NYU New York University

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Virtual Machines: Concepts & Applications

Lecture 6: HLL VM - I

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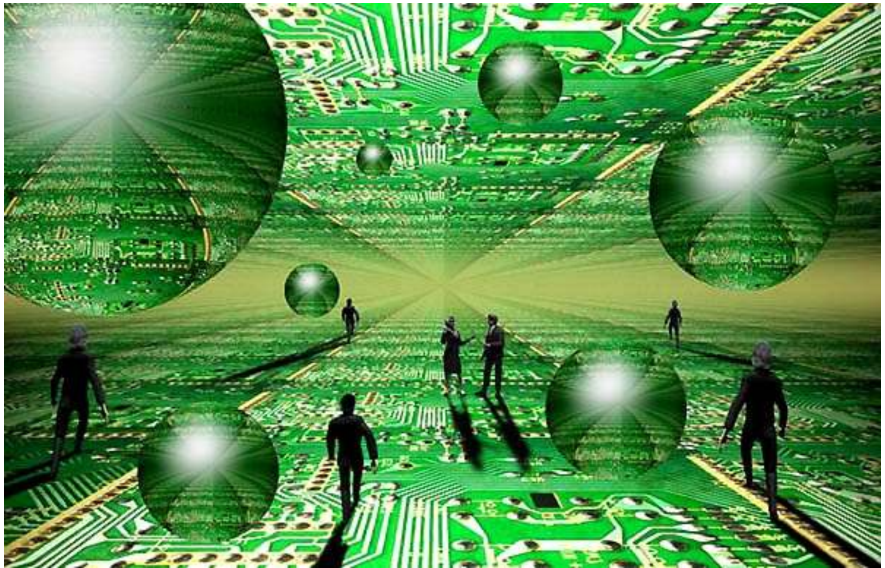
Disclaimer: Many slides of this lecture are based on the slides of authors of the textbook from Elsevier.



What are we talking about?

- Traditional process VMs are afterthoughts
- How about if we *design* a special guest ISA/system interface:
  - With portability as the main goal
  - define an abstract interface that can be supported by all conventional OSes.
  - Reflects important features of specific HLL or class of HLLs.
  - Simplifies compilation

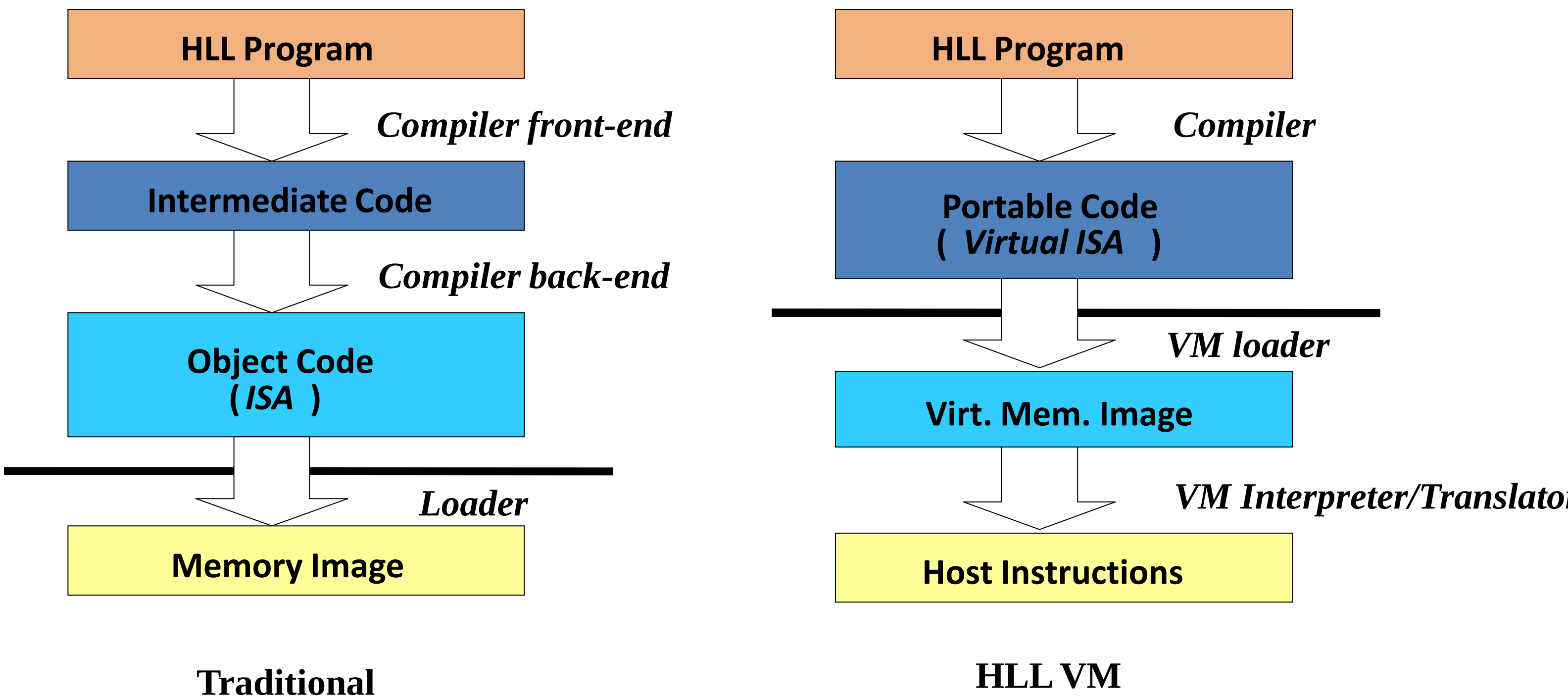
This is why we call them HLL VMs

HLL VM is similar to Process VM BUT …

- ISA defined for user-mode programs only
- ISA not designed for real hardware
  - Only to be executed on virtual processor
  - Referred to as virtual-ISA or V-ISA
- System interface is a set of standardized APIs

HLL VMs from language/compiler perspective

- Goal: complete platform independence for applications
- Virtual instruction set + libraries
  - Instead of ISA and OS interface

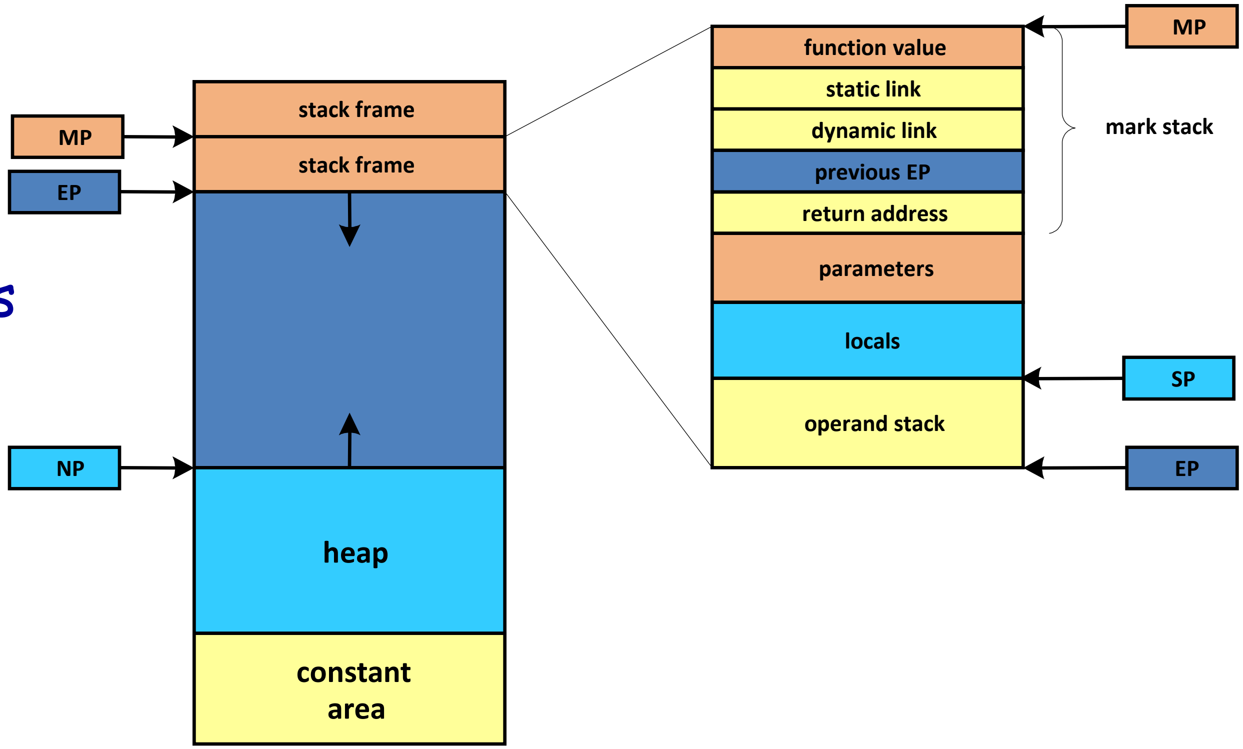


P-Code VM

- Popularized HLL VMs
- Provided highly portable version of Pascal
- Consists of
  - Primitive libraries
  - Machine-independent object file format
  - A set of byte-oriented “pseudo-codes”
  - Virtual machine definition of pseudo-code semantics

P-Code VM

- Instruction set
  - –Stack oriented
  - –Stack "Frame" is part of VM definition



MP: Mark Pointer
EP: Extreme Pointer
NP: New Pointer
SP: Stack Pointer

```
lodi    0   3    //  load variable from current frame (nest 0 depth),
                 //  offset 3 from top of mark stack.
ldci    1        //  push constant 1
addi             // add
stri    0   3    // store  variable back to location 3 of current frame
```

P-Code VM

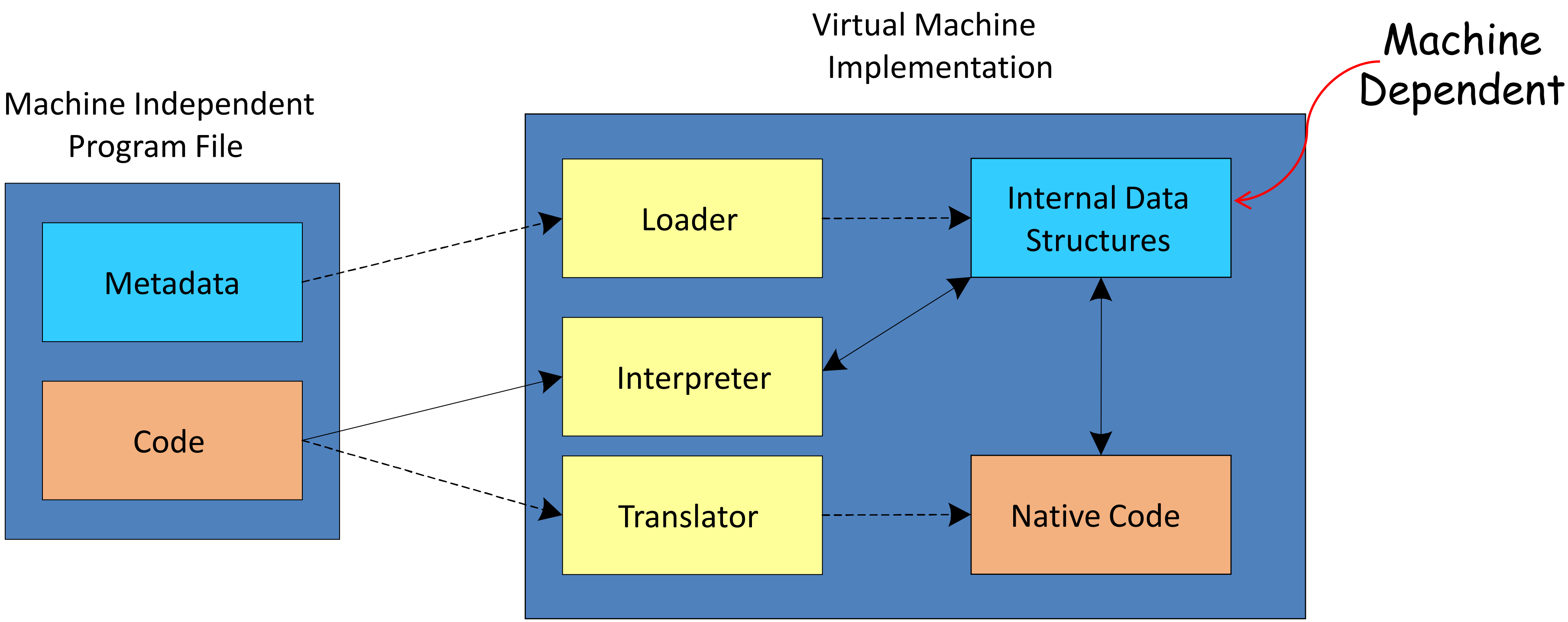
- Advantages
  - Porting is simplified
    - Don't have to develop compilers for all platforms
  - VM implementation is smaller/simpler than a compiler
  - VM provides concise definition of semantics
  - Through interpretation, startup time is reduced
  - Generic I/O and Memory interface
    - Tended to be least common denominator
    - $\Rightarrow$ Relatively weak I/O capabilities

Modern HLL VMs

- Superficially similar to P-code scheme
  - Stack-oriented ISA
  - Standard libraries
- Network Computing Environment
  - Untrusted software (this is the internet, after all)
  - Robustness (generally a good idea)
    - $\Rightarrow$ object-oriented programming
  - Bandwidth is a consideration
  - Good performance must be maintained
- Two major examples
  - Java VM
  - Microsoft Common Language Infrastructure (CLI)

Modern HLL VMs

- Compiler forms program files (e.g. class files)
  - Standard format
- Program files contain both code and metadata



Terminology

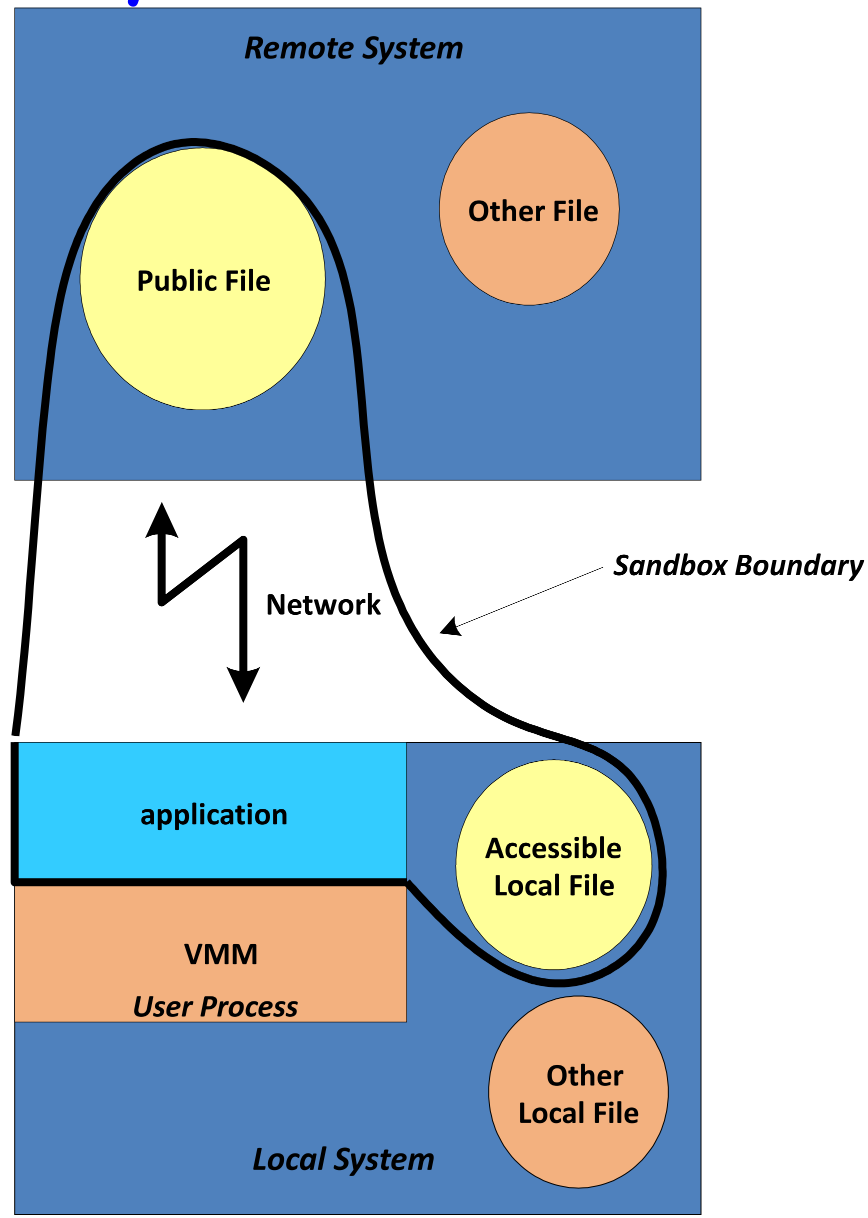
- Java Virtual Machine Architecture ⇔ CLI
  - Analogous to an ISA
- Java Virtual Machine Implementation ⇔CLR (Common Language Runtime)
  - Analogous to a computer implementation
- Java bytecodes ⇔ Microsoft Intermediate Language (MSIL), CIL, IL
  - The instruction part of the ISA
- Java Platform ⇔ .NET framework
  - ISA + Libraries; a higher level ABI

4 Characteristics of HLL VMs

- Security
- Robustness
- Networking
- Performance

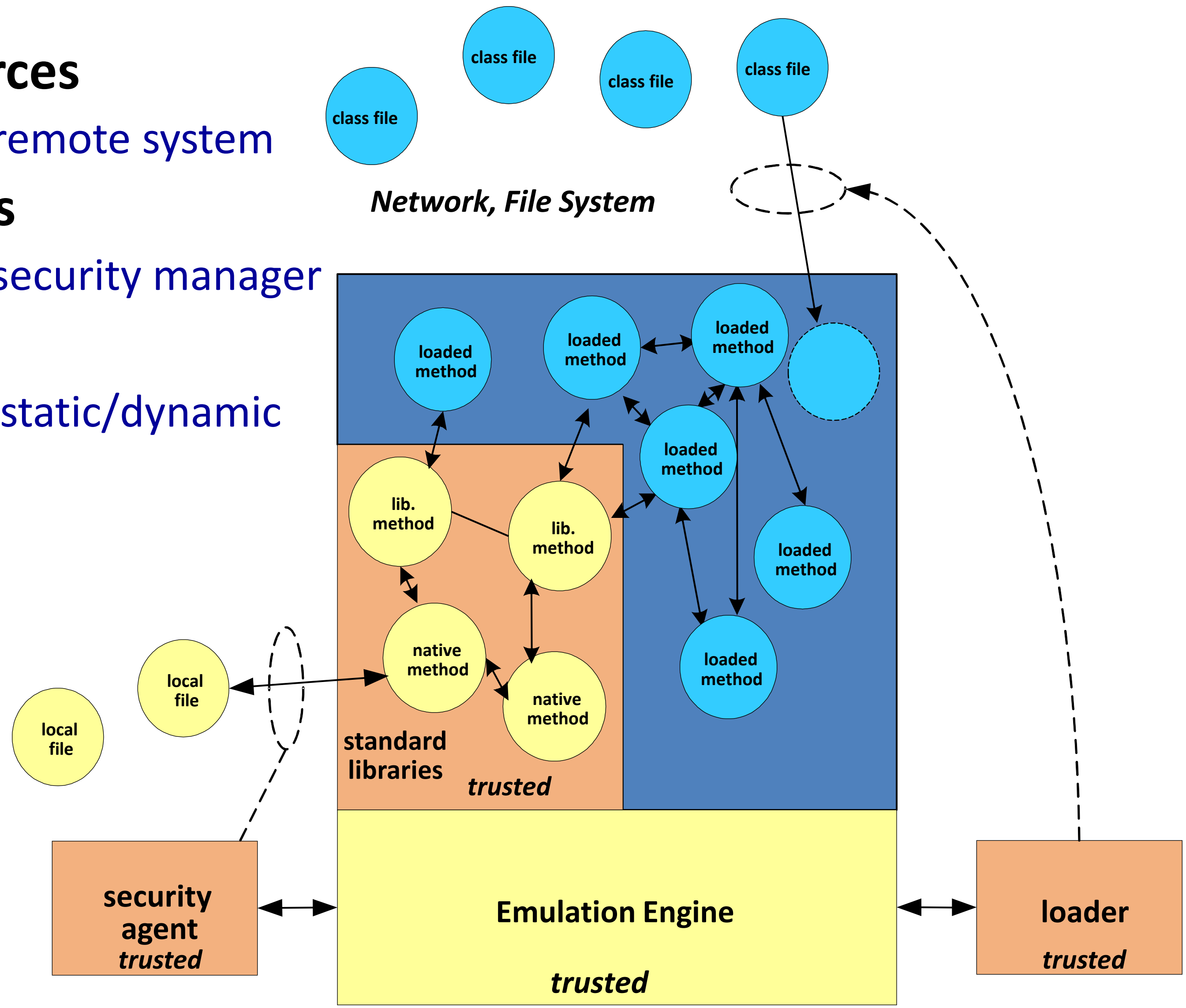
Security

- A key aspect of modern network-oriented VMs
- Must protect:
  - Local files and resources
  - Runtime from user process
- The program runs in a sandbox at the host machine. It is managed by the VM runtime.
- The ability to load an untrusted application and run it in a managed secure fashion is a very big challenge!



Protection Sandbox

- **Remote resources**
  - Protected by remote system
- **Local resources**
  - Protected by security manager
- **VM software**
  - Protected via static/dynamic checking



Robustness: Object-Orientation

- Objects
  - Data carrying entities
  - Dynamically allocated
  - Must be accessed via pointers or *references*
- Methods
  - Procedures that operate on objects
- Class
  - A *type* of object and its associated methods
  - Object created at runtime is an *instance* of the class
  - Data associated with a class may be *dynamic* or *static*

OO programming paradigm has become the model of choice for modern HLL VMs.
Both Java and CLI are designed to support OO software.

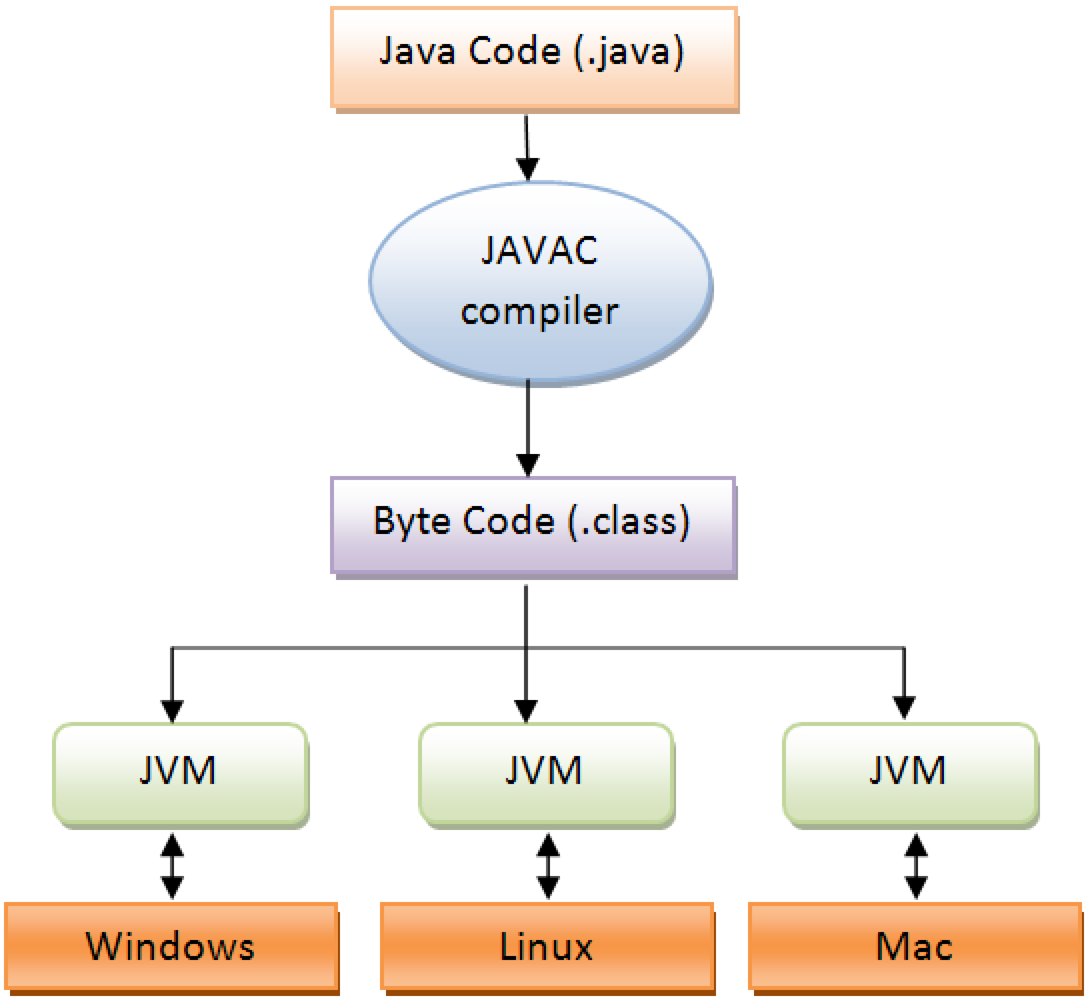
Networking

- The application must use the available bandwidth (scarce) efficiently
  - Application loaded incrementally → dynamic linking
  - Improves program startup-time

Performance

- Of course we sacrifice some performance for the sake of portability
- Yet, we can use the techniques we learned so far (and some more as we proceed) to ensure good performance.

Java Virtual Machine (JVM)



Source: http://i.stack.imgur.com/Deo2s.png

Data items

- Types are defined, but not implementation details
  - Reference types (pointers): number of bits needed is not part of Java ISA.
  - Primitive types, e.g. int, char, byte, short, long, float, double,
  - Another primitive type: ReturnAddress (not in Java HLL but in Java ISA)
- Exact sizes of data types are not given
  - Only the range of values that can be held
    - e.g. byte is between –128 and +127

Objects and Arrays

- Objects:
  - Logical structure, defined by programmer, to carry data
  - Composed of primitive data types and references
- Array
  - Fixed number of elements
  - All elements must be of the same type
  - If the elements are references then they must all point to objects of the same type

Data Storage Types

- Global
  - the main memory
  - where globally declared variables reside
- Local
  - temporary storage
  - for variables local to a method
- Operand
  - holds variables while they are being operated on by functional instructions

Allocated on the stack

Data Storage Types

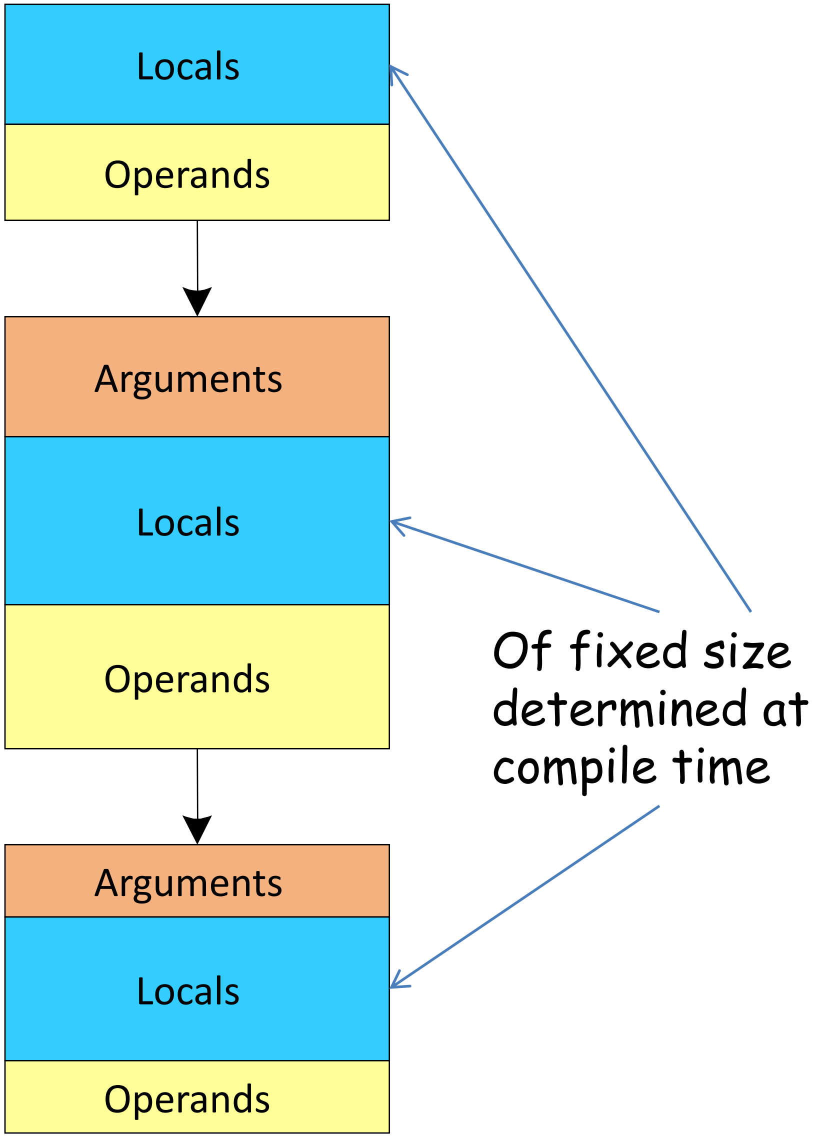
- All storage is divided into cells or slots
- A cell/slot usually holds a single data item
- Actual amount of bits needed for cell/slot is implementation dependent

Stack

- Arguments
- Locals
- Operands

In that order

- As each method is called, a stack frame is allocated.



Global Memory

- Method area
  - for holding code
- Global storage area
  - for holding arrays and objects
  - managed as a heap
  - of unspecified size with respect to JVM architecture
  - Can contain both static and dynamic objects

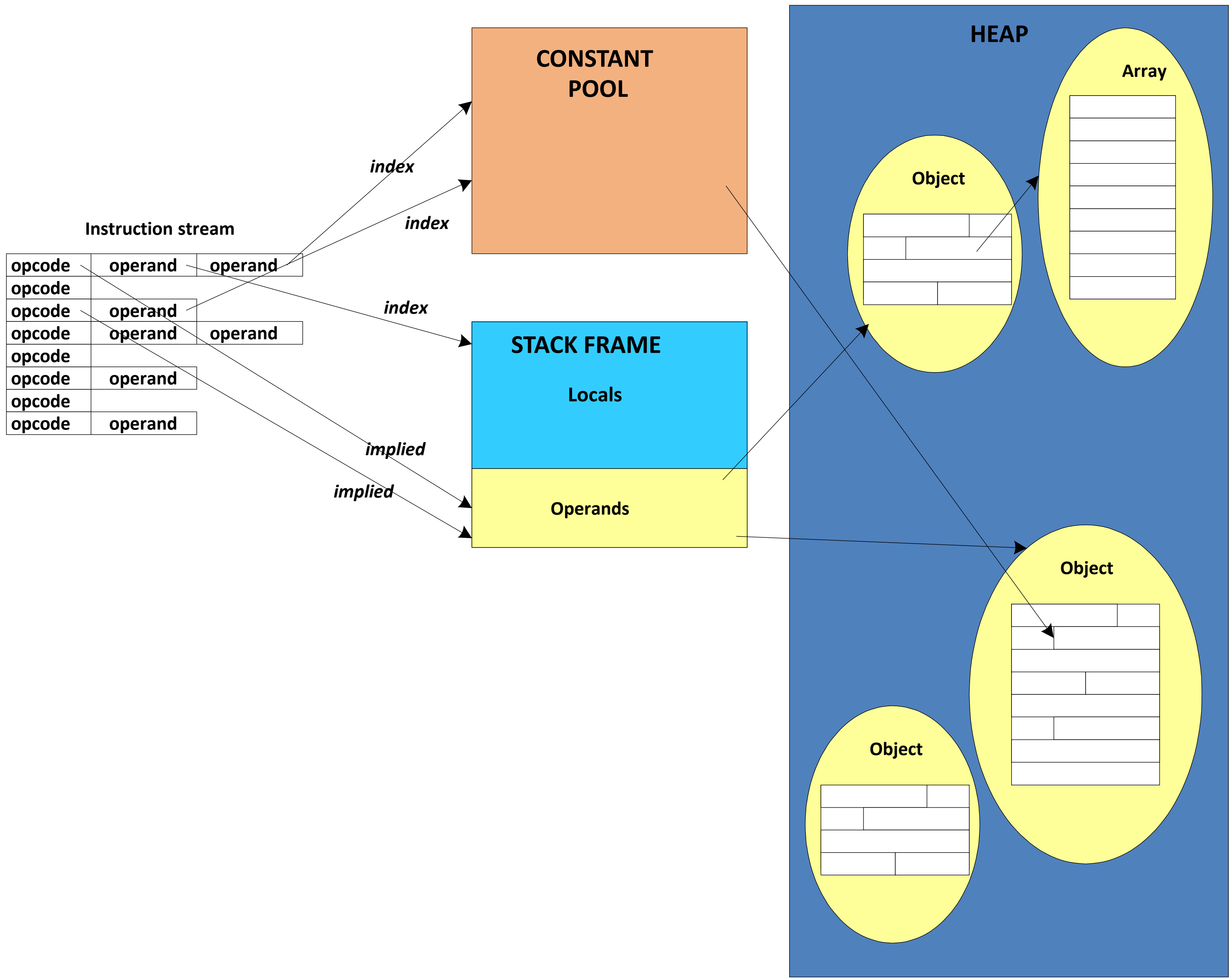
Heap

- Objects are created on heap
- Each application has only one
- Each application has its own
- JVM instructions allocate objects on heap
  - No instruction to release memory
  - Garbage collection is part of implementation
- Object representation is implementation dependent

Constant Pool

- ISA allows constants to be expressed in the instruction as immediate operands
- But some constants:
  - are used by several instructions
  - are of different ranges
- So: Constant data associated with a program is placed in a block called constant pool
- Instructions access them by indexing constant pool
- Constant pool then:
  - defined as part of the ISA
  - Exact size of constants is specified
  - Does not change with program execution

Putting is All Together: Memory Hierarchy in JVM



Network Friendliness

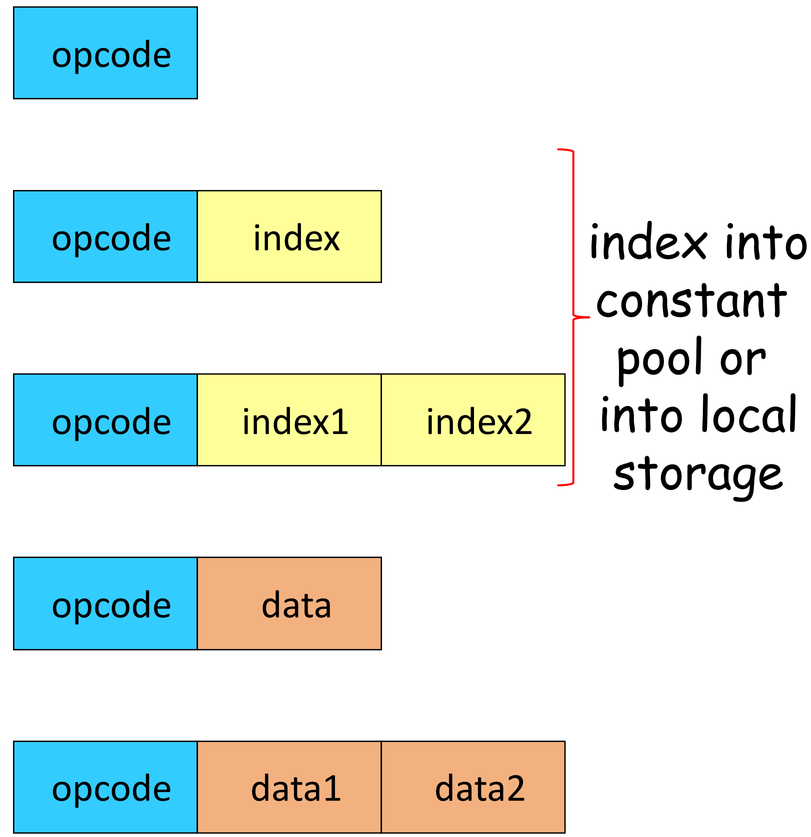
- Support dynamic class file loading on demand
  - Load only classes that are needed
  - Spread loading out over time
- Compact instruction encoding
  - Use stack-oriented ISA (as in Pascal)

Garbage Collected Heap

- Objects are created and “float” in memory space
  - Tethered by references
  - In architecture, memory is unbounded in size
  - In reality it is limited
- Garbage creation
  - During program execution, many objects are created then abandoned (become garbage)
- Collection
  - Due to limited memory space, Garbage should be collected so memory can be re-used
  - Forcing programmer to explicitly free objects places more burden on programmer
    - Can lead to memory leaks, reducing robustness
  - To improve robustness, have VM collect garbage automatically

Instruction Set

- Stack based
- Defined for class file, not memory image
- Bytecodes
  - –One byte opcode
  - –Zero or more operands
    - •Opcode indicates how many
- Can take operands from
  - –Instruction
  - –Current constant pool
  - –Current frame local variables
  - –Values on operand stack
    - •Distinguish storage types and computation types



Implied Registers

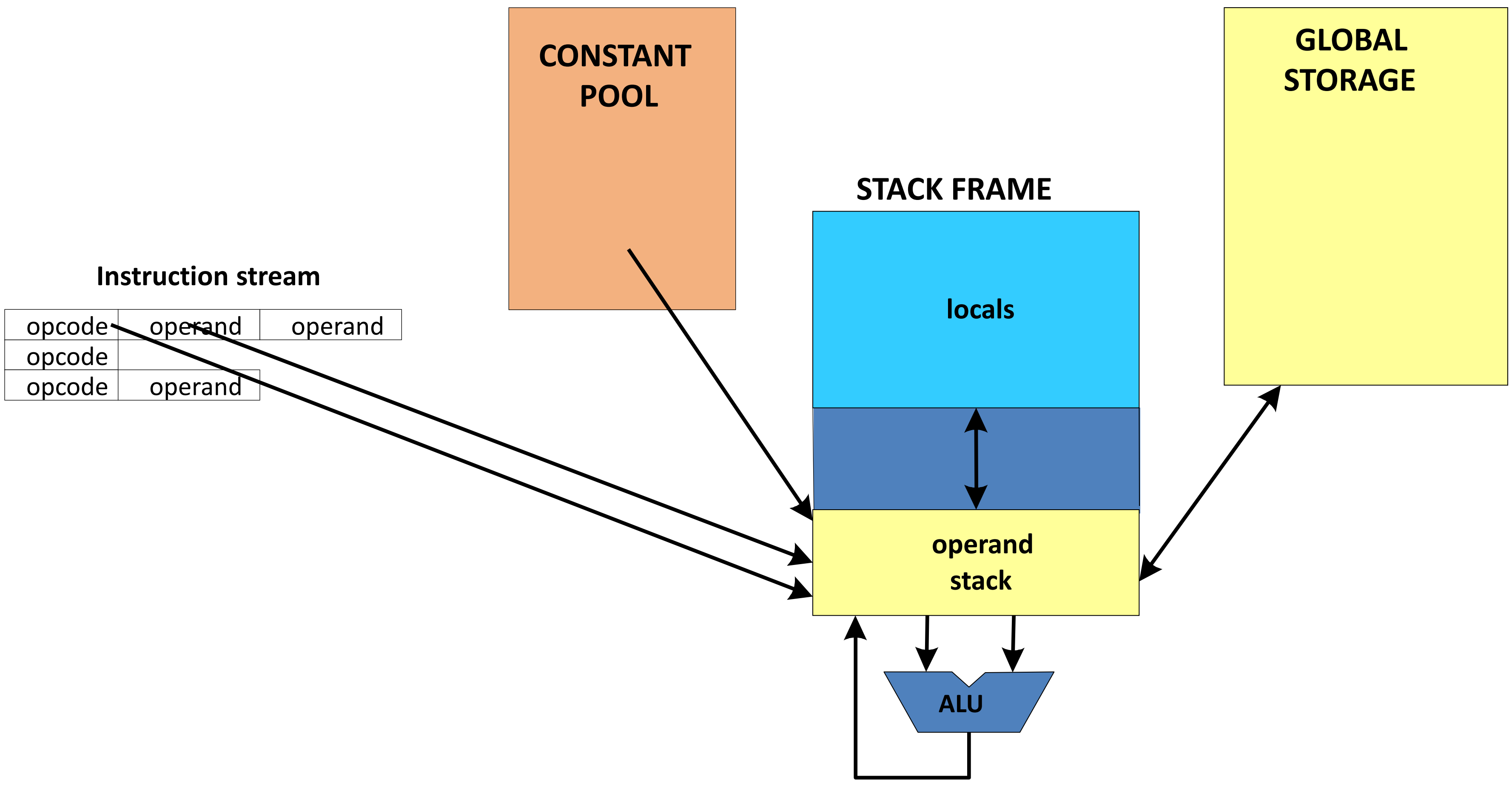
- Program Counter
- Local variable pointer
- Operand stack pointer
- Current frame pointer
- Constant pool base

Instruction Types

- Pushing constants onto the stack
- Moving local variable contents to and from the stack
- Managing arrays
- Generic stack instructions (dup, swap, pop & nop)
- Arithmetic and logical instructions
- Conversion instructions
- Control transfer and function return
- Manipulating object fields
- Method invocation
- Miscellaneous operations
- Monitors

Data Movement

- All data movement takes place through stack



Bytecode Example

```
PC      instruction
  0:      iconst_2  //pushes constant 2 onto operand stack
  1:      aload_0   //pushes local variable 0 onto the stack
  2:      getfield   #2;    //object ref on the stack, entry 2 on constant pool gives descr
  5:      iconst_0
  6:      iaload
  7:      aload_0
  8:      getfield   #2;
 11:      iconst_1
 12:      iaload
 13:      iadd
 14:      imul
 15:      ireturn
```

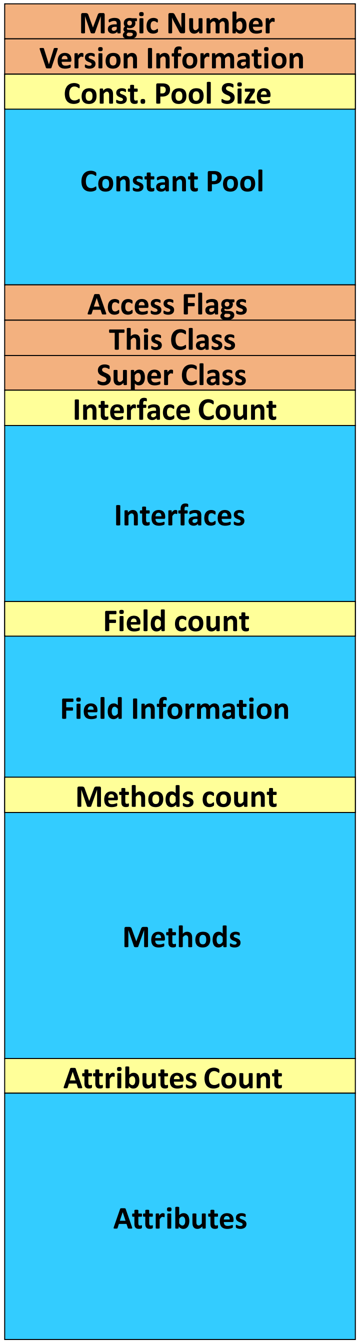
Stack Tracking

- Operand stack at any point in program have:
  - Same number of operands
  - Of same types
  - In same order

  Regardless of control flow path getting there
- Helps with static type checking by the loader

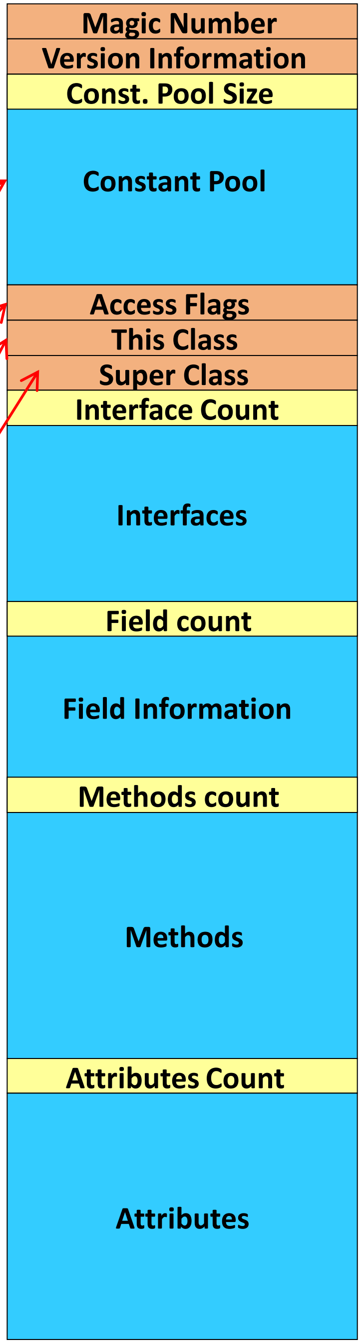
Binary Classes

- Formal ISA Specification
- Magic number and header
- Major regions preceded by counts
  - –Constant pool
  - –Interfaces
  - –Field information
  - –Methods
  - –Attributes



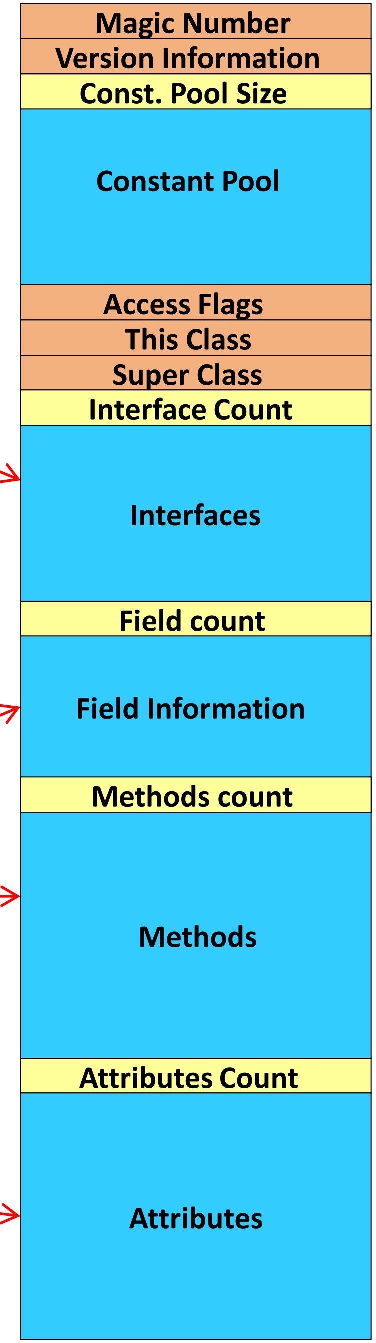
Binary Classes

- Holds all constant values and references used by the methods that are to follow.
- Provides access information, example:
  - whether public
  - whether interface
  - …
- Given as indices in the constant pool



Binary Classes

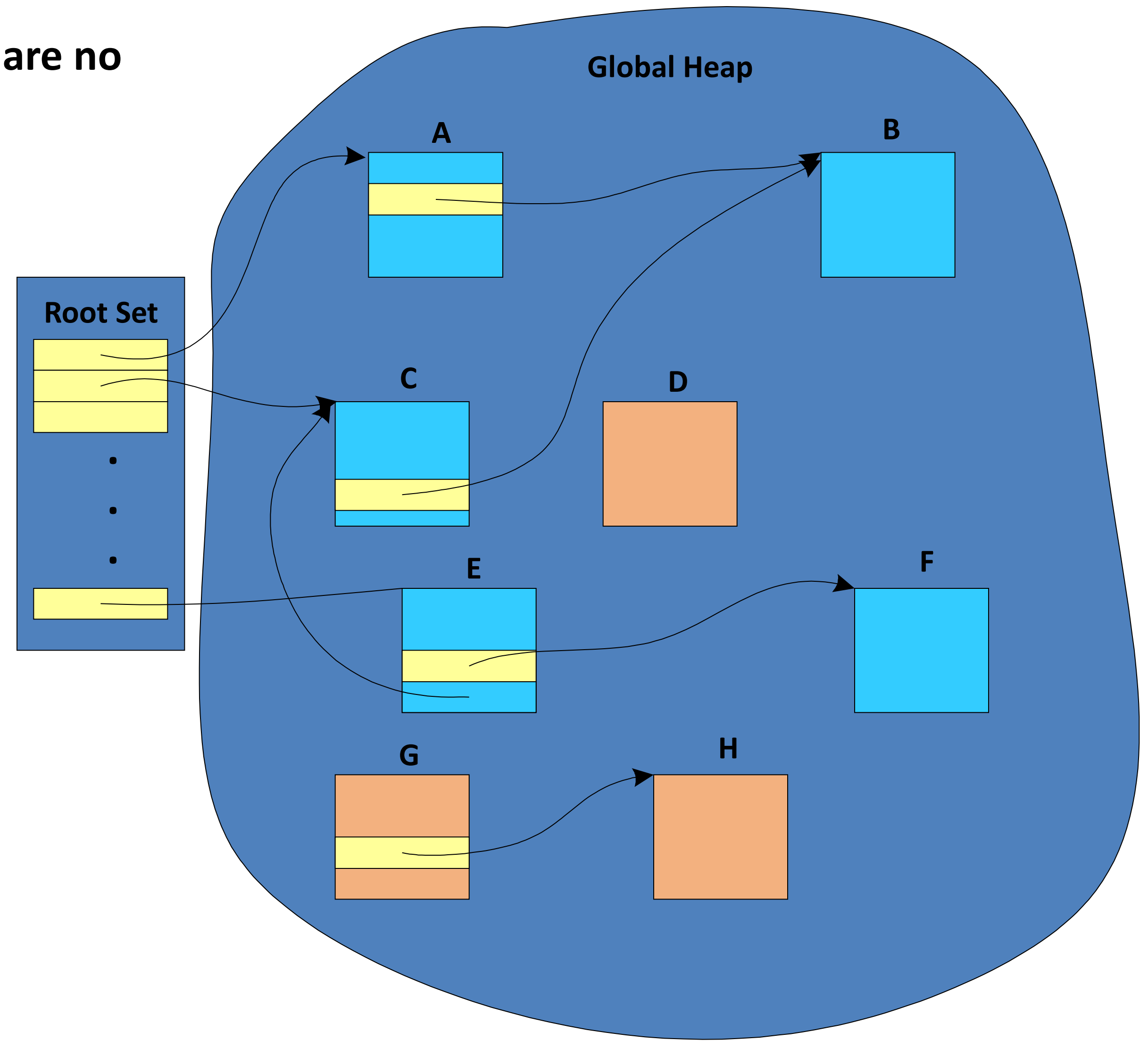
- Contains a number of references to the superinterfaces to this class
  - Given as indices in the constant pool
  - The constant pool entries are references to the interfaces
- Contains the specifications of the fields declared in this class
- The information regarding each method, as well as the methods themselves (encoded as bytecode)
- Contains detailed information regarding the previous sections



A Note About: Garbage Collection

- Garbage: objects that are no longer accessible
- Examples:

  D, G, H

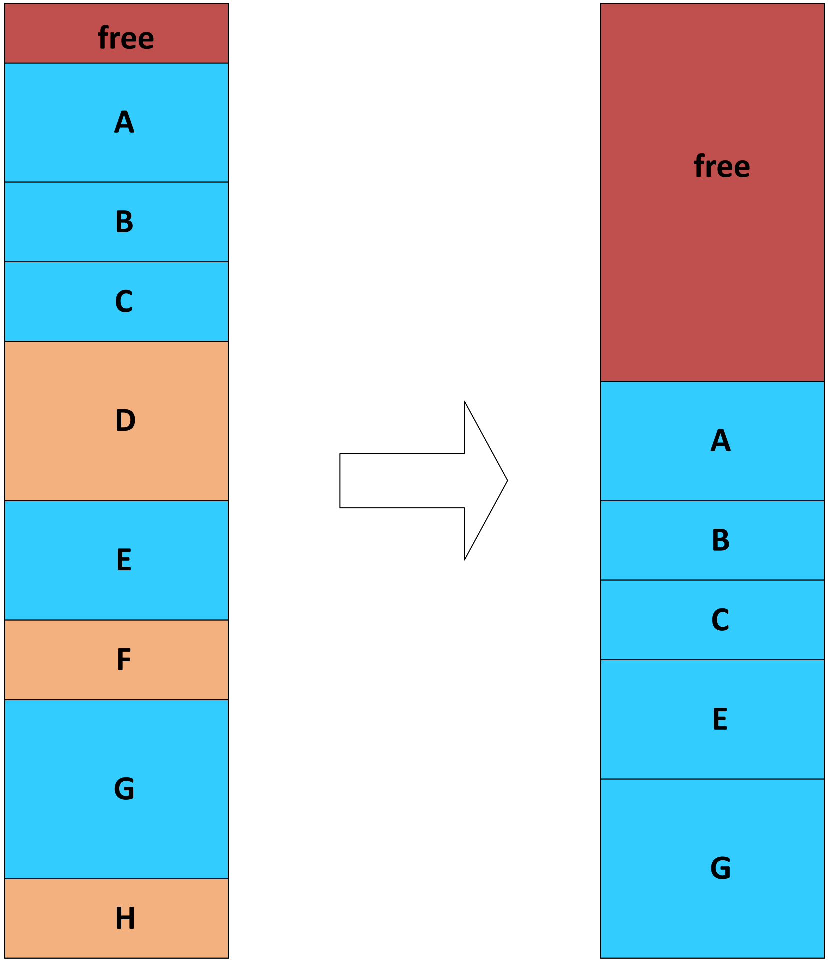


Garbage Collection

- A large topic on its own
- Mark and sweep
  - Start with *root set* of references
    - On stack, static objects, constant pool
  - Trace and mark all reachable objects
- Sweep through heap, collecting marked objects
  - Keep free space in linked list
    Advantage: Fast
  - Does not require moving object/pointers
- Disadvantage:
  - Discontiguous free space, fragmentation
  - Allocate new objects from best-fit free list

Compacting Collector

- Make free space contiguous
- Involves multiple passes through heap
- A lot of object movement => many pointer updates

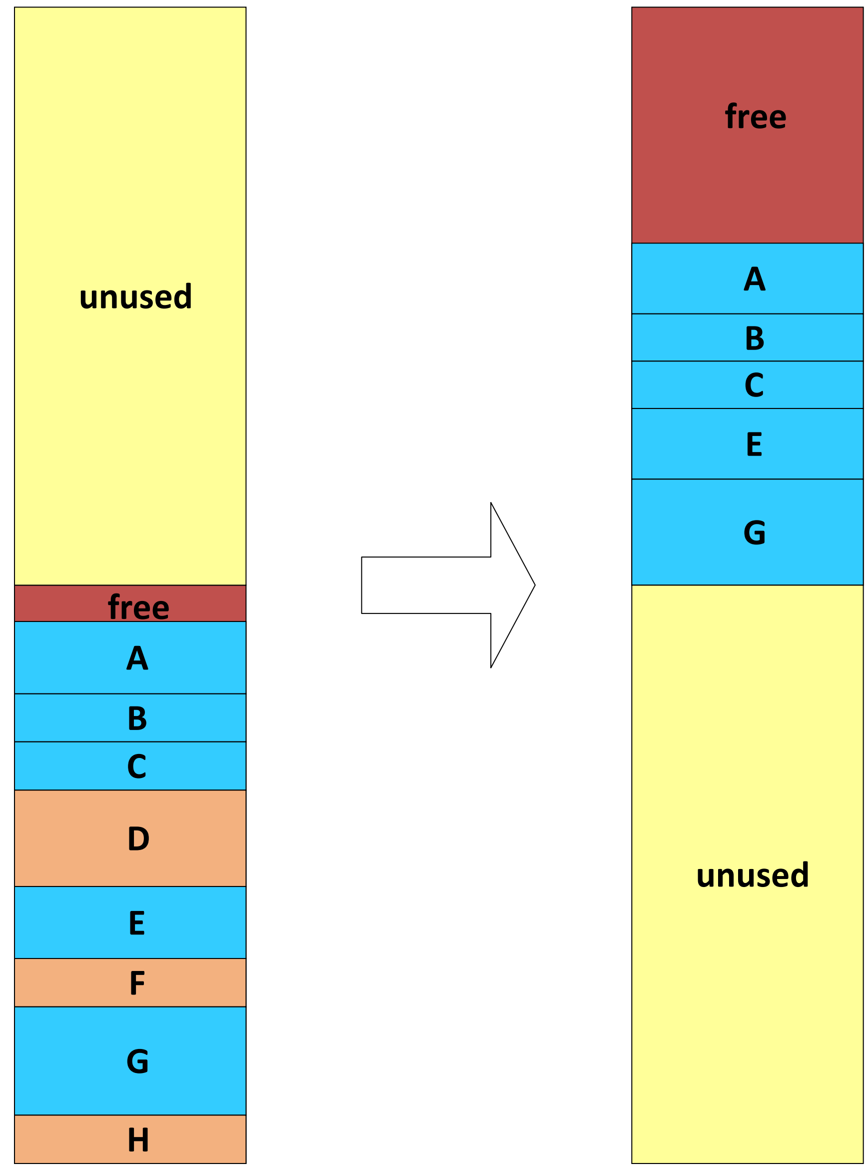


Copying Collector

- Divide heap into halves
- Collect when one half full
- Copy into unused half during sweep phase

\+ Reduces passes through heap

\- "Wastes" half of heap



Generational Collector

- Divide heap into halves
  - "tenured" and "nursery"
- Collect nursery more frequently
- Move long-lived objects into tenured half
- Objects have either very long or very short lives

JVM Bytecode Emulation

- Interpretation
  - Simple, fast startup, but slow
- Just-In-Time (JIT) Compilation
  - Compile each method when first touched
  - Simple, static optimizations
- Hot-Spot Compilation
  - Find frequently executed code
  - Apply more aggressive optimizations on that code
  - Typically phased with interpretation or JIT
- Dynamic Compilation
  - Based on Hot-Spot compilation
  - Use runtime information to optimize
  - More later…

So JVM is:

- An abstract entity that gives meaning to class files
- Has many concrete implementations
  - Hardware
  - Interpreter
  - JIT compiler
- Persistence
  - An instance is created when an application starts
  - Terminates when the application finishes

Conclusions

- HLL VM is built with portability as main goal:
  - Building a loader and JIT compiler is easier than building a full-fledged compiler
  - API and not ABI