UNIVERSITY OF BIRMINGHAM

Compilation, Interpretation & Overview of Java Virtual Machine

Lecture Objective

To introduce the basic concepts of compilation, interpretation and Java Virtual Machine.

Lecture Outline

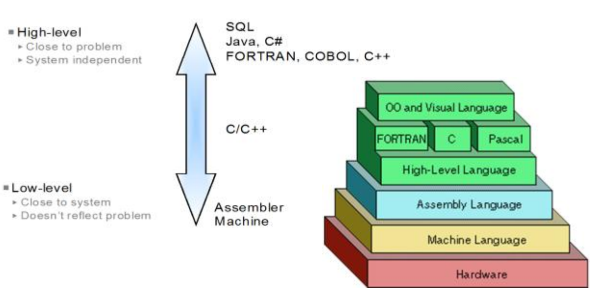
- Levels of Programming Languages
- High Level to Low Level Translation
- High Level Program Execution
- Compilation vs. Interpretation
- Combined Compilation & Interpretation
- Compilation and Execution on Virtual Machines

Levels of Programming Languages

- **High** level languages
  - e.g. Java, C/C++/C#, Fortran, Cobol, Pascal, etc
  - Easier for humans
- **Low** level languages
  - Machine code – instructions stored in memory (opcodes)
  - Hard to read and write by humans
- Next level up: **Assembly** code
  - Can be written or read by humans (using mnemonics)

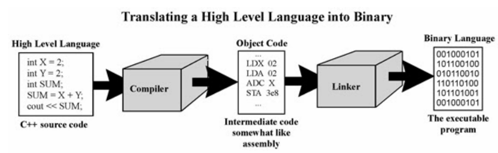
Watch on Youtube:
Most Popular Programming Languages 1965 – 2019

Levels of Programming Languages



Converting High Level to Low Level

- To execute on a computer we must have machine code!
- Assembly code is translated to machine code to run
  - **Assembler** does this (e.g. works out the relative addresses for jumps etc.). Relocatable Code.
  - **Linker**: combines different assembled parts into a Whole
  - **Loader**: loads into memory at a given location



Executing High Level Programs

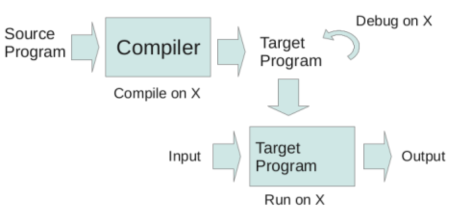
- A **program** written in a high level language can be run in two different ways:
  - Compiled into a program in the native machine language and then run on the target machine
  - Directly interpreted and the execution is simulated within an interpreter
- Which approach is more efficient?
  - Think of C++ vs. JavaScript

Compilation

- **Compiler:** converts source code (text of a program) into object code – e.g. machine code – that does the same thing as the original program
- Usually object code is **relocatable**, so can be later **linked** and **loaded** into memory.
- Advantages:
  - Done once for each program
  - With clever tricks to optimize object code (by exploiting hardware features) so that it will run fast
- Disadvantages:
  - Harder than interpreting
  - Hardware dependent i.e. cannot run of different platforms

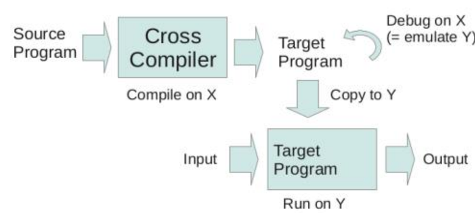
Compilation

- Compiler runs on the same platform X as the target code

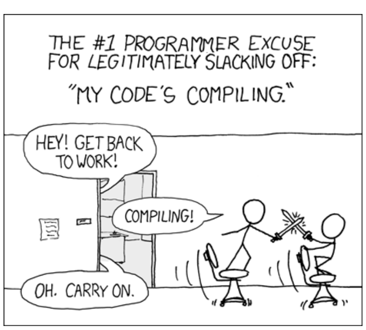


Cross Compilation

- Compiler runs on platform X, target code runs on platform Y



Compilation is a Compute Intensive process!



https://xkcd.com/303/

Interpretation

- Interpreter = another program that follows the source code (text of program) and does appropriate actions
- Same principle as:
  - Humans running through instructions of a program
  - A processor (CPU) can be viewed as a hardware implementation of an interpreter for machine code
- Advantages:
  - Facilitates interactive debugging & testing
  - User can modify the values of variables; can invoke procedures from the command line
- Disadvantages:
  - Slow Execution (as compared to compilation)

Interpretation

- Running high-level code by an interpreter

Watch on Youtube:
Compiled vs. Interpreted Languages

Research Example – Simulation Techniques

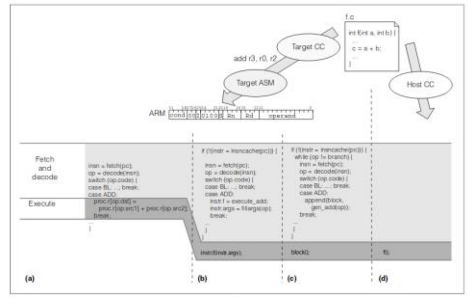


Figure 2. Software simulation techniques applied to the ARM instruction-set architecture (ISA): instruction-accurate interpretation (a), interpretive predecoding (b), dynamic binary translation (c), and native code execution (d). (ASM: assembly; CC: C language compiler.)

Full article: https://ieeexplore.ieee.org/document/5620924

Combined Compilation & Interpretation

Executing high level programs

- Compile to an intermediate level (between high and low) language that can be efficiently interpreted
  - Slower than pure compilation
  - Faster than pure interpretation
  - A single compiler, independent of CPU
  - Separate task for each CPU is to interpret the intermediate language

Example: Java

Source Code .java files

Java bytecode .class files

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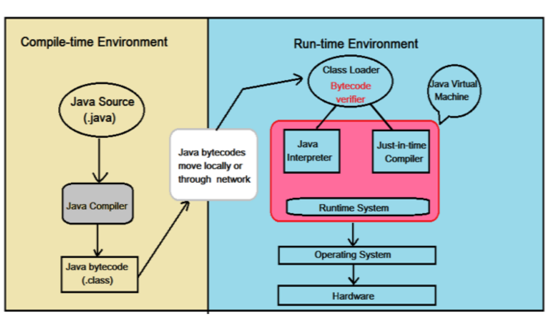
javac

The command "java" calls the JRE

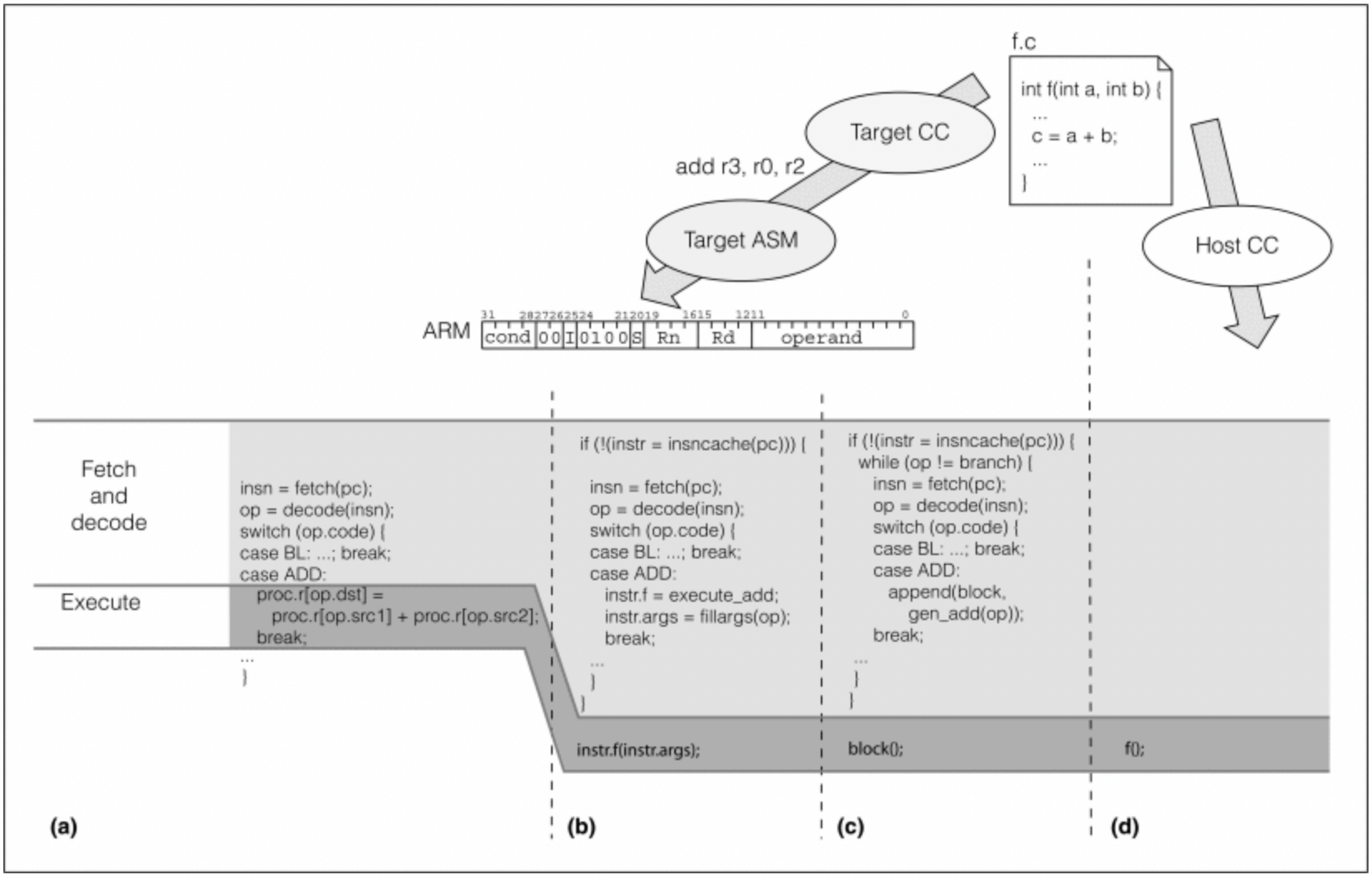
Java Runtime Environment (JRE) using Java Virtual Machine (JVM)

Combined Compilation & Interpretation



Virtual Machines

- A virtual machine executes an instruction stream in software (instead of hardware)
- Adopted by Pascal, Java, Smalltalk-80, C#, functional and logic languages, and some scripting languages
- Pascal compilers generate P-code that can be interpreted or compiled into object code (https://en.wikipedia.org/wiki/P-code_machine)
- Java compilers generate bytecode that is interpreted by the **Java Virtual Machine (JVM)**
- The JVM may translate bytecode into machine code by Just-In-Time (JIT) compilation



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instruction-accurate interpretation (a),
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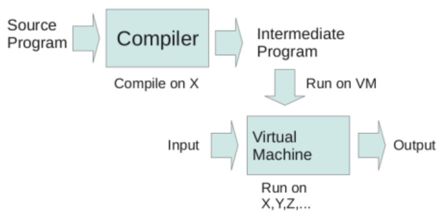
and native code execution (d).
(ASM: assembly, CC: C language compiler.)

Compilation and Execution on Virtual Machines

- ◆ Compiler generates intermediate program (language)
- ◆ Virtual machine interprets the intermediate program
  - We need to have virtual machine on each platform



Java Virtual Machine (JVM) Introduction

Watch on Youtube:
What is Java Virtual Machine?

Lecture Outline

- ◆ Java Concept and Portability
- ◆ The JVM Architecture
- ◆ Stack Machines & Expression Evaluation
- ◆ IJVM & IJVM Instruction Set / Groups
- ◆ Compiling Java to IJVM
- ◆ JVM Instruction Summary
- ◆ Interpreting JVM & Just In Time (JIT) Compilation

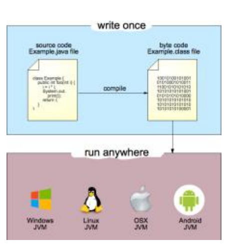
The Java Concept

- ◆ Before Java … [Bell Labs]
  - C and C++ (object-oriented C) were used for systems programming
  - WWW has evolved very fast (Animated History)
- ◆ How to load and run a program over WWW?
  - different target machines, word length, instruction sets
  - Security is another issue!
- ◆ **Java** [mid-1990s, Sun Microsystems]
  - language based on C++
  - has a virtual machine, hence portable
  - can be downloaded over WWW and executed remotely (using the applets)

An applet is a small computer program that performs a specific task. It is typically embedded within another larger app or software platform and has limited functionality.

Portability of Java

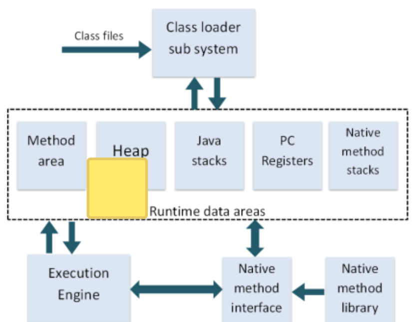
- ◆ Why not compile Java to machine code?
  - need to generate code for each target machine
  - cannot exchange executable code
- ◆ The Sun Java solution
  - design machine architecture (JVM) specifically for the Java language
  - translate Java source code into JVM code (bytecode)
  - write software interpreter for JVM in C (widely available)
- ◆ Thus bytecode can be exchanged
  - remote execution is possible



The JVM Architecture

- ◆ The architecture
  - Stack machine! Closer to modern high-level languages than the von Neumann machine (Register machines).
  - Memory: 32 bit words (=4 bytes)
  - Instructions: 226 in total, variable length, 1-5 bytes
  - Program: byte stream
  - Data: stored in words
  - Program Counter (PC) contains byte addresses
- ◆ Here simplified, Integer JVM (IJVM)
  - no floating point arithmetic
  - More details: https://en.wikipedia.org/wiki/IJVM

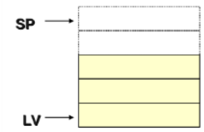
The JVM Architecture



http://www.santhoshreddymandadi.com/java/java-virtual-machine-jvm-architecture.html

Stack Machines

- **Stack**
  - Area of memory, extends upwards or shrinks downwards
  - LV (Local Variable), base of stack
  - SP (Stack Pointer), top of stack
- **Operations**
  - push on top (increment SP)
  - pop (decrement SP)
  - add top two arguments on the stack, replace with result
  - More details: https://en.wikipedia.org/wiki/Stack_machine



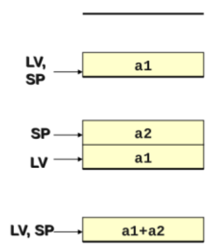
Evaluating Expressions on Stack

Evaluate
a1+a2

PUSH a1

PUSH a2

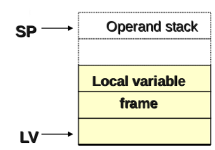
ADD

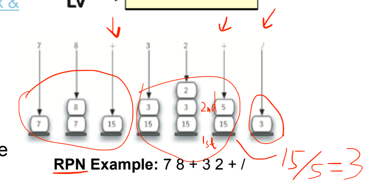


Infix Expression	Prefix Expression	Postfix Expression
A + B	+ A B	A B +
A + B * C	+ A * B C	A B C * +

What are stacks good for?

- Expression Evaluation
  - can handle bracketed expressions (a1+a2)*a3 without temporary variables:
  - PUSH a1, PUSH a2, ADD, PUSH a3, MULT (See also RPN & Infix, Prefix & Postfix Expressions)
- Direct Support for
  - Local variables for methods (stored at the base of stack, deleted when the method exits)
  - (recursive) method calls: to store return address

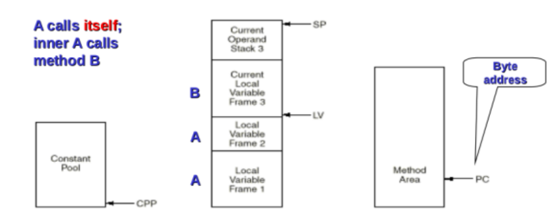




RPN Example: 7 8 + 3 2 + /

IJVM Memory

A calls itself; inner A calls method B



Protected area (contains constants, strings, pointers, etc)

Stack (local variables, expression eval.)

Method area (contains the program – byte array)

Main IJVM Instruction Groups

- Stack Operations
  - **PUSH/POP** - push/pop word on a stack
  - **BIPUSH** - push byte on stack
  - **ILOAD/ISTORE** - load/store local variable onto/from stack
- Integer Arithmetic
  - **IADD/ISUB** - add/subtract two top words on stack
- Branching
  - **IFEQ** - pop top word from stack, branch if zero
- Invoking a method / return from a method
  - **INVOKEVIRTUAL, RETURN**

IJVM Instruction Set

One byte:
byte, const, varnum

Two bytes:
disp, index, offset

Hex	Mnemonic	Meaning
0x10	BIPUSH *byte*	Push byte onto stack
0x59	DUP	Copy top word on stack and push onto stack
0xA7	GOTO *offset*	Unconditional branch
0x60	IADD	Pop two words from stack; push their sum
0x7E	IAND	Pop two words from stack; push Boolean AND
0x99	IFEQ *offset*	Pop word from stack and branch if it is zero
0x9B	IFLT *offset*	Pop word from stack and branch if it is less than zero
0x9F	IF_ICMPEQ *offset*	Pop two words from stack; branch if equal
0x84	IINC *varnum const*	Add a constant to a local variable
0x15	ILOAD *varnum*	Push local variable onto stack
0xB6	INVOKEVIRTUAL *disp*	Invoke a method
0x80	IOR	Pop two words from stack; push Boolean OR
0xAC	IRETURN	Return from method with integer value
0x36	ISTORE *varnum*	Pop word from stack and store in local variable
0x64	ISUB	Pop two words from stack; push their difference
0x13	LDC_W *index*	Push constant from constant pool onto stack
0x00	NOP	Do nothing
0x57	POP	Delete word on top of stack
0x5F	SWAP	Swap the two top words on the stack
0xC4	WIDE	Prefix instruction; next instruction has a 16-bit index

Compiling Java to IJVM

Java	Intermediate	Hex	Stack
i = j+k	**ILOAD** j	0x15 0x02	j
	ILOAD k	0x15 0x03	k j
	IADD	0x60	j+k
	ISTORE i	0x36 0x01	

JVM Instruction Summary

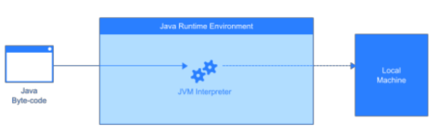
- Different from most CPUs
- Closer to high-level programming languages, rather than von Neumann architecture
- No accumulator/registers - just the stack!
- Small, straightforward instruction set
- Variable length instructions
- Typed instructions, i.e. different instruction for LOADing integer and for LOADing pointer (this is to help verify security constraints)

Interpreting JVM

- Software interpreter for JVM in C (the original Sun Microsystems solution)
  - memory for the constant pool, method area and stack
  - procedure for each instruction
  - program which fetches, decodes and executes instructions
- Produce micro-programmed interpreter
- Manufacture hardware chip (picoJava II) for embedded Java applications
  - More details: https://en.wikipedia.org/wiki/PicoJava

Just In Time (JIT) Compilation

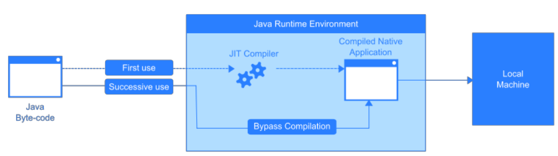
- Why not compile directly to target architecture?
  - more expensive - many varying architectures
  - more time needed to compile each instruction
- But
  - execution is slower with an interpreter!!!
  - instructions may have to be parsed repeatedly



Source:
https://en.wikibooks.org/wiki/Java_Programming/The_Java_Platform

Just In Time (JIT) Compilation

- Just In Time (JIT) Compilation
  - include Java compiler to target machine within a browser
  - compile instructions, and reuse them
  - longer wait till arrival of executable code



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Summary

- Compilation vs. Interpretation
- Interpreted languages
  - execute with the help of a layer of software, not directly on a CPU
  - usually translated into intermediate code
- Java
  - conceived as an interpreted language, to enhance portability and downloading to foreign/remote architectures (applets)
  - has **JVM**, a virtual stack machine
  - interpreted via a C language interpreter, or a hardware chip (picoJava II for embedded Java applications)