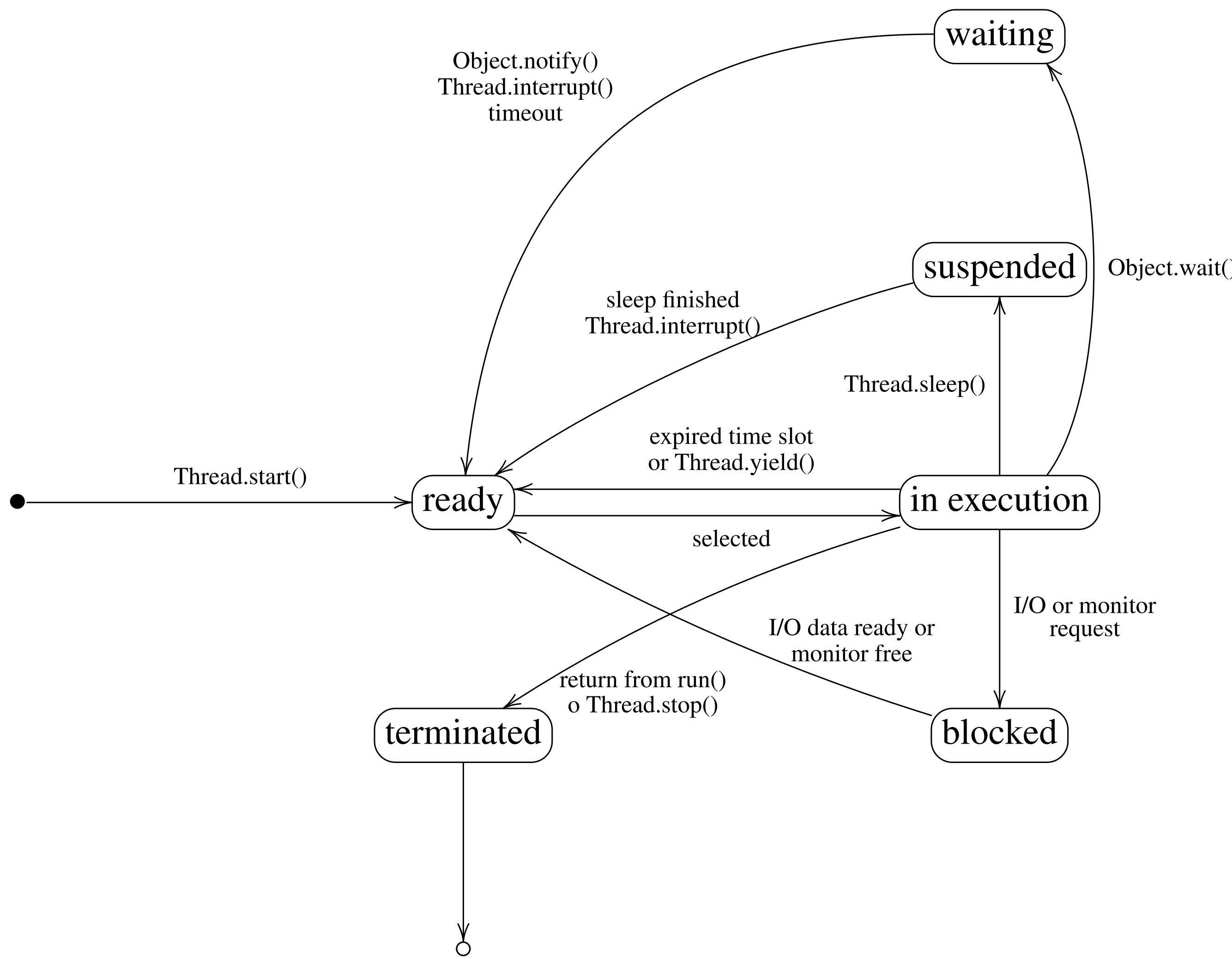
Threads

- JVM allows multiple threads per application, starting with `main`
- Created as instances of `Thread` invoking `start()` (which invokes `run()`)
- Several background (daemon) system threads for
  - Garbage collection, finalization
  - Signal dispatching
  - Compilation, etc.
- Threads can be supported by time-slicing and/or multiple processors

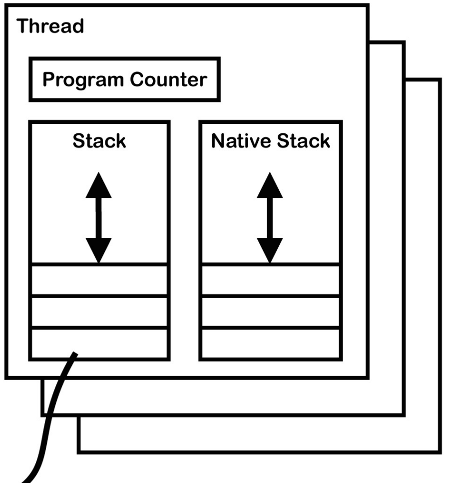
Threads (2)

- Threads have shared access to heap and persistent memory
- Complex specification of consistency model
  - volatiles
  - working memory vs. general store
  - non-atomic longs and doubles
- The *Java programming language memory model* prescribes the behaviour of multithreaded programs (JLS Ch. 17)

Java Thread Life Cycle

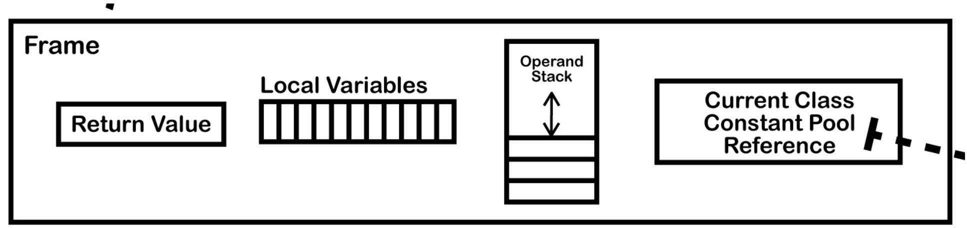


Per Thread Data Areas



- **pc**: pointer to next instruction in *method area*
  - undefined if current method is *native*
- The **java stack**: a stack of *frames* (or *activation records*).
  - A new frame is created each time a method is invoked and it is destroyed when the method completes.
  - The JVMS does not require that frames are allocated contiguously
- The **native stack**: is used for invocation of native functions, through the JNI (Java Native Interface)
  - When a native function is invoked, eg. a C function, execution continues using the native stack
  - Native functions can call back Java methods, which use the Java stack

Structure of frames



- **Local Variable Array** (32 bits) containing
  - Reference to `this` (if instance method)
  - Method parameters
  - Local variables
- **Operand Stack** to support evaluation of expressions and evalutation of the method
  - Most JVM bytecodes manipulate the stack
- Reference to **Constant Pool** of current class

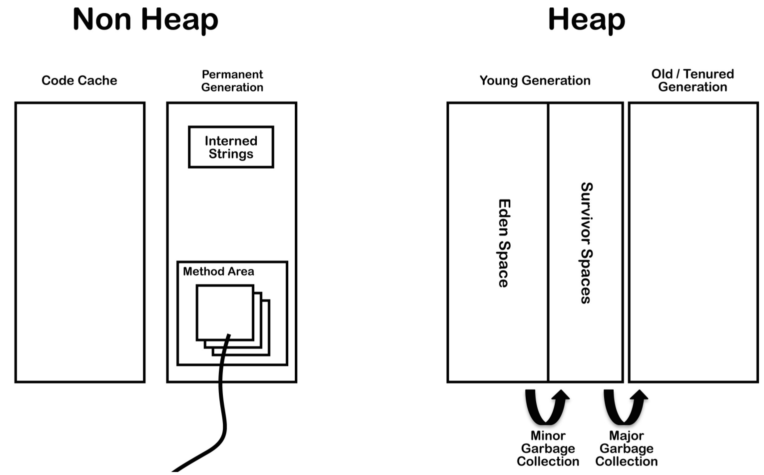
Dynamic Linking (1)

- The reference to the constant pool for the current class helps to support **dynamic linking**.
- In C/C++ typically multiple object files are linked together to produce an executable or `dll`.
  - During the linking phase symbolic references are replaced with an actual memory address relative to the final executable.
- In Java this linking phase is done **dynamically** at runtime.
- When a Java class is compiled, all references to variables and methods **are stored in the class's constant pool as symbolic references**.

Dynamic Linking (2)

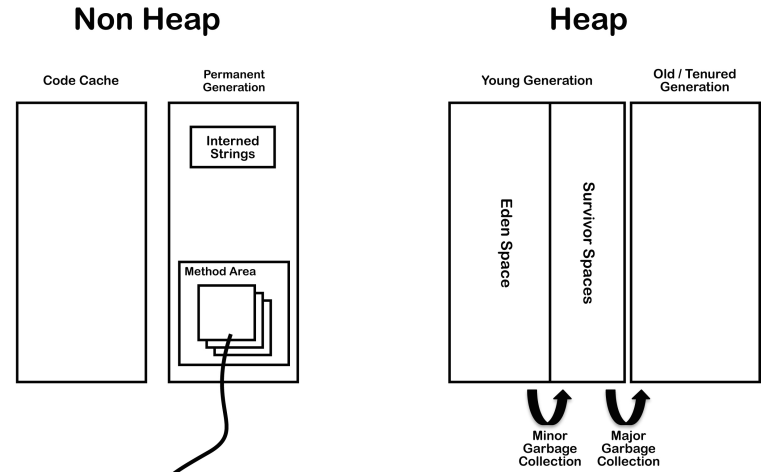
- The JVM implementation can choose when to resolve symbolic references.
  - **Eager or static resolution:** when the class file is verified after being loaded
  - **Lazy or late resolution:** when the symbolic reference is used for the first time
- The JVM **has to behave** as if the resolution occurred when each reference is first used and throw any resolution errors at this point.
- **Binding** is the process of the entity (field, method or class) identified by the symbolic reference being replaced by a direct reference
- This only happens once because the symbolic reference ***is completely replaced*** in the constant pool
- If the symbolic reference refers to a class that has not yet been resolved then this class will be loaded.

Data Areas Shared by Threads: **Heap**



- Memory for objects and arrays; unlike C/C++ they are never allocated to stack
- Explicit deallocation not supported. Only by garbage collection.
- The HotSpot JVM includes four **Generational Garbage Collection Algorithms**
- Since Oracle JDK 11: **Z Garbage Collector**

Data Areas Shared by Threads: **Non-Heap**



- Memory for objects which are never deallocated, needed for the JVM execution
  - Method area
  - Interned strings
  - Code cache for JIT

JIT (Just In Time) compilation

- The Hotspot JVM (and other JVMs) profiles the code during interpretation, looking for "hot" areas of byte code that are executed regularly
- These parts are compiled to native code.
- Such code is then stored in the **code cache** in non-heap memory.

Method area

The memory where `class` files are loaded. For each class:

- **Classloader Reference**
- From the `class` file:
  - **Run Time Constant Pool**
  - **Field data**
  - **Method data**
  - **Method code**

Note: Method area is shared among thread. Access to it has to be **thread safe**.

Changes of method area when:

- A new class is loaded
- A symbolic link is resolved by dynamic linking

Class file structure

ClassFile {

u4 magic;	**0xCAFEBABE**
u2 minor_version; u2 major_version;	**Java Language Version**
u2 constant_pool_count; cp_info contant_pool[constant_pool_count–1];	**Constant Pool**
u2 access_flags;	**access modifiers and other info**
u2 this_class; u2 super_class;	**References to Class and Superclass**
u2 interfaces_count; u2 interfaces[interfaces_count];	**References to Direct Interfaces**
u2 fields_count; field_info fields[fields_count];	**Static and Instance Variables**
u2 methods_count; method_info methods[methods_count];	**Methods**
u2 attributes_count; attribute_info attributes[attributes_count];	**Other Info on the Class**

}

Field data in the Method Area

Per field:

- Name
- Type
- Modifiers
- Attributes

FieldType descriptors

FieldType term	Type	Interpretation
B	byte	signed byte
C	char	Unicode character code point in the Basic Multilingual Plane, encoded with UTF-16
D	double	double-precision floating-point value
F	float	single-precision floating-point value
I	int	integer
J	long	long integer
L *ClassName* ;	reference	an instance of class *ClassName*
S	short	signed short
Z	boolean	true or false
[	reference	one array dimension

Method data

Per method:

- Name
- Return Type
- Parameter Types (in order)
- Modifiers
- Attributes
- Method code…

A *method descriptor* contains

- a sequence of zero or more *parameter descriptors* in brackets
- a *return descriptor* or V for *void descriptor*

Example: The descriptor of

```
Object m(int i, double d, Thread t) {...}
```

is:

```
(IDLjava/lang/Thread;)Ljava/lang/Object;
```

Method code

Per method:

- Bytecodes
- Operand stack size
- Local variable size
- Local variable table
- Exception table
- LineNumberTable – which line of source code corresponds to which byte code instruction (for debugger)

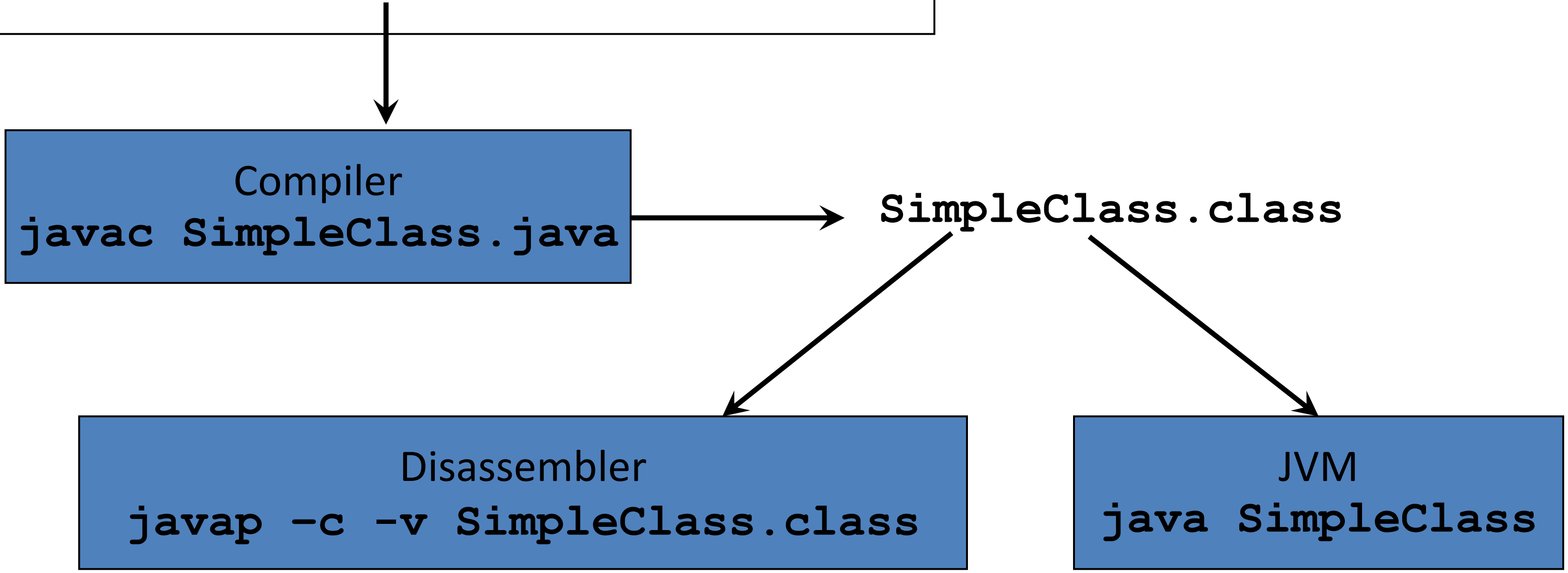
Per exception handler (one for each try/catch/finally clause)

- Start point
- End point
- PC offset for handler code
- Constant pool index for exception class being caught

Disassembling Java files: javac, javap, java

SimpleClass.java

```
package org.jvminternals;
public class SimpleClass {
    public void sayHello() {
        System.out.println("Hello");
    }
}
```



SimpleClass.class: constructor and method

```
package org.jvminternals;
public class SimpleClass {
    public void sayHello() {
        System.out.println("Hello");
}}
```

Local variable 0 = "this"

```
{
  public org.jvminternals.SimpleClass();
    descriptor: ()V
    flags: ACC_PUBLIC
    Code:
      stack=1, locals=1, args_size=1
         0: aload_0
         1: invokespecial #1    // Method java/lang/Object."<init>":()V
         4: return
      LineNumberTable:
        line 2: 0

  public void sayHello();
    descriptor: ()V
    flags: ACC_PUBLIC
    Code:
      stack=2, locals=1, args_size=1
         0: getstatic     #2    // Field java/lang/System.out:Ljava/io/PrintStream;
         3: ldc           #3    // String Hello
         5: invokevirtual #4    // Method
java/io/PrintStream.println:(Ljava/lang/String;)V
         8: return
      LineNumberTable:
        line 4: 0
        line 5: 8
}
SourceFile: "SimpleClass.java"
```

Method descriptors

Index into constant pool

String literal

Field descriptor

The constant pool

- Similar to *symbol table,* but with more info
- Contains constants and symbolic references used for dynamic binding, suitably tagged
  - numeric literals (Integer, Float, Long, Double)
  - string literals (Utf8)
  - class references (Class)
  - field references (Fieldref)
  - method references (Mehodref, InterfaceMethodref, MethodHandle)
  - signatures (NameAndType)
- Operands in bytecodes often are indexes in the constant pool

`SimpleClass.class`: the Constant pool

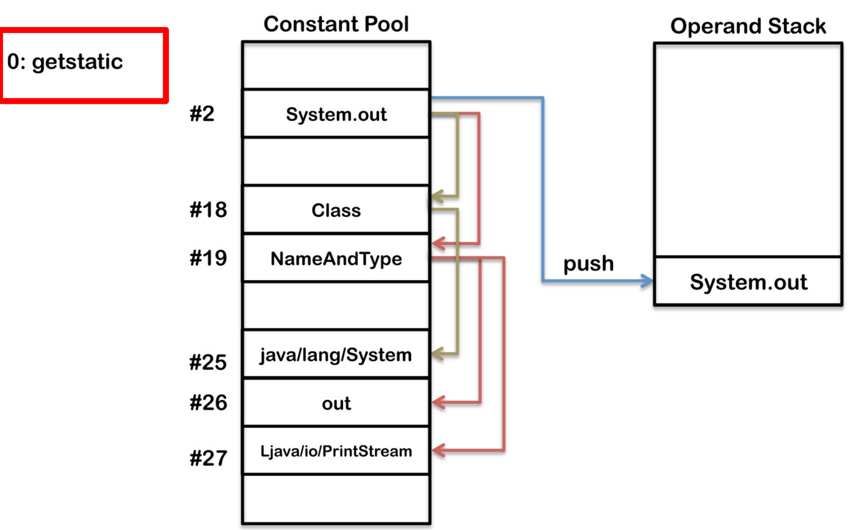
```
public class SimpleClass {
    public void sayHello() {
        System.out.println("Hello");
}}
```

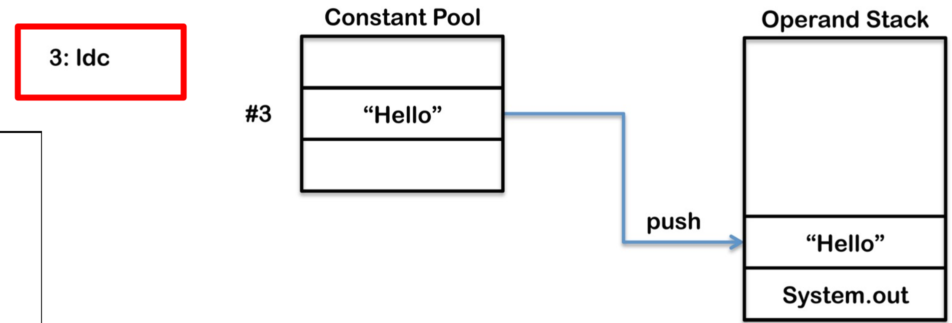
```
Compiled from "SimpleClass.java"
public class SimpleClass
  minor version: 0
  major version: 52
  flags: ACC_PUBLIC, ACC_SUPER
Constant pool:
   #1 = Methodref          #6.#14         // java/lang/Object."<init>":()V
   #2 = Fieldref           #15.#16        // java/lang/System.out:Ljava/io/PrintStream;
   #3 = String             #17            // Hello
   #4 = Methodref          #18.#19        //
java/io/PrintStream.println:(Ljava/lang/String;)V
   #5 = Class              #20            // SimpleClass
   #6 = Class              #21            // java/lang/Object
   #7 = Utf8               <init>
   #8 = Utf8               ()V
   #9 = Utf8               Code
  #10 = Utf8               LineNumberTable
  #11 = Utf8               sayHello
  #12 = Utf8               SourceFile
  #13 = Utf8               SimpleClass.java
  #14 = NameAndType        #7:#8          // "<init>":()V
  #15 = Class              #22            // java/lang/System
  #16 = NameAndType        #23:#24        // out:Ljava/io/PrintStream;
  #17 = Utf8               Hello
  #18 = Class              #25            // java/io/PrintStream
  #19 = NameAndType        #26:#27        // println:(Ljava/lang/String;)V
  #20 = Utf8               SimpleClass
  #21 = Utf8               java/lang/Object
  #22 = Utf8               java/lang/System
  #23 = Utf8               out
  #24 = Utf8               Ljava/io/PrintStream;
  #25 = Utf8               java/io/PrintStream
  #26 = Utf8               println
  #27 = Utf8               (Ljava/lang/String;)V
```

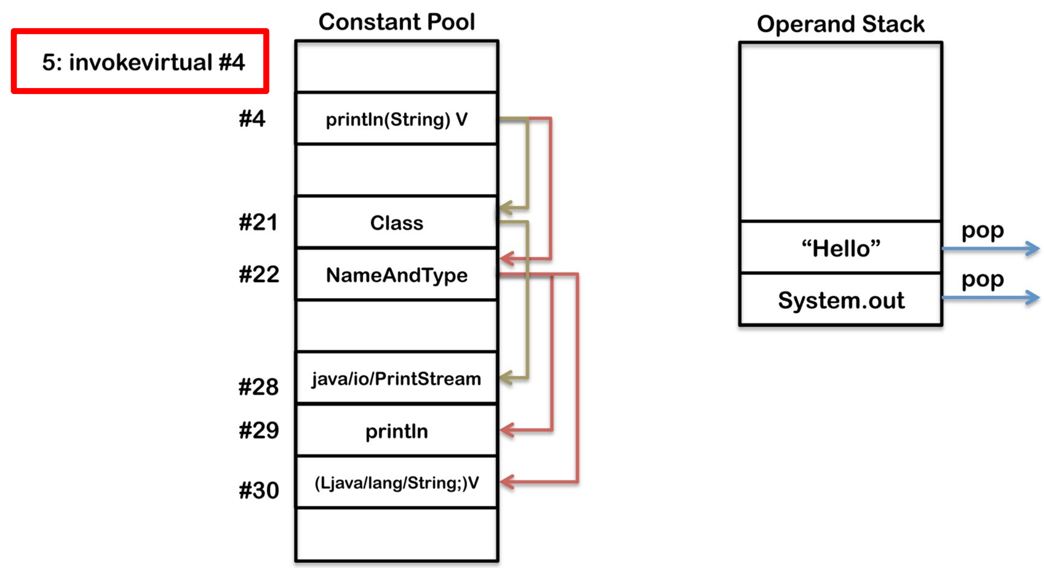
```
public void sayHello();
  descriptor: ()V
  Code:
    stack=2, locals=1, args_size=1
      0: getstatic     #2
      3: ldc           #3
      5: invokevirtual #4
      8: return
```

```
public void sayHello();
   descriptor: ()V
   Code:
     stack=2, locals=1, args_size=1
        0: getstatic     #2
        3: ldc           #3
        5: invokevirtual #4
        8: return
```

sayHello()







Loading, Linking, and Initializing

- **Loading**: finding the binary representation of a class or interface type with a given name and creating a class or interface from it
- **Linking**: taking a class or interface and combining it into the run-time state of the Java Virtual Machine so that it can be executed
- **Initialization**: executing the class or interface initialization method `<clinit>`

JVM Startup

- The JVM starts up by loading an initial class using the **bootstrap classloader**
- The class is linked and initialized
- **`public static void main(String[])`** is invoked.
- This will trigger loading, linking and initialization of additional classes and interfaces…

Loading

- Class or Interface *C* creation is triggered
  - by other class or interface referencing *C*
  - by certain methods (eg. reflection)
- Array classes are generated by the JVM
- Check whether already loaded
- If not, invoke the appropriate loader.loadClass
- Each class is tagged with the *initiating loader*
- *Loading constraints* are checked during loading
  - to ensure that the same name denotes the same type in different loaders

Class Loader Hierarchy

- **Bootstrap Classloader** loads basic Java APIs, including for example **`rt.jar`**. It may skip much of the validation that gets done for normal classes.
- **Extension Classloader** loads classes from standard Java extension APIs such as security extension functions.
- **System Classloader** is the default application classloader, which loads application classes from the classpath
- **User Defined Classloaders** can be used to load application classes:
  - for runtime reloading of classes
  - for loading from different sources, eg. from network, from an encrypted file, or also generated on the fly
  - for supporting separation between different groups of loaded classes as required by web servers
- Class loader hooks: `findClass` (builds a byte array), `defineClass` (turns an array of bytes into a class object), `resolveClass` (links a class)

Runtime Constant Pool

- The constant_pool table in the `.class` file is used to construct the *run-time constant pool* upon class or interface creation.
- All references in the run-time constant pool are initially symbolic.
- Symbolic references are derived from the `.class` file in the expected way
- Class names are those returned by **`Class.getName()`**
- Field and method references are made of name, descriptor and class name

Linking

- Link = verification, preparation, resolution
- **Verification**: see below
- **Preparation**: allocation of storage (method tables)
- **Resolution** (optional): resolve symbol references by loading referred classes/interfaces
  – Otherwise postponed till first use by an instruction

Verification

- When?
  - Mainly during the load and link process
- Why?
  - No guarantee that the class file was generated by a Java compiler
  - Enhance runtime performance
- Examples
  - There are no operand stack overflows or underflows.
  - All local variable uses and stores are valid.
  - The arguments to all the JVM instructions are of valid types.
- Relevant part of the JVM specification: described in ~170 pages of the JVMS (total: ~600 pages)

Verification Process

- Pass 1 – when the class file is loaded
  - The file is properly formatted, and all its data is recognized by the JVM
- Pass 2 – when the class file is linked
  - All checks that do not involve instructions
    - `final` classes are not subclassed, `final` methods are not overridden.
    - Every class (except `Object`) has a superclass.
    - All field references and method references in the constant pool have valid names, valid classes, and a valid type descriptor.

Verification Process – cont.

- Pass 3 – still during linking
  - **Data-flow analysis** on each method.
  - Ensure that at any given point in the program, no matter what code path is taken to reach that point:
    - The operand stack is always the same size and contains the same types of objects.
    - No local variable is accessed unless it is known to contain a value of an appropriate type.
    - Methods are invoked with the appropriate arguments.
    - Fields are assigned only using values of appropriate types.
    - All opcodes have appropriate type arguments on the operand stack and in the local variables
    - A method must not throw more exceptions than it admits
    - A method must end with a return value or throw instruction
    - Method must not use one half of a two word value

Verification Process – cont.

- Pass 4 - the first time a method is actually invoked
  - a virtual pass whose checking is done by JVM instructions
    - The referenced method or field exists in the given class.
    - The currently executing method has access to the referenced method or field.

Initialization

- <clinit> initialization method is invoked on classes and interfaces to initialize class variables
- happens on direct use: method invocation, construction, field access
- static initializers are executed
- direct superclass need to be initialized prior
- synchronized initializations: state in Class object
- <init>: initialization method for instances
  - **invokespecial** instruction
  - can be invoked only on uninitialized instances

Initialization example (1)

```
class Super {
    static { System.out.print("Super ");}
}
class One {
    static { System.out.print("One ");}
}
class Two extends Super {
    static { System.out.print("Two ");}
}
class Test {
  public static void main(String[] args) {
   One o = null;
   Two t = new Two();
   System.out.println((Object)o == (Object)t);
  }
}
```

What does **`java Test`** print?

Super Two False

Initialization example (2)

```
class Super { static int taxi = 1729;}
}
class Sub extends Super {
    static { System.out.print("Sub ");}
}
class Test {
    public static void main(String[] args) {
   System.out.println(Sub.taxi);
}}
```

What does **`java Test`** print?

Only prints "1729"

A reference to a static field (§8.3.1.1) causes initialization of only the class or interface that actually declares it, even though it might be referred to through the name of a subclass, a subinterface, or a class that implements an interface. (page 385 of [JLS-8])

Finalization: method `finalize()`

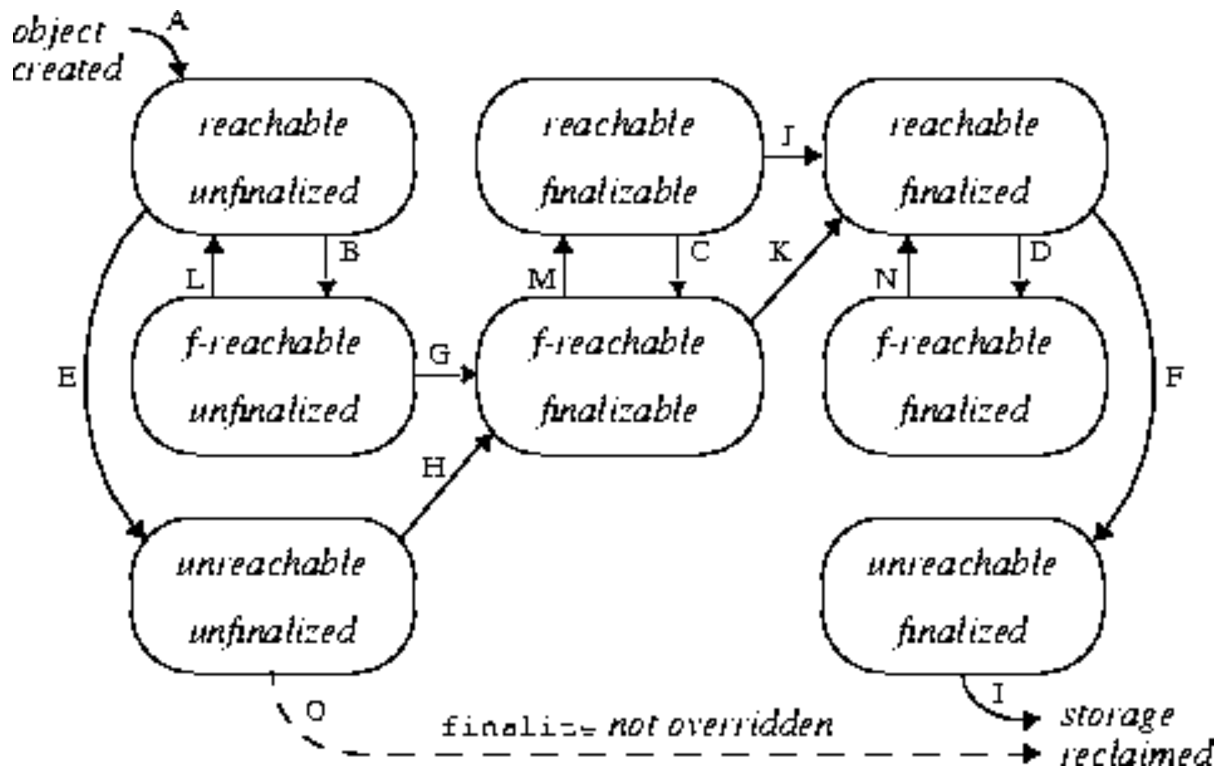
- Invoked just before garbage collection
- JLS does not specify when it is invoked
- Also does not specify which thread
- No automatic invocation of super's finalizers
- Very tricky!

```
void finalize() {
      classVariable = this; // the object is reachable again
}
```

- Each object can be
  - Reachable, finalizer-reachable, unreachable
  - Unfinalized, finalizable, finalized

Finalization State Diagram

https://notendur.hi.is/snorri/SDK-docs/lang/lang083.htm



`finalize()` is never called a second time on the same object, but it can be invoked as any other method!

JVM Exit

- `classFinalize` similar to object finalization
- A class can be unloaded when
  - no instances exist
  - class object is unreachable
- JVM exits when:
  - all its non-daemon threads terminate
  - `Runtime.exit` or `System.exit` assuming it is secure
- finalizers can be optionally invoked on all objects just before exit

Resources

- JVMS Chapter 2 - The Structure of the Java Virtual Machine
- *JVM Internals, by James D. Bloom* http://blog.jamesdbloom.com/JVMInternals.html
- JLS Chapter 17 – Memory model