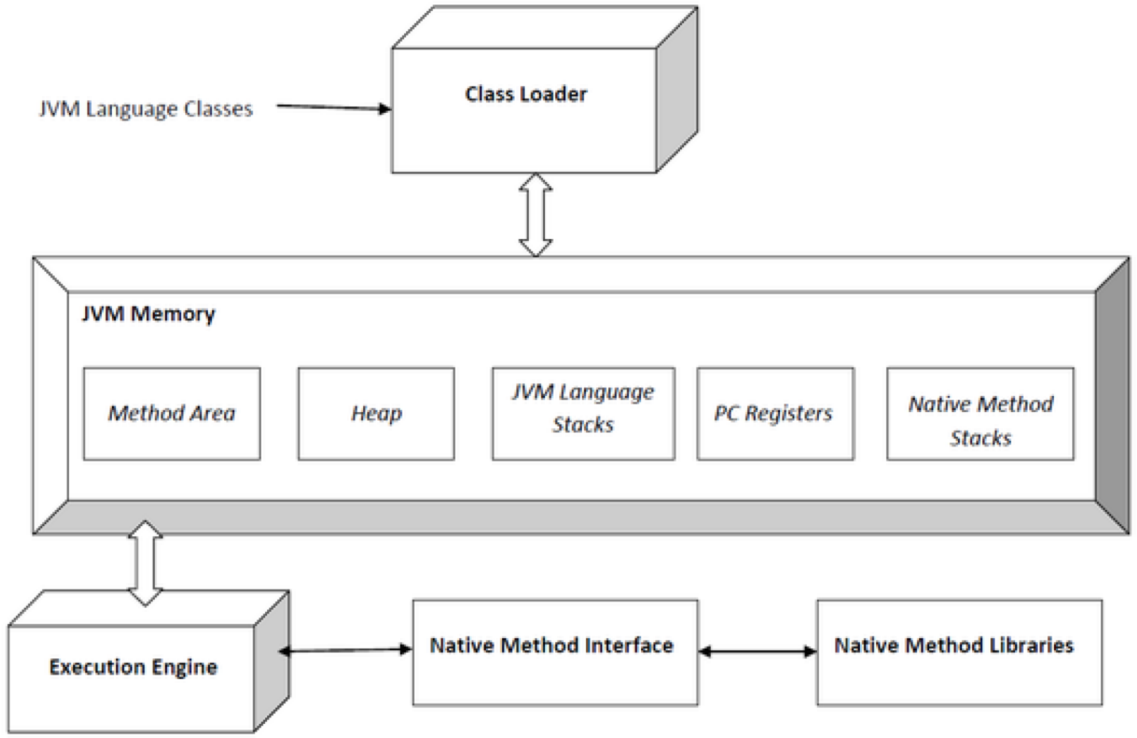
Architecture of the Java Virtual Machine



Linking In The Java Virtual Machine

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% java HelloWorld "Hello!" "Hi!"

public static void HelloWorld.main(args)   args.length = 2
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- Game plan
  - The `class` file format.
  - JVM startup and exit actions.
  - Class loading, linking, initialization (simplified: fast path only).

The `class` File Format

- [Ref: JVM SE16, Chapter 4]
- A `class` file consists of a stream of 8-bit bytes.
- 16-bit and 32-bit quantities are constructed from two or four 8-bit bytes.
- Multibyte data items are always stored in big-endian order.
- Shorthand
  - `u1` for unsigned one-byte quantity.
  - `u2` for unsigned two-byte quantity.
  - `u4` for unsigned four-byte quantity.
- A class file consists of a single `ClassFile` structure.
  - Essentially, a sequence of self-describing nested tables.

The `class` File Format

```
ClassFile {
  u4 magic;                          // 0xCAFEBABE
  u2 minor_version;                  // Minor version number, in {0, 65535}
  u2 major_version;                  // Major version number, in [45,60]

  // String constants, class and interface names, field names, etc.
  u2 constant_pool_count;
  cp_info constant_pool[constant_pool_count-1];

  u2 access_flags;
  u2 this_class;                     // index into constant_pool
  u2 super_class;                    // index into constant_pool

  u2 interfaces_count;
  u2 interfaces[interfaces_count]; // indices into constant_pool

  // Complete description of a field
  u2 fields_count;
  field_info fields[fields_count];

  // Complete description of a method
  u2 methods_count;
  method_info methods[methods_count];

  // Information used both for JVM function and for tools
  u2 attributes_count;
  attribute_info attributes[attributes_count];
}
```

Constants, Fields, and Methods

- Constant pool
  - The central repository of names found in the class.
  - Consists of a number of variable-sized (but self-describing) entries of type `cp_info`, describing 17 kinds of possible constants.

```
cp_info {
  u1 tag;
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- Fields
  - Described by a `field_info` structure.
  - Variable-sized, but self-describing.

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cp_info {
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```
field_info {
  u2 access_flags;
  u2 name_index;
  u2 descriptor_index;
  u2 attributes_count;
  attribute_info
    attributes[attributes_count];
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- Fields
  - Described by a `field_info` structure.
  - Variable-sized, but self-describing.
- Methods
  - Described by a `method_info` structure.
  - Variable-sized, but self-describing.
  - A key attribute is `Code`, which contains the JVM code for the method.

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cp_info {
  u1 tag;
  u1 info[];
}
```

```
field_info {
  u2 access_flags;
  u2 name_index;
  u2 descriptor_index;
  u2 attributes_count;
  attribute_info
    attributes[attributes_count];
}
```

```
method_info {
  u2 access_flags;
  u2 name_index;
  u2 descriptor_index;
  u2 attributes_count;
  attribute_info
    attributes[attributes_count];
}
```

Java Virtual Machine Startup and Exit

- [Ref: JVM SE16, §5.2, §5.7]
- JVM startup
  - Create an initial class (or interface) using a class loader.
  - Link this initial class.
  - Initialize this initial class.
  - Invoke the `public static` method `void main(String[])` of this class.

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- The invocation of this method drives all further execution, including the linking and creation of additional classes and interfaces, and the invocation of additional methods.
- JVM exit
  - The Java Virtual Machine exits when some thread invokes the `exit` method of class `Runtime` or class `System`, or the `halt` method of class `Runtime`, and the `exit` or `halt` operation is permitted by the security manager.

Run-Time Constant Pool

- [Ref: JVM SE16, §5.1]
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- Two kinds of entries:
  - Symbolic references, which may later be resolved.
  - Static constants (i.e., string and numeric constants), which require no further processing.
- All static constants and some types of symbolic references are loadable, i.e., they may be pushed onto the evaluation stack by the `ldc` family of instructions.

Class Creation and Loading

- [Ref: JVM SE16, §5.3]
- Creation of a class (or interface) C denoted by the name N consists of the construction in the method area of the JVM of an implementation-specific internal representation of C.
  - A non-array class is created by loading its binary representation using a class loader L.
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  - The run-time identity of class is the pair $\langle N, L \rangle$.
- Loading a class (when L is the bootstrap class loader)
  - The JVM passes the argument N to an invocation of a method on the bootstrap class loader to search for a representation of C in a platform-dependent manner (i.e., a `class` file).
  - Then the JVM attempts to derive a class C from the `class` file.
    - Parse the `class` file into an implementation-specific internal representation.
    - If C has a direct superclass D, resolve the symbolic reference from C to D. Likewise for any superinterfaces.

Class Linking

- [Ref: JVM SE16, §5.4]
- Linking a class (or interface) involves verifying and preparing that class, its direct superclass, and its direct superinterfaces, if necessary.
- Linking also involves resolution of symbolic references in the class or interface, though not necessarily at the same time as the class or interface is verified and prepared.
- The JVM specification allow an implementation to be flexible in scheduling linking activities “eagerly” or “lazily”, as long as the following invariants are maintained.
  - A class is completely loaded before it is linked.
  - A class is completely verified and prepared before it is initialized.

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  - Preparation may occur at any time following creation but must be completed prior to initialization.
- Resolution is the process of dynamically determining one or more concrete values from a symbolic reference in the run-time constant pool.
  - Required when a JVM instruction like `new`, `invokevirtual`, or `getfield` is executed.
  - Initially, all symbolic references in the run-time constant pool are unresolved.

Class Initialization

- [Ref: JVM SE16, §5.5]
- Initialization of a class consists of executing its class initialization method (i.e., `<clinit>`).
  - Prior to initialization, a class must be linked, i.e., verified, prepared, and optionally resolved.
- Details of the initialization process are complicated.
  - Because the JVM is multithreaded, initialization of a class requires careful synchronization, since some other thread may be trying to initialize the same class at the same time.
  - There is also the possibility that initialization of a class may be requested recursively as part of the initialization of that class.
  - The implementation of the JVM is responsible for taking care of synchronization and recursive initialization following a specified procedure.