

COMPILER CONSTRUCTION

Intermediate Representations & Runtime Support

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Spring 2020



Chapter 10
Intermediate Representations

Chapter 12
Runtime Support



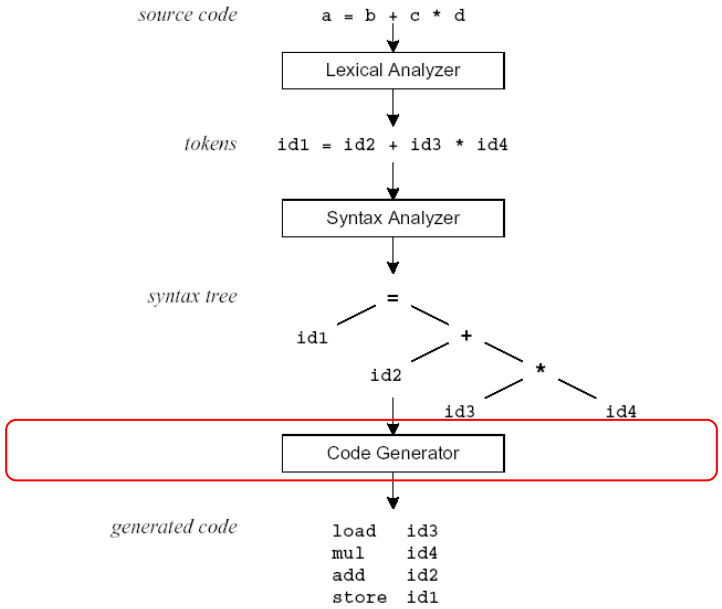
Outline

1. This file gives an overview of the **Intermediate Representation** (Ch. 10) for the compilers
2. This file also covers the *key concepts* of the **Runtime Support** (Ch. 12)
3. We talk about the intermediate language for Java
4. The above covers the basic knowledge required for the programming assignment #3



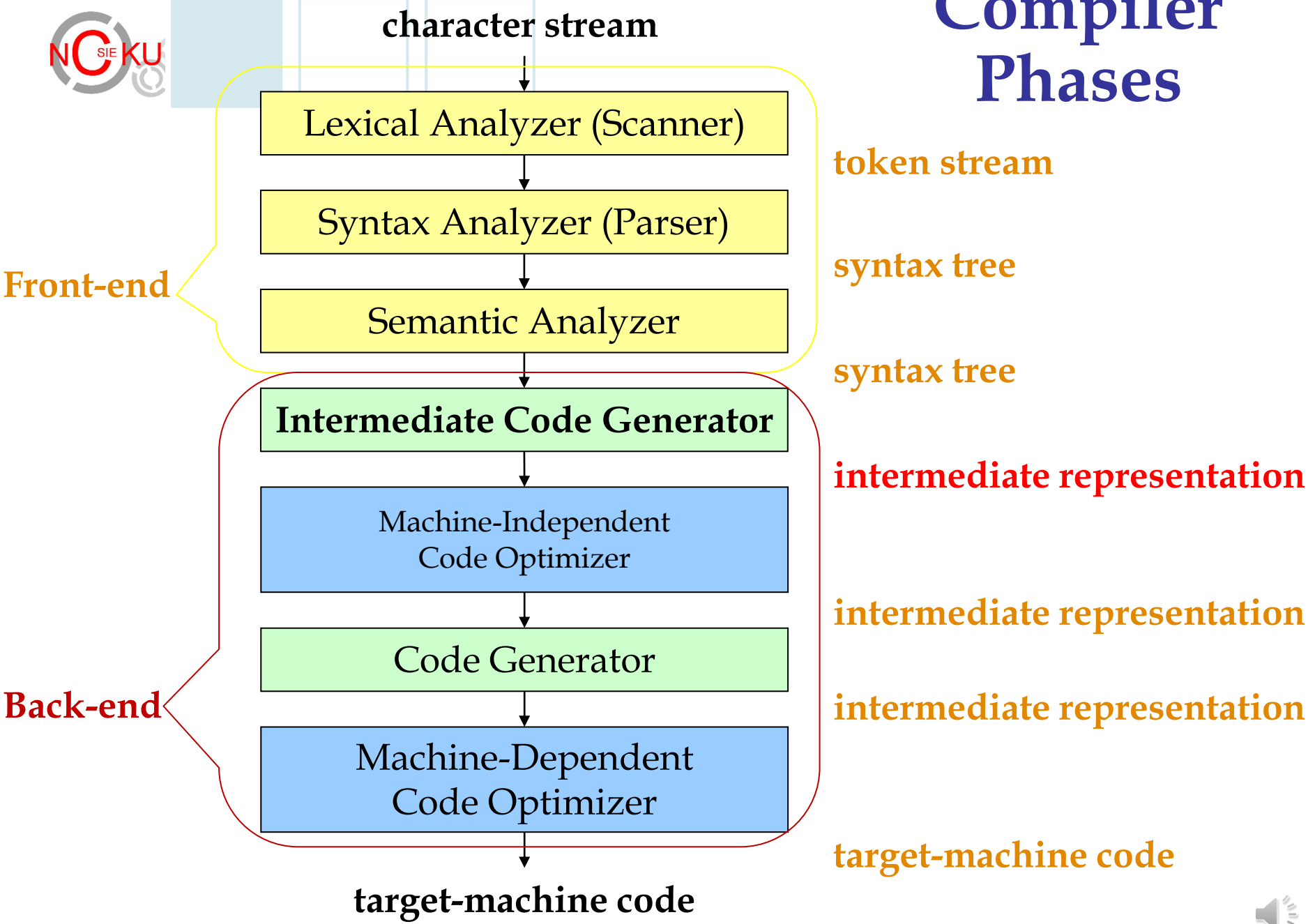
About the 3rd Assignment

- Lex and Yacc are able to do the following
- Now, our target is to generate the Java Assembly code
  - More precisely, the assembly code generation is at the Intermediate Code Generator phase of the compiler (see the next page)



A simplified view

Compiler Phases





Intermediate Representation

- An intermediate representation (IR)
  - is the **data structure** or **code** used internally by a compiler or virtual machine **to represent source code**
  - Compiler passes are performed on the IR
  - E.g., during the code generation process, an iteration process is performed to iterate over the IR node and generate the corresponding code for each IR node
- An IR is designed to be conducive for further processing, such as optimization and translation
- A "good" IR must be accurate
  - capable of representing the source code without loss of information and
  - independent of any particular source or target language
- An IR may take one of several forms
  1. an in-memory data structure, or
  2. a special tuple- or stack-based code readable by the program
  - In the 2nd case, it is also called **an intermediate language**

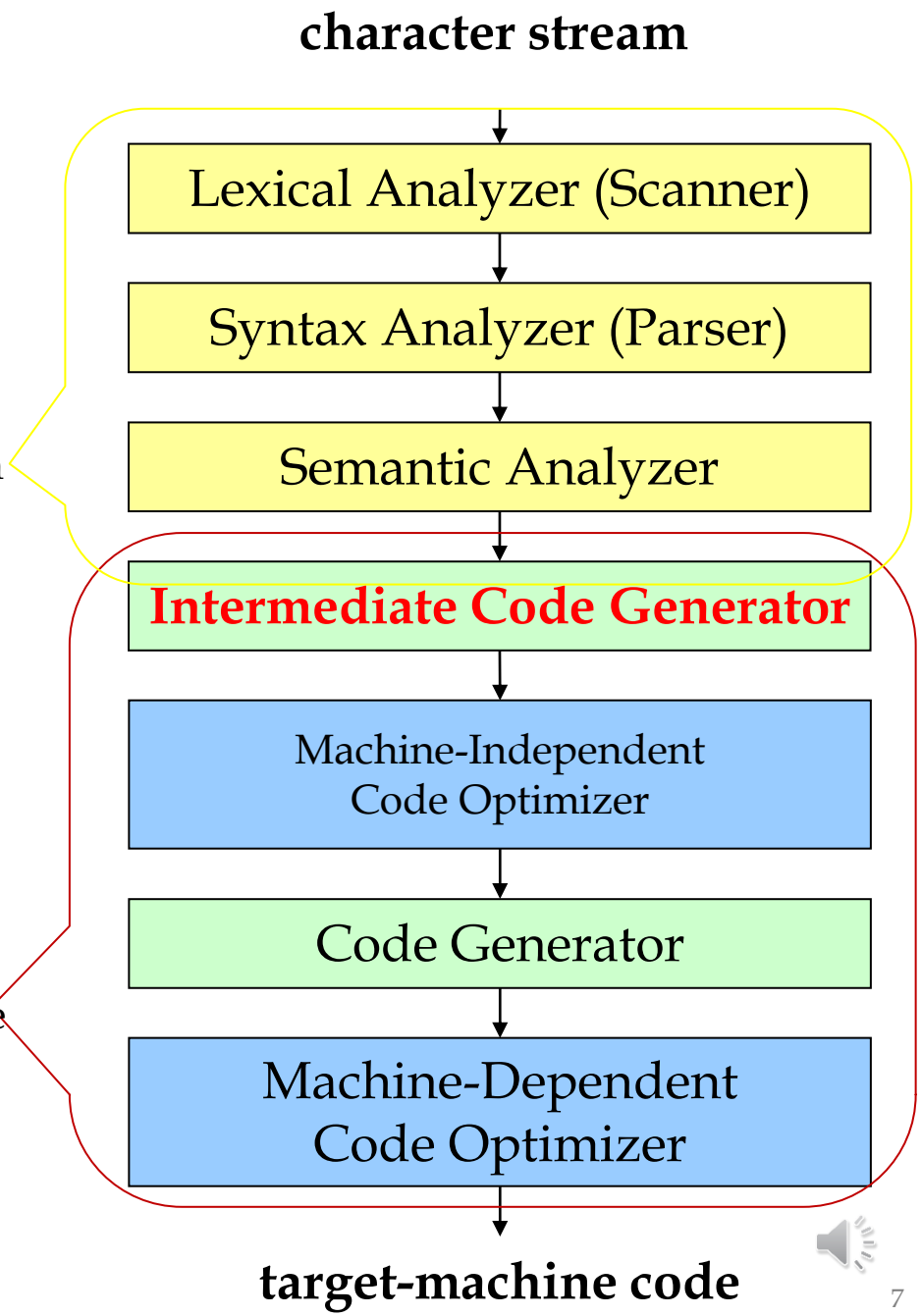
Courtesy of https://en.wikipedia.org/wiki/Intermediate_representation

Front- & Back-ends

- **Front-end** handles different source languages (e.g., C, C++)
- Conventionally, front-end is tightly coupled with back-end in a compiler tool
- E.g., GCC is **monolithic architecture**, making reusing part of their code almost impossible
- Huge obstacle if you want to try new ideas on compilers for real world impact

- **Back-end** is more close to target machine (e.g., ARM or x86 machines)
- Various back-ends are built for target-dependent optimizations

- Current trend is defining a clear Intermediate Language so as to **decouple the front-end and back-end**
- **The notable example is Clang and LLVM**





Classical Compiler Design (1/2)

- **Three phases structure**
  - The most popular design for a traditional compiler (like most C compilers)
  - whose major components are the front end, the optimizer and the backend, as shown in the figure below
  - **Communications are done through the intermediate representation(s), e.g., AST**
- Front end
  - parses source code, checking it for errors, and builds a language-specific Abstract Syntax Tree (AST) to represent the input code
- AST
  - is optionally converted to a new representation for optimization, and the optimizer and backend are run on the code

Courtesy of http://www.aosabook.org/en/llvm.html



Classical Compiler Design (2/2)

- Optimizer
  - is responsible for doing a broad variety of **transformations** to try to improve the code's **performance**
    - such as minimizing the execution time (or energy consumption) by eliminating redundant computations
  - is usually more or less **independent of language and target**
- Back-end
  - also known as the **code generator**
  - then maps the **intermediate code** onto the **target instruction set**
  - In addition to making *correct* code, it is responsible for generating *good* code that **takes advantage of special features of the supported architecture**
  - Common parts of a compiler back-end include instruction selection, register allocation, and instruction scheduling
- This model applies equally well to interpreters and JIT compilers
  - The Java Virtual Machine (JVM) is also an implementation of this model,
  - which uses **Java bytecode** as the interface between the front end and optimizer

Courtesy of http://www.aosabook.org/en/llvm.html



Implications of the Three Phases Design

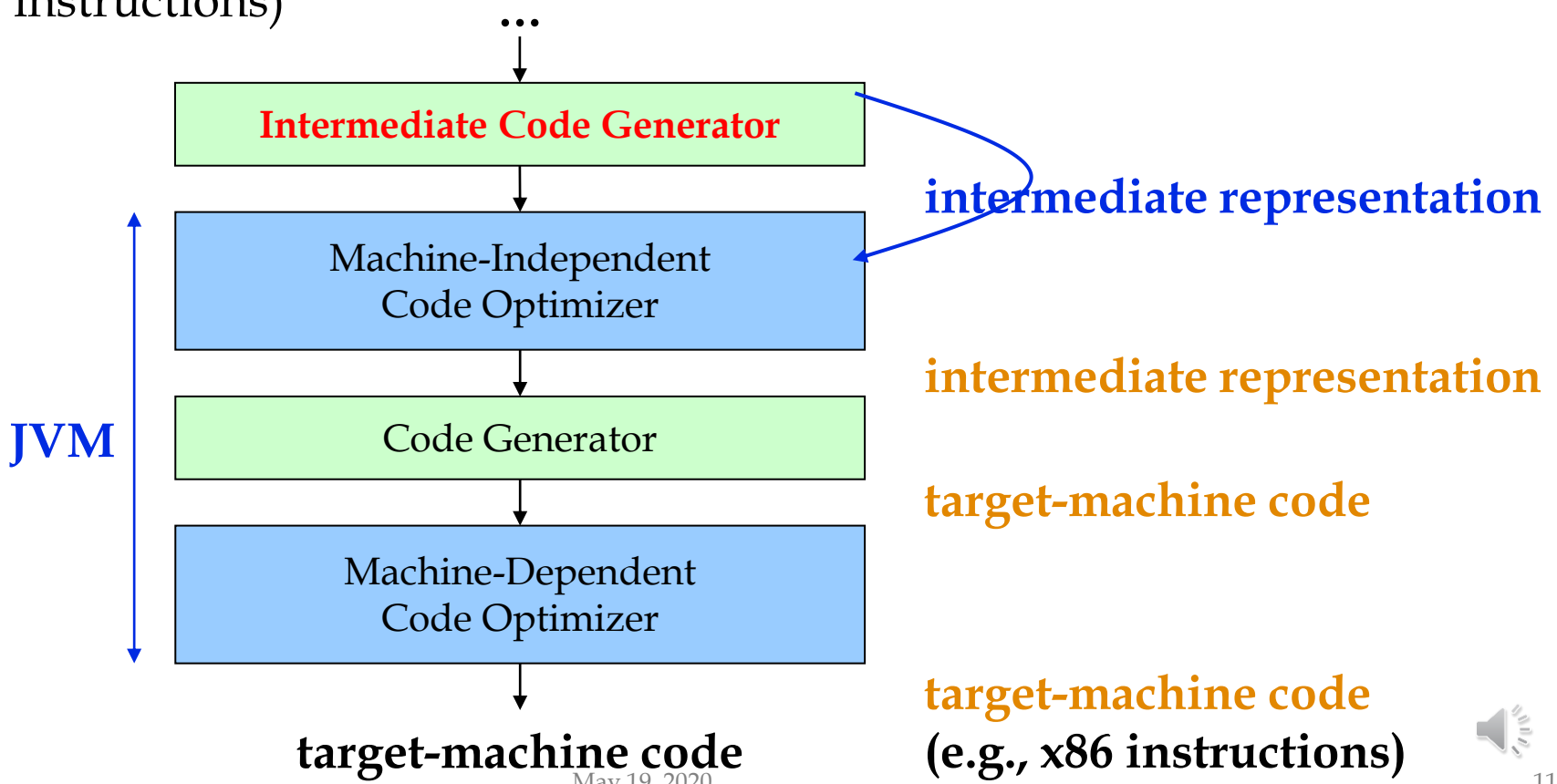
- The most important win of this classical design comes when a compiler decides to support **multiple source languages or target architectures**

- If the compiler uses a **common code representation** in its optimizer,
  - then a front-end can be written for any language that can compile to it, and
  - a back-end can be written for any target that can compile from it

Courtesy of http://www.aosabook.org/en/llvm.html

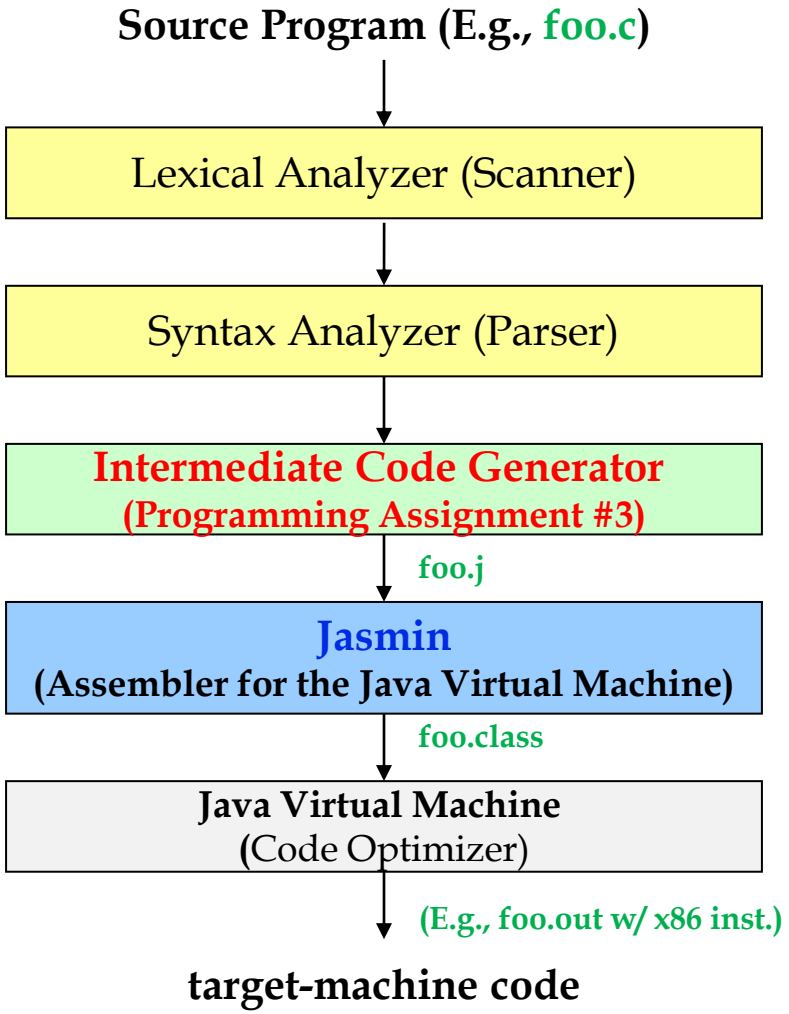
Java Virtual Machine Example

- For Java-like high-level languages, we can think that the generated intermediate representation (e.g., **Java bytecode**) is the input for Java Virtual Machine (JVM)
- Java Virtual Machine converts the **Java bytecode** (.class files) into the **machine code** accepted by the target machine (e.g., x86 instructions)





Workflow of Our 3rd Programming Assignment



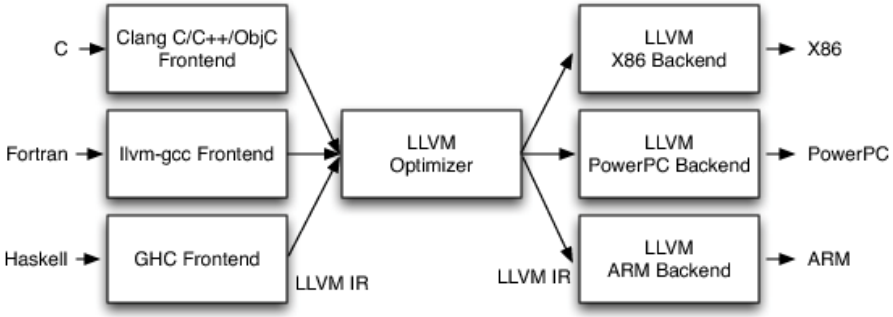


Another Three Phases Design Example: LLVM

In an LLVM-based compiler

- A front-end
  - is responsible for parsing, validating and diagnosing errors in the **input code**,
  - then translating the parsed code into **LLVM IR** (usually, but not always, by building an AST and then **converting the AST to LLVM IR**)
- LLVM IR
  - is optionally fed through a series of analysis and optimization passes which improve the code,
  - then is sent into a code generator to produce native machine code, as shown in the figure below
  - This is a very straightforward implementation of the three-phase design, but this simple description glosses over some of the power and flexibility that the LLVM architecture derives from LLVM IR

Multiple languages



Multiple targets



LLVM IR is a Complete Code Representation

- LLVM IR is both well specified and the ***only*** interface to the optimizer
  - This property means that all you need to know to write a front-end for LLVM is what LLVM IR is, and how it works
  - Since LLVM IR has a first-class textual form, it is both possible and reasonable to **build a front end that outputs LLVM IR** as ***text***,
  - then uses Unix pipes to **send it through the optimizer** sequence and code generator of your choice
  - Serialization: LLVM IR is (de)serialized to/from a binary format known as LLVM **bitcode**

- It might be surprising, but this is actually a pretty novel property to LLVM
  - Even the widely successful and relatively well-architected GCC compiler does not have this property: its **GIMPLE mid-level representation** is not a self-contained representation
  - As a simple example, when the GCC code generator goes to emit DWARF debug information, it reaches back and walks the source level "tree" form
  - GIMPLE itself uses a "tuple" representation for the operations in the code, but (at least as of GCC 4.5) still represents operands as **references back to the source level tree form**

- The implications of this are that **front-end authors need to know and produce GCC's tree data structures as well as GIMPLE to write a GCC front end**

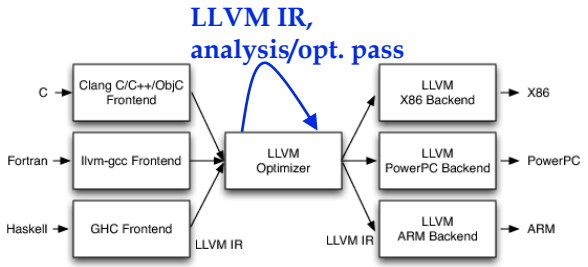
Courtesy of http://www.aosabook.org/en/llvm.html



LLVM is a Collection of Libraries

- LLVM is designed as a set of libraries,
  - rather than as a monolithic command line compiler like GCC or an opaque virtual machine like the JVM or .NET virtual machines
  - LLVM is an infrastructure, a collection of useful compiler technology that can be brought to bear on specific problems (like building a C compiler, or an optimizer in a special effects pipeline)

- The design of the optimizer
  - It reads LLVM IR in, chews on it a bit, then emits LLVM IR which hopefully will execute faster
  - It is organized as **a pipeline of distinct optimization passes** each of which is run on the input and has a chance to do something
  - Examples of passes are the inliner (which substitutes the body of a function into call sites), expression reassociation, loop invariant code motion
  - For example, at **-O3** it runs a series of 67 passes in its optimizer (as of LLVM 2.8)
  - **The sequence of applied passes does matter!!!**



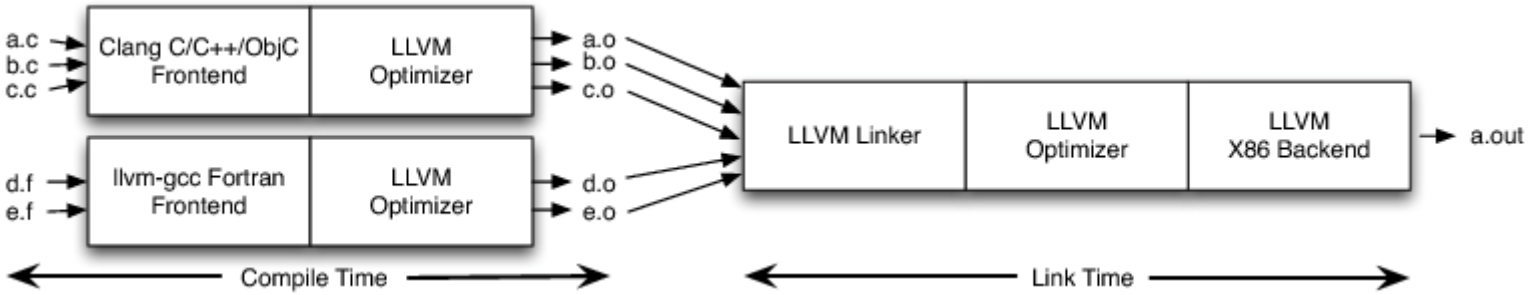
Courtesy of http://www.aosabook.org/en/llvm.html



A Modular Design of LLVM (LTO) (1/2)

- LLVM provides functionality, but lets the client decide most of the ***policies*** on how to use it
- Thanks to the serialization property
  - we can do part of compilation, save our progress to disk, then continue work at some point in the future
  - This feature provides a number of interesting capabilities: including support for **link-time** and **install-time optimization**, both of which delay code generation from "compile time"
- Link-Time Optimization (LTO)
  - The compiler traditionally only sees one translation unit (e.g., a *.c* file with all its headers) at a time and therefore cannot do **optimizations** (like inlining) **across file boundaries**
  - LLVM compilers (like Clang) support this with the **-flto** or **-O4** command line option
    - This option instructs the compiler to emit LLVM **bitcode** to the **.o** file instead of writing out a native object file, and delays code generation to link time, as shown below

Link-Time Optimization

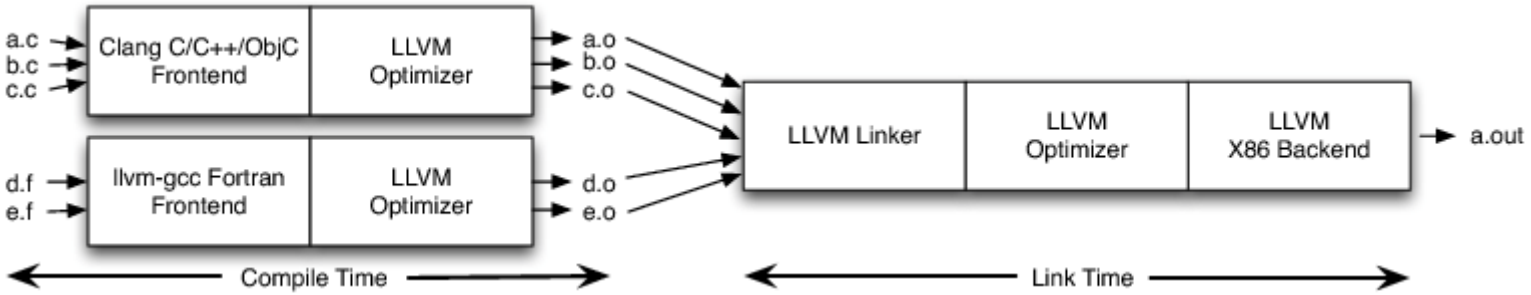


Courtesy of http://www.aosabook.org/en/llvm.html

A Modular Design of LLVM (LTO) (2/2)

- The linker detects LLVM **bitcode** in the **.o** files instead of native object files
  - Then, linker reads all the bitcode files into memory, links them together, and runs the LLVM optimizer over the aggregated program
  - Details differ depending on which operating system you're on
- Since the optimizer can now see across a much larger portion of the code,
  - it can **inline**, **propagate constants**, do more **aggressive dead code elimination**, and more across file boundaries
  - While many modern compilers support LTO, most of them (e.g., GCC, Open64, the Intel compiler, etc.) do so by having an expensive and slow serialization process
- In LLVM, LTO falls out naturally from the design of the system, and
  - **works across different source languages** (unlike many other compilers) because **the IR is truly source language neutral**

Link-Time Optimization



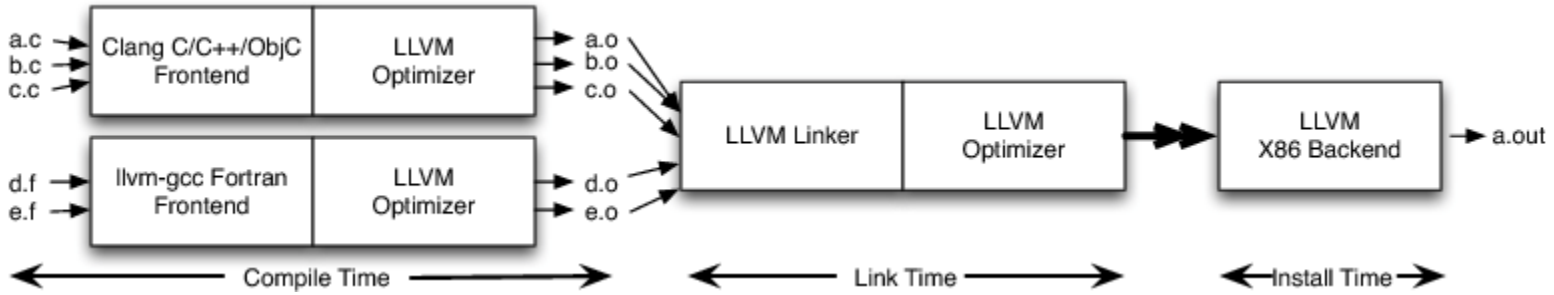
Courtesy of http://www.aosabook.org/en/llvm.html

- In fact, LLVM supports link-time, install-time, run-time, and offline optimization
- You can find out more by yourself

A Modular Design of LLVM (ITO)

- Install-time optimization (ITO)
  - refers to the idea of delaying code generation even later than link time, all the way to install time, as shown below
- Install time is a very interesting time
  - the cases when software is shipped in a box, downloaded, uploaded to a mobile device, etc.
  - This is when you find out **the specifics of the device you're targeting**
  - In the x86 family for example, there are broad variety of chips and characteristics
  - By delaying instruction choice, scheduling, and other aspects of code generation, **you can pick the best answers for the specific hardware an application ends up running on**

Install-Time Optimization



Courtesy of http://www.aosabook.org/en/llvm.html



Key Features of JVM

- The JVM is designed with the following principles in mind

1. Compactness

- Java class files are designed to be relatively compact
  - because JVMs are deployed in browsers and mobile devices
  - compared with the register machines
- In particular, the JVM's instructions are in nearly **zero-address form**
  - so that most instructions manipulate data at the top of Java's **runtime stack**
  - We refer to the topmost location as **top-of-stack** (TOS)



Key Features of JVM (Compactness)

- Example
  - Executing the **iadd** instruction, it
  1. pops two items off the stack and
  2. pushes their sum onto the TOS
  - Only **a single byte** is needed to represent such an operation (**iadd**) because the instruction's operands are **implicit**
- Generally, such compaction is achieved with **a loss of runtime performance**
  - stack manipulation is typically slower than processing operands in a register file
- **Mixing multiple instructions** to further achieve compactness
- Example
  - There are many ways to push 0 on TOS
  1. The shortest instruction, **iconst_0**, takes only a single byte
  2. The most general instruction, **ldc_w 0**, takes three bytes
     - for the instruction and consumes a constant-pool entry
  - While the **iconst_0** instruction is not strictly necessary, its inclusion allows greater code compaction, because pushing 0 on TOS is a frequent operation



Key Features of JVM (Cont'd)

2. Safety

- The JVM's instructions are designed to execute safely: an instruction can reference storage only if said storage is of the **type** allowed by the instruction and only if the storage is located in an area **appropriate for access**
- because the JVM may be deployed in an environment that cannot tolerate badly behaved programs

- Moreover, the instructions are designed so that most **safety errors can be caught prior to executing code**



Key Features of JVM (Cont'd)

- JVM adopts a more secured address form
- In a **pure zero-address form** (which the JVM is not), a **register load** is accomplished by
  a) computing a register number that is **pushed on TOS**, then
  b) pops the register number from the stack,
  c) accesses the register's contents, and
  d) pushes the contents on TOS
- However, the **purely zero-address form** is problematic,
  - from a security point of view,
  - because **the registers that could be accessed by a load instruction may not be known until runtime**



Key Features of JVM (Cont'd)

- The **purely zero-address form** is problematic

- **Runtime checks could be deployed to check the validity of a load instruction,**
  - **but degrades performance**

- Or, a more reliable and efficient approach would check such instructions prior to running the code



Key Features of JVM (Cont'd)

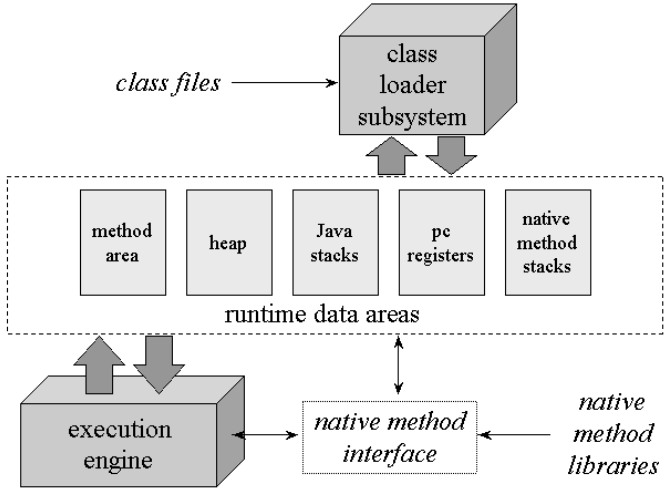
- A more reliable approach in JVM
  - The load instruction in the JVM is not zero-address, but instead
  - **specifies the register number as an immediate operand of the instruction**
- Example
  - the instruction **iload 5** causes
  - the contents of register 5 to be pushed on TOS

- When a class file is loaded, **bytecode verifier** checks the instructions
  - to ensure that register 5 falls within the range of registers its method can access
  - The instruction will always access register 5, because the immediate operands of an instruction cannot be changed at runtime
  - Thus, by discovering that the register reference is valid prior to running the code, no further checks of this kind are necessary at runtime
- The JVM instruction set and class file format are designed to facilitate such checks



Architecture of Java Virtual Machine

- The block diagram of the Java virtual machine that includes:
  - **a class loader subsystem**: a mechanism for loading types (classes and interfaces) given fully qualified names
  - **an execution engine**: a mechanism responsible for executing the instructions contained in the methods of loaded classes

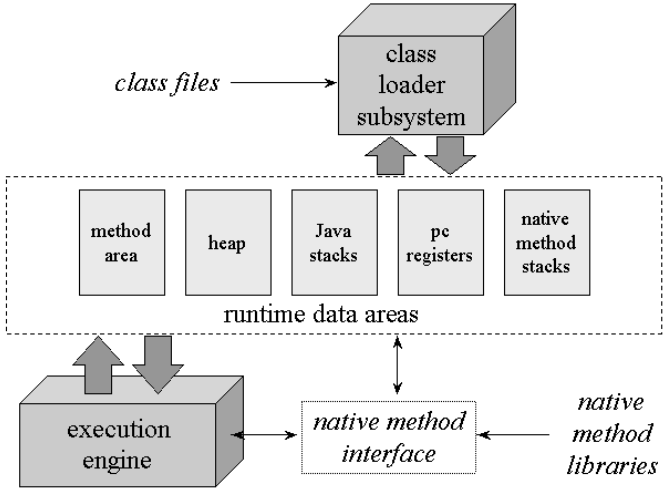


Courtesy of http://www.artima.com/insidejvm/ed2/jvm2.html



Architecture of Java Virtual Machine (Cont'd)

- When a JVM runs a program, it needs **memory** to store many things
  - including bytecodes and other information it extracts from loaded class files, objects the program instantiates, parameters to methods, return values, local variables, and intermediate results of computations
- The JVM organizes the memory it needs to execute a program into several ***runtime data areas***
  - Many decisions about the structural details of the runtime data areas are implementation dependent

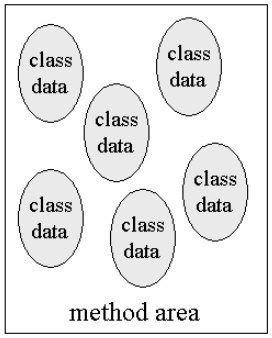


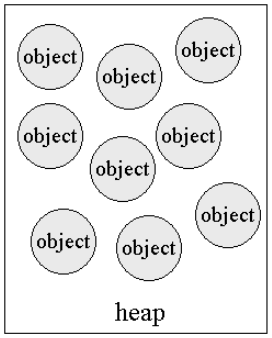
Courtesy of http://www.artima.com/insidejvm/ed2/jvm2.html



Runtime Data Areas (Shared)

- Runtime data areas are either
  - **shared among all of an application's threads or**
  - private to individual threads





- An instance of the JVM is usually created for an application
  - has ***one method area*** and ***one heap***
  - these areas are shared by all threads running inside the virtual machine
- When the virtual machine loads a **class file**,
  - it parses information about a type from the binary data contained in the class file
  - it places this type information into the method area
  - Class (static) variables are kept in **method area**
- As the program runs,
  - the virtual machine places all objects the program instantiates onto the **heap** as shown in the figure
  - The heap memory is managed by JVM (through Garbage Collection)

Courtesy of http://www.artima.com/insidejvm/ed2/jvm2.html



Runtime Data Areas (Private)

- Runtime data areas are either
  - shared among all of an application's threads or
  - **private to individual threads**

- A new Java thread gets its own ***pc register*** (program counter) and ***Java stack***
- If the thread is **executing a Java method** (not a native method),
  - the value of the **pc register** indicates the next instruction to execute
  - A thread's **Java stack** stores the state of Java (not native) method invocations for the thread

- The state of native method invocations is stored in an implementation-dependent way in ***native method stacks***
  - as well as possibly in registers or other implementation-dependent memory areas

Courtesy of http://www.artima.com/insidejvm/ed2/jvm2.html



Java Stack

- The Java stack is composed of ***stack frames*** (or ***frames***)
- A stack frame contains **the state of one Java method invocation**
  - The state includes its local variables, the parameters with which it was invoked, its return value (if any), and intermediate calculations
- When a thread invokes a method,
  - the JVM pushes a new frame onto that thread's Java stack
- When the method completes,
  - the JVM pops and discards the frame for that method

Courtesy of http://www.artima.com/insidejvm/ed2/jvm2.html



Java Stack (Cont'd)

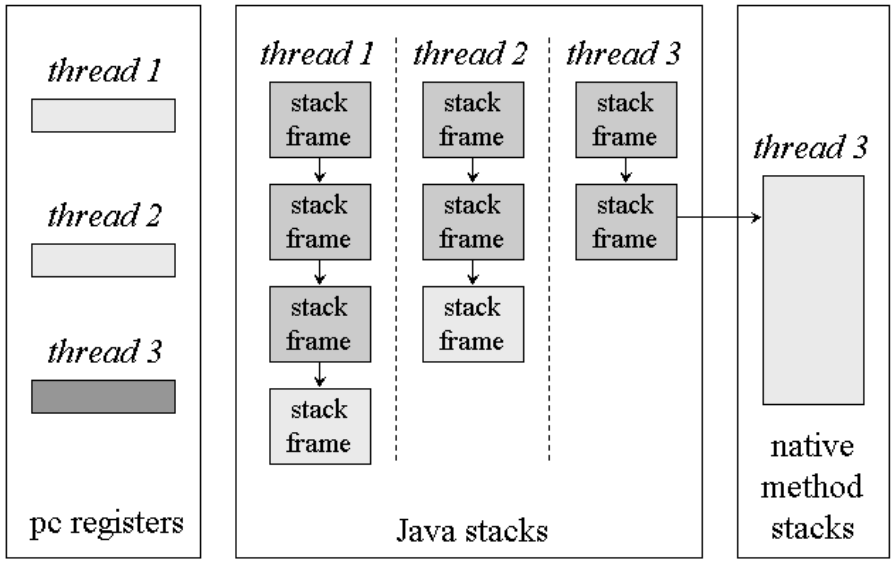
- The **JVM has no registers** to hold intermediate data
  - The instruction set uses the Java stack for storage of intermediate data values
- This approach was taken by Java's designers to
  - keep the Java virtual machine's instruction set compact and
  - facilitate implementation on architectures with few or irregular general purpose registers
- The **stack-based architecture** of the JVM's instruction set
  - facilitates the code optimization work done by just-in-time and dynamic compilers that operate at run-time in some virtual machine implementations

Courtesy of http://www.artima.com/insidejvm/ed2/jvm2.html



Memory Areas for Java Threads

- The figure shows memory areas that JVM creates for each thread
- These areas are private to the owning thread
- No thread can access the pc register or Java stack of another thread

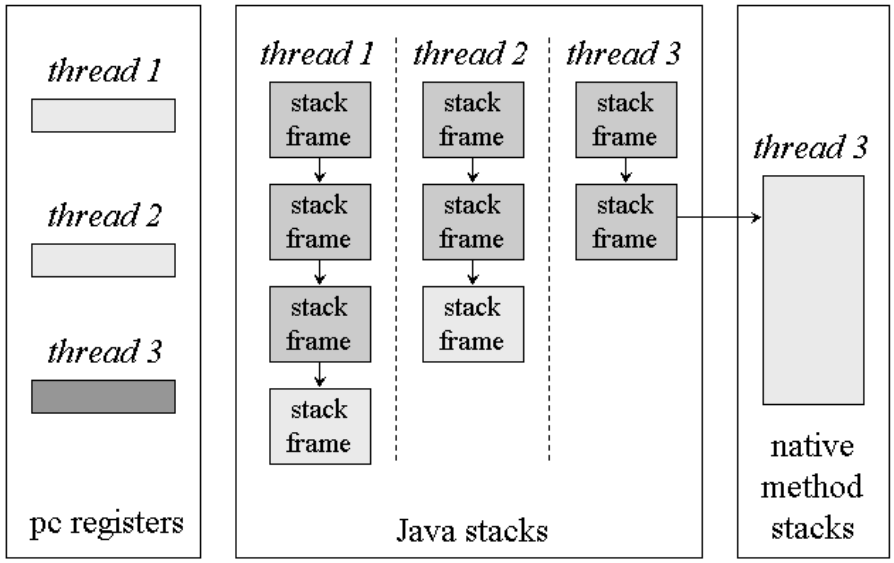


Courtesy of http://www.artima.com/insidejvm/ed2/jvm2.html



Memory Areas for Java Threads

- Figure shows a snapshot of a JVM instance
  - in which three threads are executing
- At the instant of the snapshot, threads one and two are executing Java methods
- Thread three is executing a native method
- The stacks are shown growing downwards
  - The ***top of each stack*** is shown at the bottom of the figure



Courtesy of http://www.artima.com/insidejvm/ed2/jvm2.html



Intermediate Language for Java Virtual Machine

- Java Virtual Machine interprets **class** files
  - which are binary encodings of the data and instructions needed to execute a Java program
- The Java bytecode is considered as the intermediate language for Java, whereas
  - in the textbook, JVM is used to represent the same concept
  - Both terms are used in this file
  - Hence, JVM could refer to **the machine** or **the language** in this file
- To simplify exposition, the contents of a class file are typically discussed in printable form
  - For example, the instruction that specifies **integer addition** has the numerical value of 96, but we typically refer to it as **iadd**



A Class File (Formal Definition)

- A Java class file is consist of 10 basic sections:
  1. Magic Number: 0xCAFEBABE
  2. Version of Class File Format: the minor and major versions of the class file
  3. Constant Pool: Pool of constants for the class
  4. Access Flags: for example whether the class is abstract, static, etc.
  5. This Class: The name of the current class
  6. Super Class: The name of the super class
  7. Interfaces: Any interfaces in the class
  8. Fields: Any fields in the class
  9. Methods: Any methods in the class
  10. Attributes: Any attributes of the class (for example the name of the source file, etc.)

```
ClassFile {
    u4             magic;
    u2             minor_version;
    u2             major_version;
    u2             constant_pool_count;
    cp_info        constant_pool[constant_pool_count-1];
    u2             access_flags;
    u2             this_class;
    u2             super_class;
    u2             interfaces_count;
    u2             interfaces[interfaces_count];
    u2             fields_count;
    field_info     fields[fields_count];
    u2             methods_count;
    method_info    methods[methods_count];
    u2             attributes_count;
    attribute_info attributes[attributes_count];
}
```

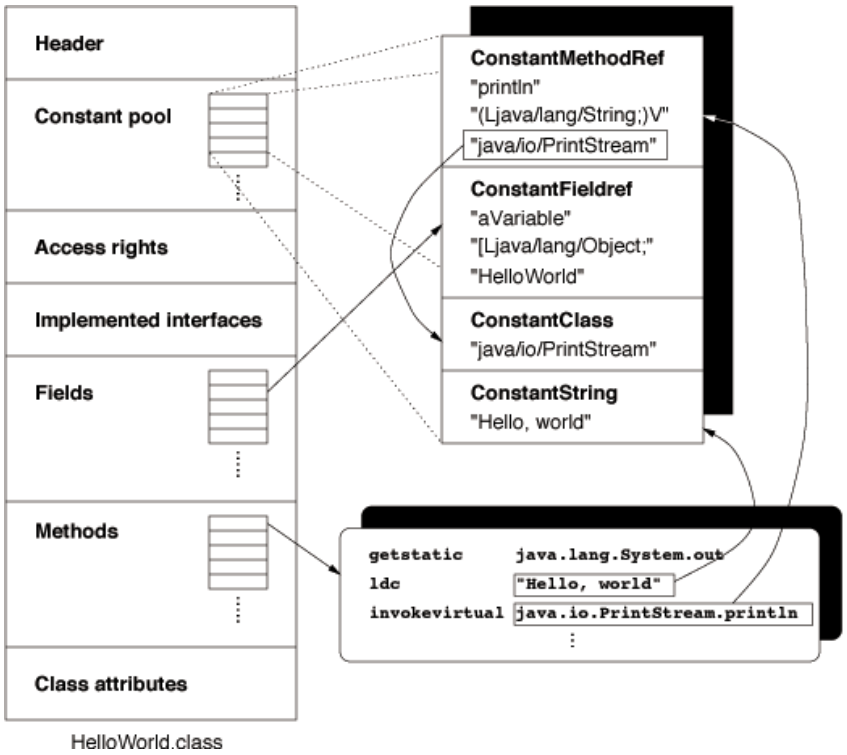
Courtesy of https://docs.oracle.com/javase/specs/jvms/se7/html/jvms-4.html; http://www.programering.com/a/MzN4QzNwATU.html; http://viralpatel.net/blogs/tutorial-java-class-file-format-revealed/



A Class File (Cont'd)

- The diagram depicts that a Java Class file is divided into different components
  - The length of the Java class is not known before it gets loaded
  - Variable length sections such as constant pool, methods, attributes, etc.
- A class file consists of a stream of **8-bit bytes** (one-byte-aligned)
  - All 16-bit, 32-bit, and 64-bit quantities are constructed by reading in two, four, and eight consecutive 8-bit bytes, respectively
  - Multibyte data items are always stored in **big-endian order**, where the high bytes come first
- The **order of different sections** in a Java Class file
  - is strictly defined so that the JVM knows what to expect in a Class file and in which order it is loading different components

Schematic Class File Structure



Courtesy of https://docs.oracle.com/javase/specs/jvms/se7/html/jvms-4.html; http://www.programering.com/a/MzN4QzNwATU.html; http://viralpatel.net/blogs/tutorial-java-class-file-format-revealed/



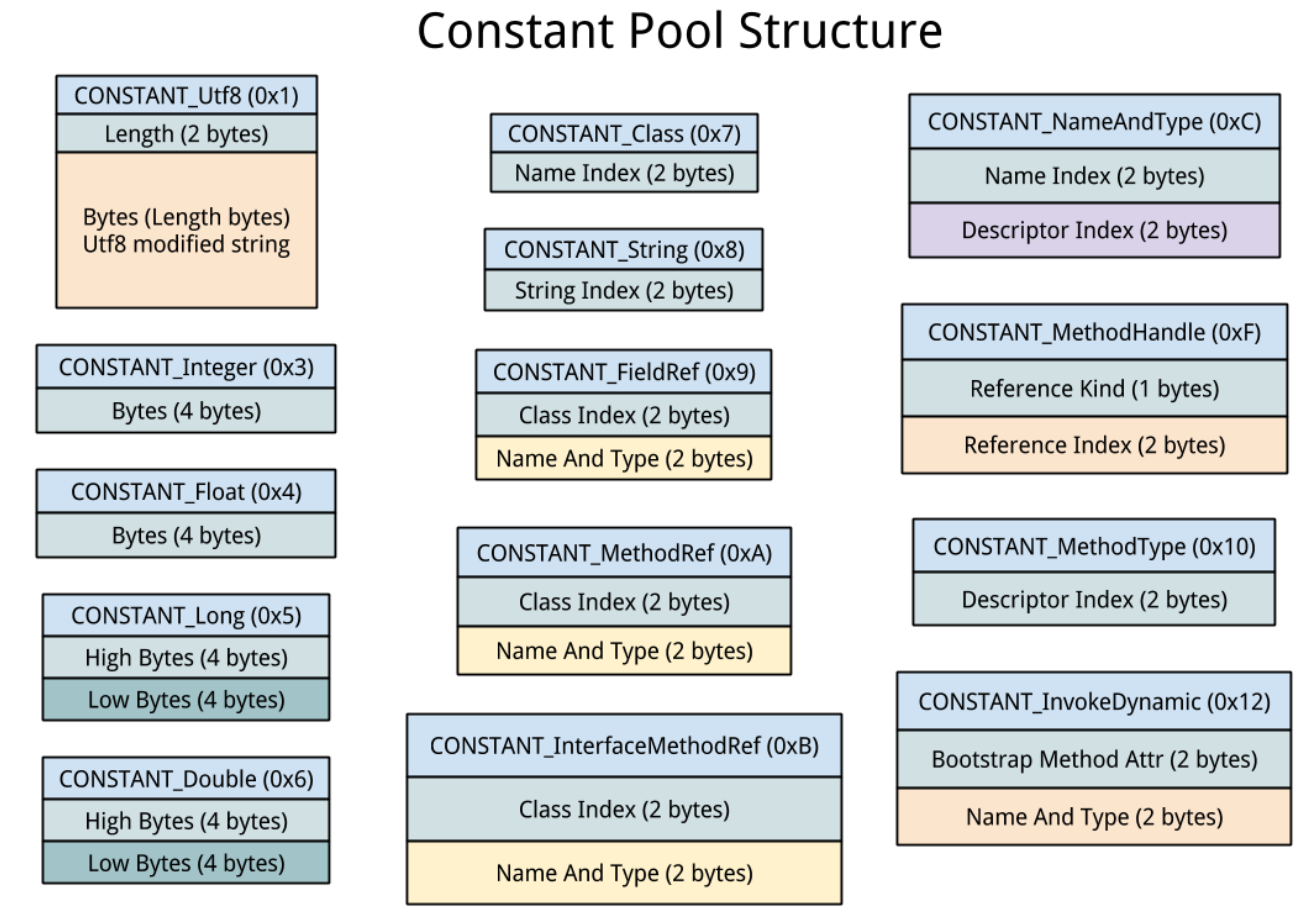
Constant Pool

- Keep all the **constants** related to the Class or an Interface
  - Include class names, variable names, interface names, method names and signature, final variable values, string literals, etc.
  - Contain variable-length arrays
  - Are placed by its array size; hence JVM knows how many constants it will expect while loading the class file
  - **constant_pool_count** is equal to the number of entries in the **constant_pool** array plus one
- Within each array elements, first byte represents a tag
  - specifying **the type of constant** at that position in the array
  - JVM identifies the type of the constant by reading **one-byte tag**
  - If one-byte tag represents a **UTF-8 String literal (Asciz),**
  - JVM knows that next 2 bytes represents length of the String literal and rest of the entry is string literal itself
- You can analyse the Constant Pool of any class file using **javap** command
- Explore more by yourself

```
C:\>javap -verbose Main
Compiled from "Main.java"
public class Main extends java.lang.Object
SourceFile: "Main.java"
minor version: 0
major version: 50
Constant pool:
const #1 = Method #4.#13; // java/lang/Object."<init>":()V
const #2 = int 16707053;
const #3 = class #14; // Main
const #4 = class #15; // java/lang/Object
const #5 = Asciz <init>;
const #6 = Asciz ()V;
const #7 = Asciz Code;
const #8 = Asciz LineNumberTable;
const #9 = Asciz main;
const #10 = Asciz ([Ljava/lang/String;)V;
const #11 = Asciz SourceFile;
const #12 = Asciz Main.java;
const #13 = NameAndType #5:#6;// "<init>":()V
const #14 = Asciz Main;
const #15 = Asciz java/lang/Object;
```

An entry Type Value

More about the Types of Constant Pool Elements

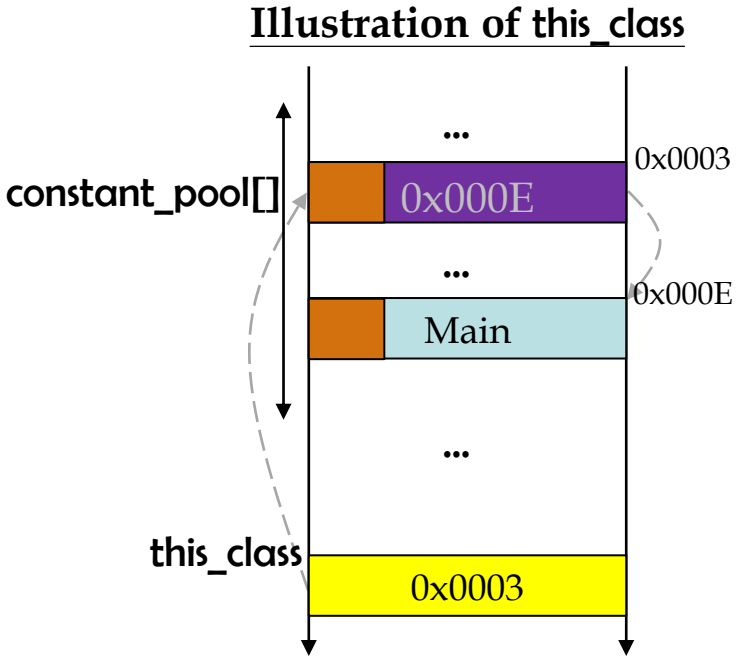


Courtesy of https://blog.lse.epita.fr/articles/69-0xcafebabe-java-class-file-format-an-overview.html
https://docs.oracle.com/javase/specs/jvms/se6/html/ClassFile.doc.html#29297



this Class

- **This Class** (**this_class**) is a two byte entry that points to **an index in Constant Pool**
- In the figure, **this_class** has a value 0x0003
  - which is an index in Constant Pool
  - At the address 0x0003, it has two parts:
  1. first part is the **one-byte tag** that represents the type of entry in constant pool, in this case it is **Class** or **Interface**
  2. second entry is **two-byte** having index again in Constant pool
  - The two-byte contains value 0x000E
  - Thus it points to **constant_pool**[0x000E] which is the String literal having name of the interface or class (e.g., Main)
  - **super_class** is similar



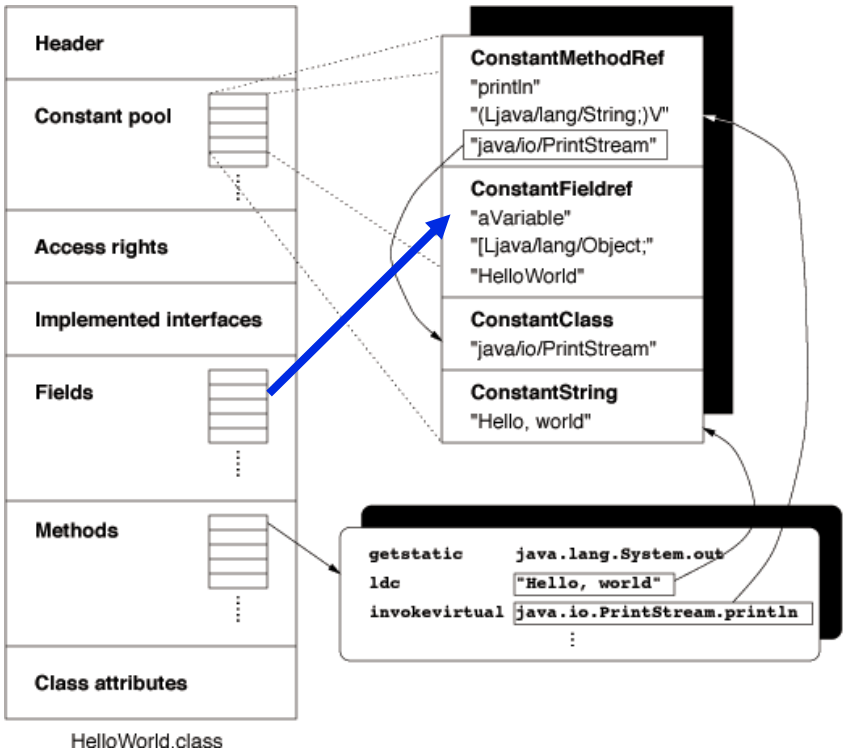
Courtesy of http://viralpatel.net/blogs/tutorial-java-class-file-format-revealed/
(Class instance creation) http://docs.oracle.com/javase/specs/jls/se8/html/jls-12.html#jls-12.5;



Fields

- A field
  - is an instance or a class level **variable** (property) of the class or interface
- Fields section contains only those fields
  - that **are defined by the class or an interface** of the file and
  - not those fields which are inherited from the super class or super interface
- First two bytes in Fields section represents count (**fields_count**)
  - that is the total number of fields in Fields Section
- Following the count is an array of variable length structure one for each field
  - Each element in this array represent one field
  - Some information is stored in this structure whereas some information, like **name of the fields**, are stored in Constant pool

Schematic Class File Structure



HelloWorld.class

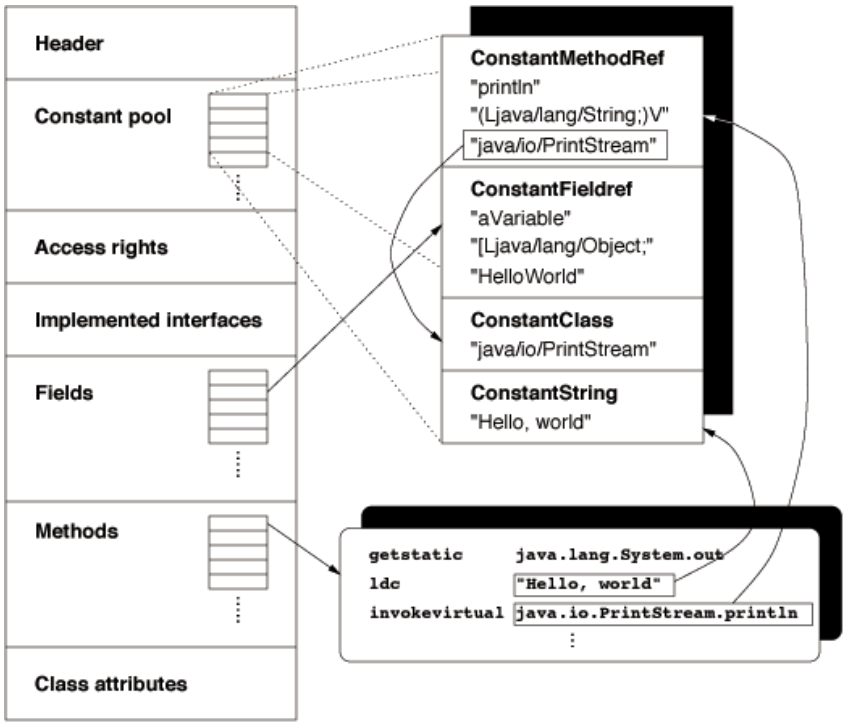
```
field_info {
    u2 access_flags;
    u2 name_index;
    u2 descriptor_index;
    u2 attributes_count;
    attribute_info attributes[attributes_count];
} // You can check what are the attributes for field.
```



Methods

- The Methods component host the methods
  - that are explicitly **defined by this class**,
  - not any other methods that may be inherited from super class
- First two byte (**methods_count**) is
  - the count of the **number of methods** in the class or interface
- The rest is again a variable length array which holds each method structure
  - Method structure contains several pieces of information about the method
  - E.g., method argument list, its return type, the number of stack words required for the method's local variables, stack words required for method's operand stack, a table for exceptions, etc.

Schematic Class File Structure

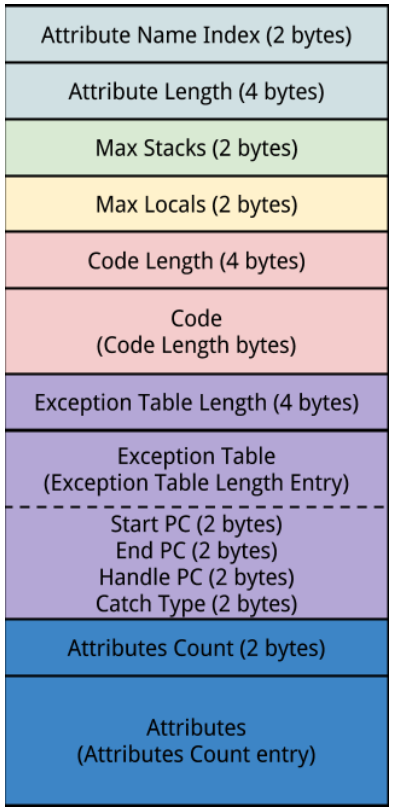




Attributes

- Attribute section contains several attributes about the fields, methods, and class
  - E.g., one of the attribute is the source code attribute which reveals the name of the source file from which this class file was compiled (Main.java in the previous example)
- There are several attribute types
  - each one of them can be applied to one or several fields, methods, classes and codes
- Example attribute types:
  - **Code** (as illustrate in the figure)
  - Local variables, constant value, information about the stack and exceptions
  - Inner Classes, Bootstrap Methods, Enclosing methods
  - Annotations
  - Information for debug/decompilation
  - Complementary information (Deprecated, Signature...)

Schematic Code Attribute

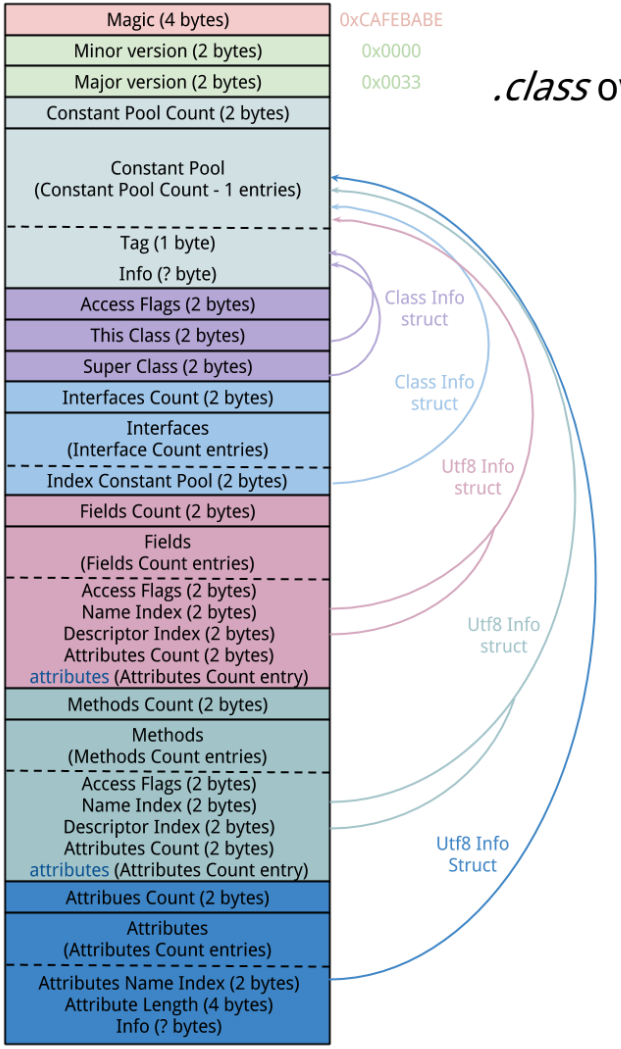


Courtesy of https://blog.lse.epita.fr/articles/69-0xcafebabe-java-class-file-format-an-overview.html; http://docs.oracle.com/javase/specs/jvms/se7/html/jvms-4.html#jvms-4.3.2;



More about the class File

- For those who are interested in the details

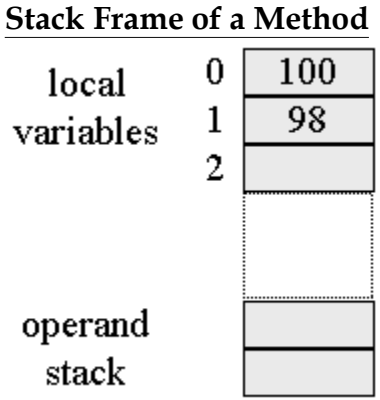


Courtesy of https://blog.lse.epita.fr/articles/69-0xcafebabe-java-class-file-format-an-overview.html



Java Stack Frame

- Java virtual machine creates a new Java Stack Frame for the thread
- The **stack frame** has three parts for each method
  - **local variables**, **operand stack**, and **frame data**
  - The method that is currently being executed by a thread is the thread's *current method*
  - The stack frame for the current method is the *current frame*
  - More about the **stack frame** is described in Sec. 12.2
  - Frame data is used to record constant pool resolution, normal method return, exception table, etc.
- An unlimited number of **virtual registers** in JVM
  - as is frequently the case with IRs, which is not tied to physical machines
  - Each method declares how many registers it can reference
- NOTE
  - **JVM does not have registers**
  - Registers used here refer to the **local variables**
  - Local variables and registers are used interchangeably here



Courtesy of http://www.artima.com/insidejvm/ed2/jvm8.html



Registers/Local Variables

- JVM registers typically host a method's **local variables**
  - which are similar to a machine's architected registers (Sec. 13.3)
  - Actually, we could see it this way: JVM local variables are mapped to the method's local variables
- JVM registers starting from 0 are set aside for a method's actual parameters
  - For **static methods**, register 0 holds the method's first declared parameter
  - For **instance-based methods**, register 0 holds **this** (the object's self-reference in the heap) and register 1 holds the method's first declared parameter

Registers/Local Variables (Cont'd)



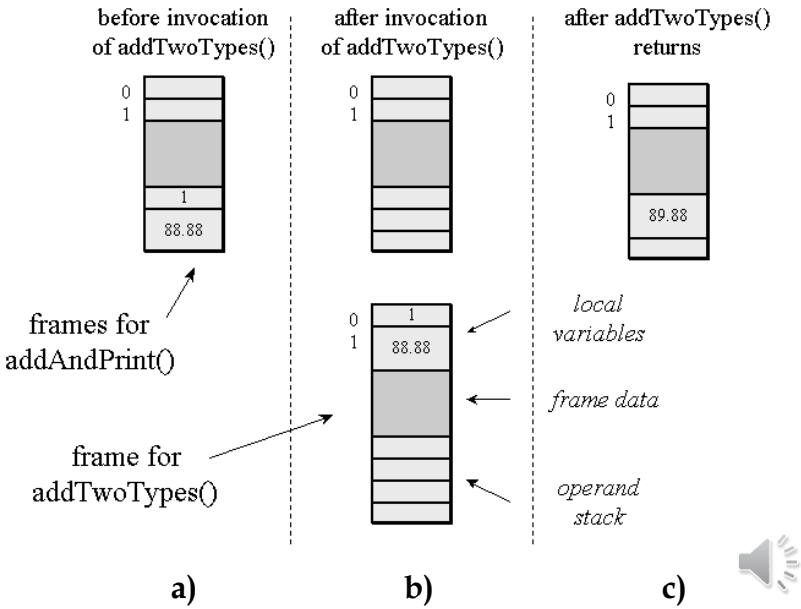
- When a method is invoked,
  - parameter values are automatically **popped from the caller's stack frame** and
  - **deposited into the callee's stack frame described as below**
- The figure depicts the stack status of a Java thread
  a) At the **addAndPrint()** method,
  - before invoking the **addTwoTypes()** method, the **addAndPrint()** method first pushes an int one and double 88.88 onto its operand stack
  - The **addAndPrint()** method uses the constant pool to identify the **addTwoTypes()** method
  - The resolved constant pool entry points to information in the method area about the **addTwoTypes()** method
  - The virtual machine allocates enough memory for the **addTwoTypes()** frame from a heap
  - It then pops the double and int parameters (88.88 and one) from **addAndPrint()**'s operand stack and places them into **addTwoType()**'s local variable slots one and zero

```
class Example3c {

   public static void addAndPrint() {
      double result = addTwoTypes(1, 88.88);
      System.out.println(result);
   }

   public static double addTwoTypes(int i, double d) {
      return i + d;
   }
}
```

Illustration of Stack Status before and after method invocation



Registers/Local Variables (Cont'd)



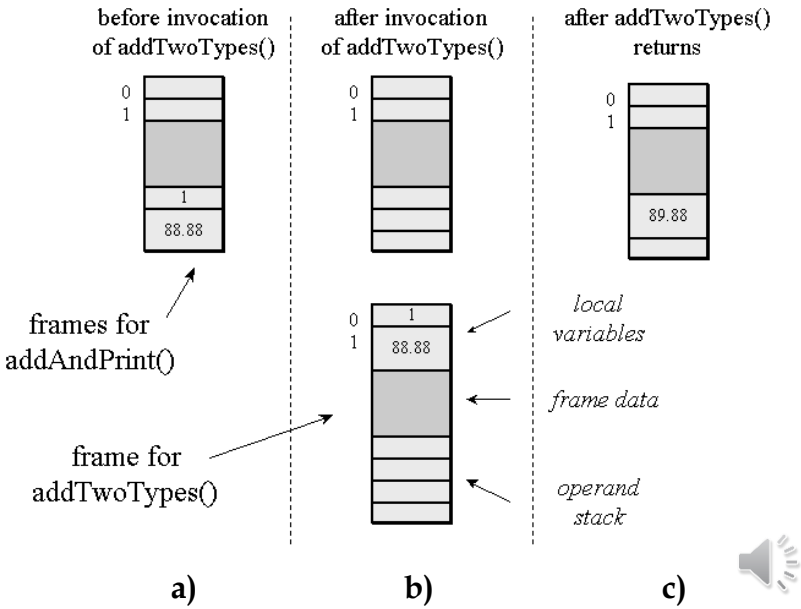
- The figure shows the stack status of a Java thread
  - b) It then invokes the **addTwoTypes()** method,
  - which calculates the sum for the local variables and it pushes the result (double return value, 89.88) onto its operand stack
  - Upon the method returns,
  - the virtual machine uses the information in the frame data to locate the stack frame of the invoking method, **addAndPrint()**
  - It pushes the double return value onto **addAndPrint()**'s operand stack and frees the memory occupied by **addTwoType()**'s frame
  - c) After **addTwoTypes()** returns,
  - it makes **addAndPrint()**'s frame current and continues executing the **addAndPrint()** method at the first instruction past the **addTwoType()** method invocation
  - NOTE: Some of the details described are implementation dependent

```
class Example3c {

   public static void addAndPrint() {
      double result = addTwoTypes(1, 88.88);
      System.out.println(result);
   }

   public static double addTwoTypes(int i, double d) {
      return i + d;
   }
}
```

Illustration of Stack Status before and after method invocation





Data Types for Intermediate Language

- Primitive types are designated by **a single character**, as shown in Fig. 10.4
- A reference type ***t*** is designated as **L*t*;** with ***t*** specified as follows
- Each dot in the type is replaced by a `/'
  - which results in a Unix–like file path to the class file for the type
  - The JVM uses such paths to locate a class file at runtime
- Example
  - The String type in Java is actually found in the java.lang package
  - Its full type name is therefore **java.lang.String** and it has the type designation **Ljava/lang/String;** in the JVM
  - Because of its need to represent String constants efficiently, the JVM is aware of the String reference type, almost as if it were a primitive type

Type	JVM designation
`boolean`	`Z`
`byte`	`B`
`double`	`D`
`float`	`F`
`int`	`I`
`long`	`J`
`short`	`S`
`void`	`V`
Reference type *t*	`L`*t*`;`
Array of type *a*	`[`*a*

Figure 10.4: Java types and their designation in the JVM. All of the integer-valued types are signed. For reference types, *t* is a fully qualified class name. For array types, *a* can be a primitive, reference, or array type.

Be aware of the size of instructions and the size of data kept in Stack.



Java Assembly Instructions

- Arithmetic
- Register Transfer (Local Variable)
- Accessing Static Fields
- Accessing Instance Fields
- Branching
- Static Method Calls
- Instance-Specific Method Calls
- Other Method Calls
- Stack Operations



Arithmetic Instructions

- Instructions that compute results based on simple mathematical functions
  - operate by popping their required number of operands (typically 2) from the operand stack,
  - computing the required result, and
  - finally pushing the result on TOS



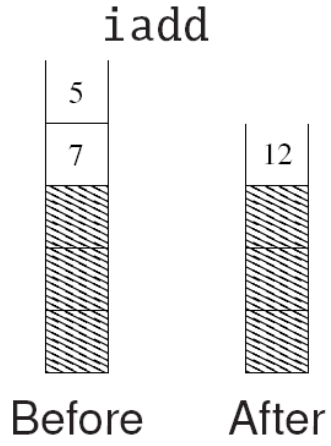
Arithmetic Instructions (Cont'd)

- Instructions that perform addition on primitive types:
  - **iadd** (int), **fadd** (float), **ladd** (long), and **dadd** (double)
- There are no instructions for integer types that are shorter than int, such as byte and short
  - Such arithmetic is performed on int types
- There are also instructions available for performing the usual arithmetic operations,
  - such as subtraction, multiplication, division, and remainder



Arithmetic Instructions: Example

- The **iadd** instruction
  - pops the top two elements off of the operand stack &
  - pushes their sum onto the stack



- The instruction expects the operands to be primitive **int** types, and the result is also **int** type
  - All operations involving **int** types are performed using 32-bit, **two's complement** arithmetic

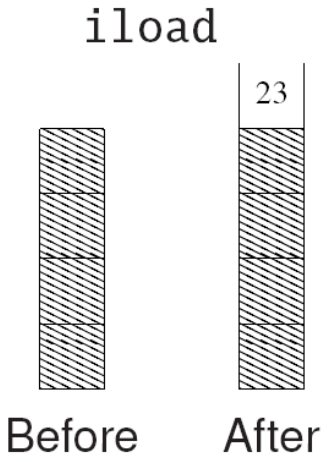
- Such arithmetic never throws any exceptions
  - I.e., overflow or underflow occur silently



Register Transfer Instructions

- The JVM's registers are **untyped**, so they can hold any kind of value
  - For values that require two registers (long and double types), an even-odd pair of registers must be used

- The **iload** instruction
  - pushes the contents of a JVM register on TOS
  - The instruction must contain an immediate operand designating the register whose contents should be loaded
  - If register 2 contains the value 23, then the example shows the results of executing **iload 2**



- The register is unaffected by the instruction



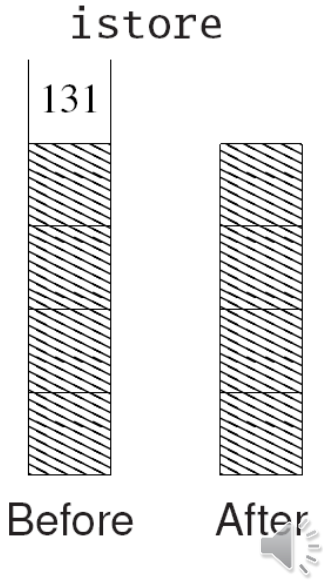
Register Transfer Instructions (Cont'd)

- To facilitate instruction compression,
  - the JVM has some single-byte instructions that **load low-numbered registers**
- The **iload 2** instruction takes two bytes:
  - one for the instruction and one for the operand
- The operation can be abbreviated as **iload_2**,
  - which takes only a single byte, as the opcode implies that register 2 is loaded



Register Transfer Instructions (Cont'd)

- Instructions are also available for moving data from the stack to a register
- The **istore** instruction
  - pops a value from the stack and
  - stores it in the register specified as an immediate operand of the instruction
- Example
  - An **istore 10** would pop the value 131 from the stack and store it in register 10
  - There is no abbreviated form of this instruction because register 10 is beyond the registers provisioned for the single-byte **istore** instructions





Register Transfer Instructions (Cont'd)

- There are variations of **iload** and **istore** for each supported data type
  - E.g., **fload** ***n*** reads a float value from register ***n*** and pushes it on TOS
- There are no register instructions specific to the boolean type
  - The JVM uses an int representation for boolean, with 0 representing false and 1 representing true
  - Types char, byte, and short are similarly treated as int at the register level, because 32 bits can accommodate their values as well

- All reference types are loaded and stored using **aload** and **astore** instructions, respectively
- An object reference takes the same space as an int, 32 bits
- The value of 0 is reserved to represent **null**



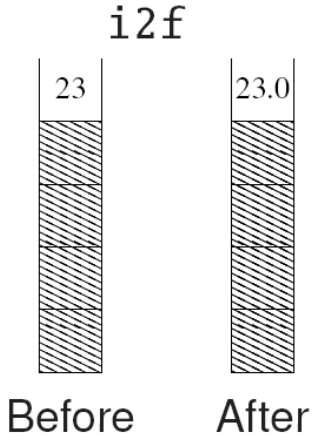
Registers and Types

- Static analysis is performed to check type consistency
  - Although registers are untyped,
  - **bytecode verification** is performed on the code to ensure that values flow in and out of registers without compromising Java's type system
  - Such analysis prevents a JVM program from loading a reference to an object (using **aload**) and
  - subsequently **performing math on the reference** to trick the JVM into accessing storage inappropriately
- In this regard, the JVM appears to be stricter than the Java language
  - an int value can be treated as a float without casting in Java
- However, it is important to understand that the transition from int to float could be done implicitly by JVM
  - Semantic analysis as described in Ch. 2 and 8 can insert the int-to-float **type conversion**, which is then realized by generating an **i2f** instruction



Registers and Types (Cont'd)

- Type conversion instructions operate by
  - popping a value off the stack and
  - pushing its converted value
- The stack must contain a value of the appropriate type at its top
  - In the example, the int 23 is at the TOS
  - When the instruction **i2f** has finished, the value is effectively replaced by its float representation
- **The bit patterns for 23 and 23.0 are different,**
  - with the former in two's complement and the latter in IEEE floating point format





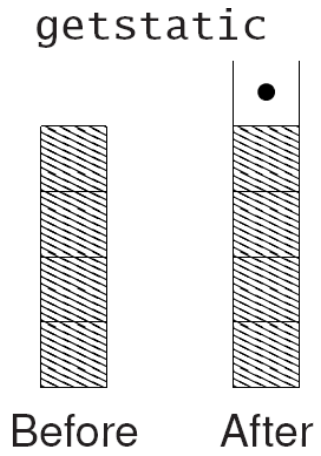
Accessing Static Fields

- A class's **static fields** are visible to every instance of the class
  - Space for such fields is provisioned when the class is loaded and initialized
  - Thereafter, a static field can be loaded or stored by the **getstatic** and **putstatic** instructions, respectively
- The action of **getstatic** is similar to
  - the various load instructions (**iload**, **aload**, etc.) in that the result of the fetch is pushed on TOS
- The get static field instruction as coded in Jasmin is follows:
  - **getstatic** ***name type***
  - where ***name*** is the name of the static field, prefaced by its fully qualified class name, and ***type*** is the expected type of the result



Accessing Static Fields (Cont'd)

- Many Java programs reference System.out for console output
- Such accesses are actually references to the static field **java.lang.System.out**, whose type is **java.io.PrintStream**
- Example
  - After the instruction executes: **getstatic java/lang/System/out Ljava/io/PrintStream**
  - the stack has a new element at TOS
  - The • on the stack represents the reference to System.out



- The length of **getstatic** instruction is 3 bytes
  - one specifies the getstatic opcode and the other two form a 16-bit integer specifying a **constant-pool** entry
  - Recall that constant-pool entries are denoted ordinally (0, 1, 2, etc.) and not by their byte-offset in the constant pool
  - In this case, the designated constant-pool entry contains the name and type operand values for the **getfield** instruction

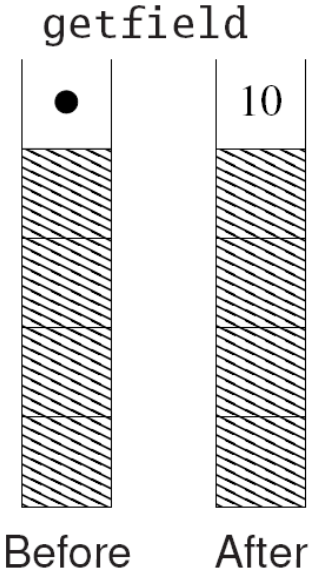


Accessing Instance Fields

- A class can declare **instance fields**
  - for which instance-specific storage is allocated
  - Every instance of type **t** is provided with storage for **t**'s instance fields
  - To access those fields, a particular instance of **t** must be provided
- The **getfield** instruction pushes the value of a particular instance field on TOS
- The syntax for a **getfield** instruction is exactly the syntax of the **getstatic** instruction
  - **a name** and **type** are specified as immediate operands
  - However, because the instruction also requires an instance of the accessed field, the semantics of the instruction specify that the **TOS must contain a reference to the instance** whose field is to be accessed

Accessing Instance Fields (Cont'd)

- Consider a **Point** class such that each instance has int fields: **x** and **y**
  - Consider a particular instance that has 10 and 20 values for its **x** and **y**, respectively
  - The example shows a **Point** reference (•) on TOS
  - The instruction **getfield Point/x I**
  - retrieves the value of • 's **x** field, making sure it is an int, and pushes the value (10) on TOS

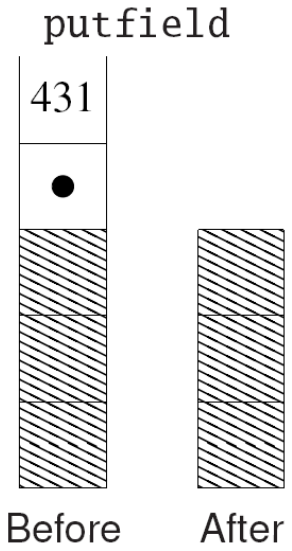


Accessing Instance Fields (Cont'd)

- The **putfield** instruction is the instance-specific version of the **putstatic** instruction
- Example
  - The object reference (•) refers to an instance of a **Point** object
  - The instruction **putfield Point/x I**
  - pops two values from TOS

1. The first is the value (431) that should be stored at the field (**x**) specified in the **putfield** instruction
2. The second is a reference to a **Point** object, shown as •

  - When the instruction completes, • 's **x** field will have the value 431, and the stack will have two fewer items





Branching Instructions

- The JVM provides instructions to
  - **alter the control flow of the executing program**
  - Control can be transferred unconditionally to the instruction at location **q** by a **goto** instruction
- The instruction occupies 3 bytes:
  - one byte specifies the **goto** **opcode** and
  - the other two bytes are concatenated to form **a signed 16-bit offset** denoted here as Δ
  - If **p** is the location of the current **goto** instruction, control is transferred to the opcode at **q = p+Δ**
  - In Jasmin, offsets are computed automatically, and targets are specified symbolically using labels



Branching Instructions (Cont'd)

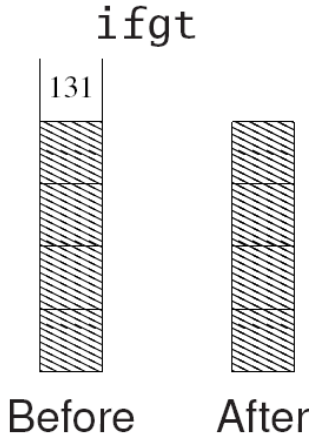
- Two classes of branching instructions

1. There are several kinds of instructions that accommodate conditional branches
   - Each such instruction contains an opcode that specifies the **conditional test** and a branch to be taken if the test is true
   - Six such instructions in JVM, one for **every possible comparison of an int value against 0**: **ifeq** (=), **ifne** (!=), **iflt** (<), **ifle** (≤), **ifgt** (>), and **ifge** (≥)
   - A separate opcode is provisioned for each instruction
2. Some programs call for comparisons of non-zero values
   - While the instructions described above are sufficient for such programs, a shorter sequence of instructions can be generated using the following relatively more complex instructions
   - Six instructions are in this family: **if_icmpeq** (a = b), **if_icmpne** (a != b), **if_icmplt** (a < b), **if_icmple** (a ≤ b), **if_icmpgt** (a > b), and **if_icmpge** (a ≥ b)

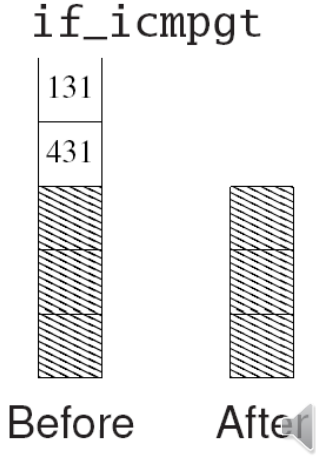


Branching Instructions (Cont'd)

- The **ifgt** instruction and its cognates expect that
  - the TOS is a signed int value
  - The branch is taken if the condition (in this case, greater-than-zero) is satisfied
- Example
  - 131 is popped and compared against 0
  - Because 131 > 0, the branch will be taken
  - Had the comparison failed, control would pass to the instruction following the **ifgt** instruction (i.e., **ifgt <label>**)



- Consider a source program that at some point has
  - a = 431 and b = 131 and must next evaluate whether a > b
  - After an **iload** instruction is issued for a and b, in that order, the stack appears as shown on the left
- Example
  - the **if_icmpgt** instruction pops the top two elements and performs the comparison 431 > 131
  - Because this test succeeds, the branch is taken



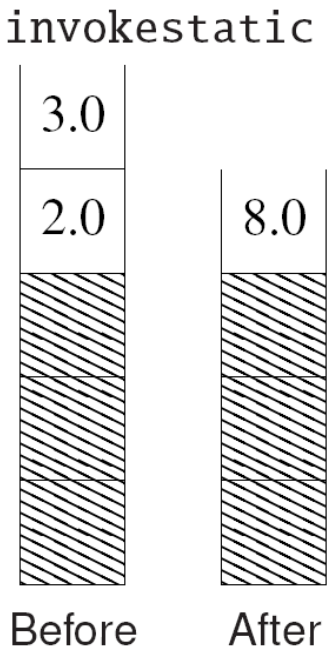


Static Method Calls Instructions

- There are several forms of method-calling instructions in the JVM
- In object-oriented languages, a method could be **common to all instances of some type *t*** or **instance specific**
  - In the former case, Java designates such methods as static
  - A static method of type ***t***, like a static field, is referenced by its type ***t*** and does not require an instance of ***t*** to be called
  - An example of a static method is **Math.pow** (**double a,double b**), which returns a^b
  - Such methods are called using the **invokestatic** instruction

Static Method Calls Instructions (Cont'd)

- The **Math.pow** static method is called using the Jasmin notation
  - **invokestatic java/lang/Math/pow(DD)D**
  - which specifies the full path to the method and also contains the **signature** of the method
- Example
  - Two values (2.0 and 3.0) are popped and supplied to the **Math.pow** static method as its first and second parameters, respectively
  - When **Math.pow** completes, its result (8.0) is pushed on TOS





Static Method Calls Instructions (Cont'd)

- From the above example, it should be clear that a method's parameters are pushed on the stack in **left-to-right order**
  - If a static method takes ***n*** parameters, then its ***n*** th parameter is on TOS just as the method is called
- For a **method signature**,
  - the symbols between the parentheses indicate the method's input parameter types, using the notation described in Fig. 10.4
  - I.e., in the above example, **two double parameters** (**(DD)**) are expected
  - A method's return type is specified just after the parentheses
  - In the above example, the return type is also **double**
- Although the Jasmin notation shows the method and its signature as part of the **invokestatic** instruction,
  - the method and signature descriptive information is actually held in the **constant pool**
  - The **invokestatic** instruction occupies 3 bytes,
    - with the second two bytes forming an ordinal index into the constant pool



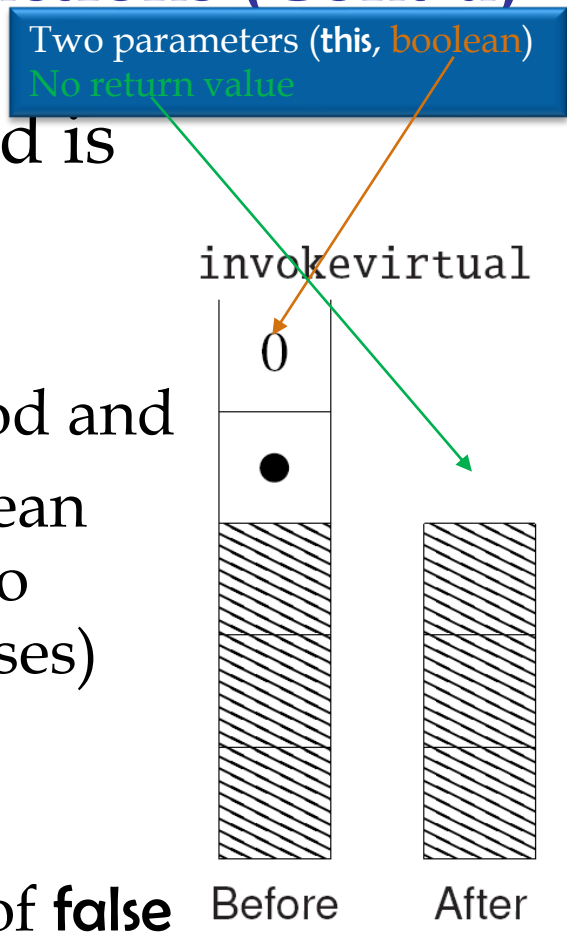
Instance-Specific Method Calls Instructions

- An instance-specific method
  - such as **PrintStream.print**()
  - is invoked in a manner similar to **invokestatic** with the following differences
  - Because the method is instance-specific, **an instance must be pushed on the stack** before the method's parameters
  - The instance becomes **this** inside the called method
  - The **invokevirtual** operator is used instead of **invokestatic**
- An instance-specific method
  - formally declaring that it takes **n** parameters ($p_1, p_2, \ldots p_n$)
  - actually takes **n + 1** parameters where p_0 is effectively the called method's **this**



Instance-Specific Method Calls Instructions (Cont'd)

- The **PrintStream.print(boolean)** method is called using the Jasmin notation
  - **invokevirtual java/io/PrintStream/print(Z)V**
  - which specifies the full path to the method and
  - indicates that the method takes one boolean parameter (indicated by **Z**) and returns no values (indicated by **V** after the parentheses)
  - In the example, the · is an instance of a **PrintStream** class (e.g., **System.out**)
  - The 0 on TOS is Java's integer encoding of **false** for the boolean data





Other Method Calls Instructions

- Almost all methods in Java are called by **invokevirtual** or **invokestatic**
  - However, important exceptions include **constructor calls** and **calls based on super**,
  - which are handled by the **invokespecial** instruction

- A **constructor call** is special in the following sense
  - An **uninitialized reference** to an object instance is pushed on TOS (usually by a new instruction)
  - The method name actually involved is **<init>** within the type of the object pushed on TOS
  - The constructor consumes the reference from TOS as its input parameter (**this**) along with any declared parameters
  - All constructors are **void** so nothing is returned from the constructor call
  - A code generator must be aware of this behavior and issue the appropriate instructions to be able to access the instantiated object
- Example
  - **invokespecial java/lang/StringBuffer/<init>()V**
  - calls the method "<init>" (the special name used for instance initialization methods) in the class "**java.lang.StringBuffer**", and
  - it has the descriptor "**()V**" (i.e. it takes no arguments and no results)



Other Method Calls Instructions (Cont'd)

- The **invokespecial** method
  - can also be used to invoke a **private** method, but this appears to be for efficiency reasons only
- A **private** method cannot be overridden,
  - so there is no reason to employ a virtual method dispatch



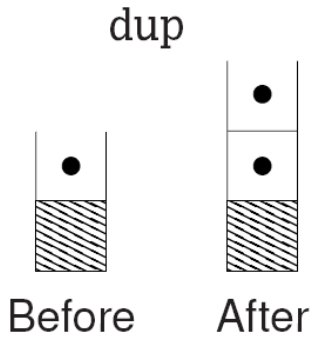
Stack Operations Instructions

- The JVM provides some instructions specifically for **manipulating items near the TOS**
- Such instructions may seem superfluous,
  - in that they **can be simulated using other instructions** and registers
  - They are included to facilitate shorter instruction sequences for common program fragments
  - E.g., **dup**, **dup_x1**, **pop** and **swap**



dup Instruction

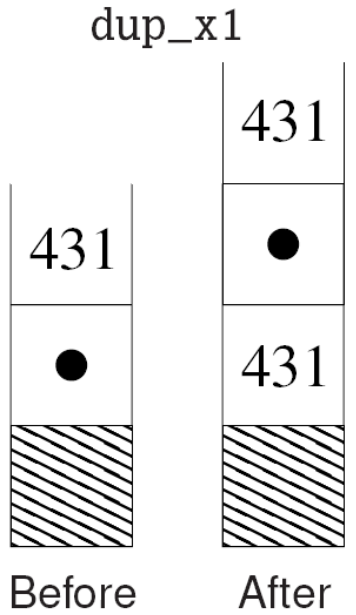
- Example
  - the duplication of the cell at TOS
  - The instruction works for any 32-bit type (i.e., all types except long and double)
- The instruction nicely accommodates multiple assignments (x=y=z=value)
  - There is a **dup2** instruction that duplicates the top two cells to accommodate long and double types
- It is also useful for constructing new objects
  - The **new *t*** instruction
  - leaves a reference on TOS to the newly allocated storage of type ***t***,
  - but that storage cannot be accessed until a constructor has been invoked
  - Constructors consume the reference to the allocated storage (along with their other parameters), but they **return nothing** (they are void)
  - Thus, **to remember the reference after the return of the Constructor**, the TOS is usually duped before the constructor invocation sequence is generated





dup_x1 Instructions

- This instruction **duplicates** the TOS element,
  - but it situates the duplicated cell as shown in the example, **two cells below the TOS**
- One application of this instruction is
  - the duplication of a value that participates in an embedded assignment
- Consider **foo(this.x ← y)**,
  - where **y** happens to have the value 431
  - The example starts with **y**'s value already loaded on the stack
  - The example ends with the stack prepared for the **putfield** instruction followed by the method call to **foo**
  - The **dup_x1** instruction duplicates the 431 and places it below the **this** reference (shown as •)
  - Recall that the field assigned by a **putfield** is an immediate operand of the instruction
  - Thus, when the **putfield** for **x** completes, the top two elements will be removed from the stack, leaving the duplicated 431 as the parameter value for **foo**
  - This instruction nicely demonstrates that the JVM instruction set was designed not to be simple but to allow for compact code sequences





QUESTIONS?