COMP 520 - Compilers

Lecture 17 (Tue Apr 19, 2022)

Virtual Machines

- Reading
  - Skim Chapter 8

Topics

- review a simple code generation example
- Virtual machines
  - why target a virtual machine?
  - some virtual machines
    - mJAM (miniJava Abstract Machine)
    - JVM (Java Virtual Machine)
    - .NET and MSIL (Microsoft intermediate language)
- Nomenclature
  - TAM and mJAM are *Abstract Machines*
  - the more commonly used name is a *Virtual Machines*

AST + RED + mJAM code

- miniJava program

```java
class PA4Tiny {
    public static void main(String[] args){
        /* 1: simple literal */
        int x = 1;
        System.out.println(x);
    }
}
```

- mJAM assembler code

```
0          LOADL         0
1          CALL          newarr
2          CALL          L10
3          HALT   (0)
4   L10:   LOADL         1
5          LOAD          3[LB]
6          CALL          putintnl
7          RETURN (0)    1
```

preamble

main

AST

```
Package
  ClassDeclList [1]
  . ClassDecl
  .   "PA4Tiny" classname
  .   FieldDeclList [0]
  .   MethodDeclList [1]
  .   . (public static) MethodDecl
  .   .   VOID BaseType
  .   .   "main" methodname
  .   .   ParameterDeclList [1]
  .   .   . ParameterDecl
  .   .   .   ArrayType
  .   .   .     ClassType
  .   .   .       "String" classname
  .   .   .   "args"parametername
  .   .   StmtList [2]
  .   .   . VarDeclStmt
  .   .   .   VarDecl
  .   .   .     INT BaseType
  .   .   .     "x" varname
  .   .   .   LiteralExpr
  .   .   .     "1" IntLiteral
  .   .   . CallStmt
  .   .   .   QualRef
  .   .   .     "println" Identifier
  .   .   .     QualRef
  .   .   .       "out" Identifier
  .   .   .       IdRef
  .   .   .         "System" Identifier
  .   .   .   ExprList [1]
  .   .   .   . RefExpr
  .   .   .   .   IdRef
  .   .   .   .     "x" Identifier
```

KA: 4[CB]

KA: -1[LB]

KA: 3[LB]

predefined method *putintnl*

What is a virtual machine

- A software interpreter M for a (low-level) "machine" language
  - M typically
    - interprets instruction codes in binary form
    - implements stack based execution of the operations
  - M is written in some language (e.g. C) and compiled into code for physical machine M'
    - …. which is interpreted by M' hardware

- Cost of a virtual machine vs direct translation to hardware instructions
  a) program p translated into M and interpreted using M'
    - simple translation (stack model)
  b) program p translated directly into M' and interpreted using M'
    - complex translation (register model)

  but … strategy (b) typically runs a factor of 2x - 20x faster than (a)

Why target a virtual machine? (1)

- Simplicity of code generation
  - stack machine
  - “convenient” and “appropriate” operations

- Portability
  - n languages, m target machines
    - using a virtual machine as intermediate target, need n translators plus m interpreters
  - write once, run anywhere
    - but performance is an issue

- Compactness
  - virtual machines can have very compact object code
    - amenable to caching (data cache)

Why target a virtual machine? (2)

- Type/memory safety (only for appropriate VM designs)
  - Can verify type correctness of code even when not generated by a compiler
    - Why useful
      - Assures memory safety
      - Better security
- Runtime flexibility and interoperability
  - dynamic loading of classes
  - standard libraries
  - native libraries
- Guard intellectual property
  - does not require distribution of source code
    - however, not very resistant to reverse engineering

Some virtual machines

- All of these execute stack-oriented binary code

Virtual Machine	dynamic loading?	type checking?	types
mJAM	no	some	boolean, int, classtypes, linear arrays of int or classtypes
JVM (1995)	yes	yes	boolean, byte, short, char, int, long, float, double class types, array types, interface types
.NET CLI (2000)	yes	yes	bool, char, string, object (unsigned) int{8,16,32,64}, float{32,64} tuple types $\alpha \times \beta \times \cdots$ typeref α, functionref $\alpha \rightarrow \beta$, multidimensional array α

JVM – Java Virtual Machine

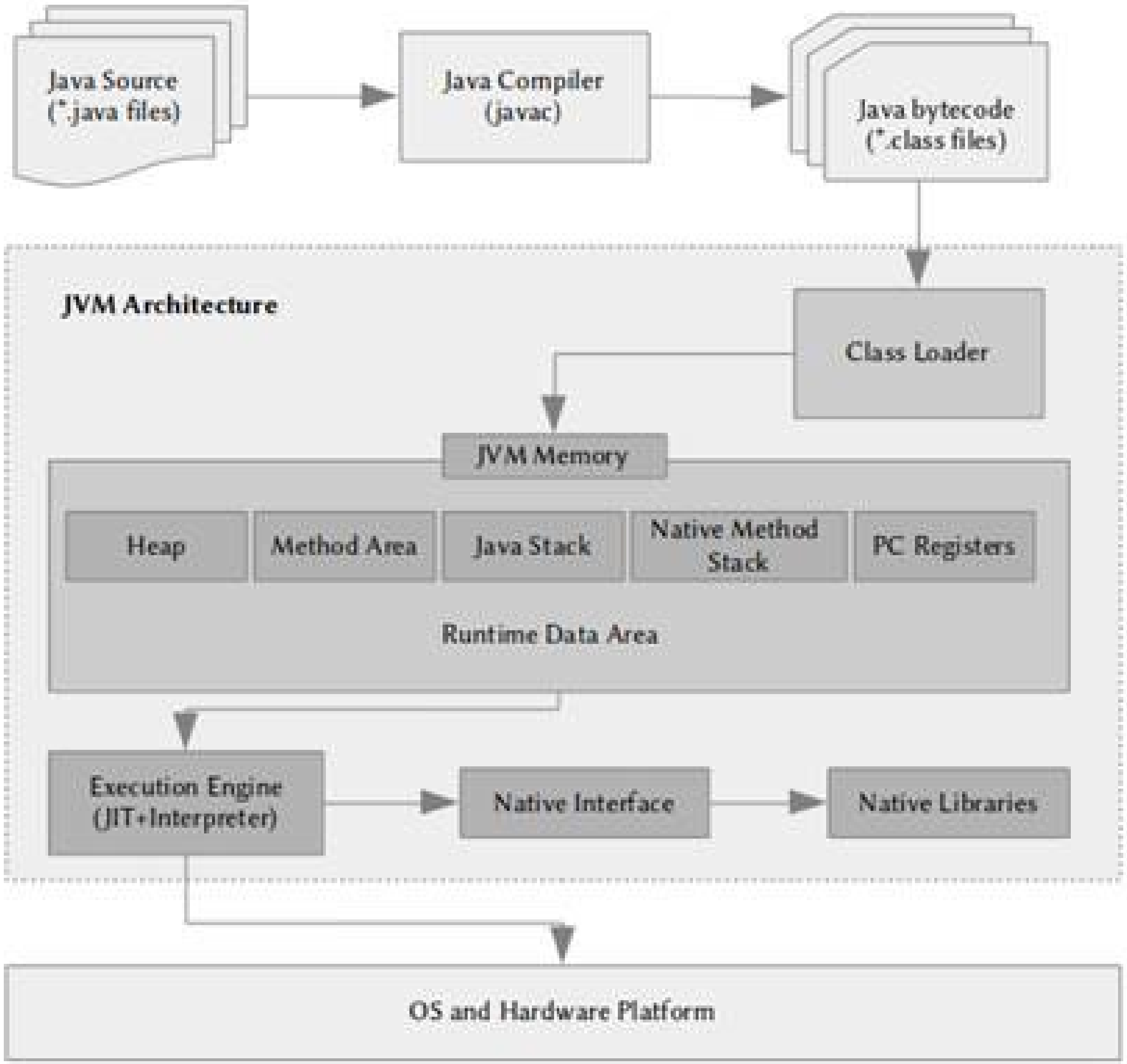
- Some properties of the JVM
  - Input: classfiles
    - binary .class files – one per class, loaded on use
      - byte code for static initialization, constructors, and methods
      - complete names of external classes and methods used
      - types and names of public fields and methods provided by the class
      - types of parameters and local variables in each method
  - Data memory
    - all storage locations are 4 bytes wide
      - long and double values written into two consecutive locations (?64 bit architectures)
    - expression evaluation stack and call stack are logically distinct
      - all object references have one level of indirection to simplify use of a compacting and generational garbage collector
  - Instructions
    - byte code has variable length operands
      - space efficient, but introduces overheads in decoding
    - types of arguments are encoded in the instruction name
      - iadd, ladd, fadd, dadd

JVM: Dynamic loading

- Essentially the ability to execute separately compiled components using a load-on-use strategy
  - JVM response to a method invocation in a class that is not loaded
    - Run the class loader on the appropriate class file
      - load code, constants, and type information into JVM
      - add class descriptor verify loaded code (option)
    - Link invocation(s) to methods
      - connect symbolic references to actual code location
      - or through dynamic dispatch table
    - Initialization
      - run static initialization for loaded class
    - Execution
      - run requested method in loaded class

- Dynamic loading may invalidate assumptions made in previously loaded methods
  - ex: all invocations are monomorphic (always the same dynamic type)

JVM Architecture

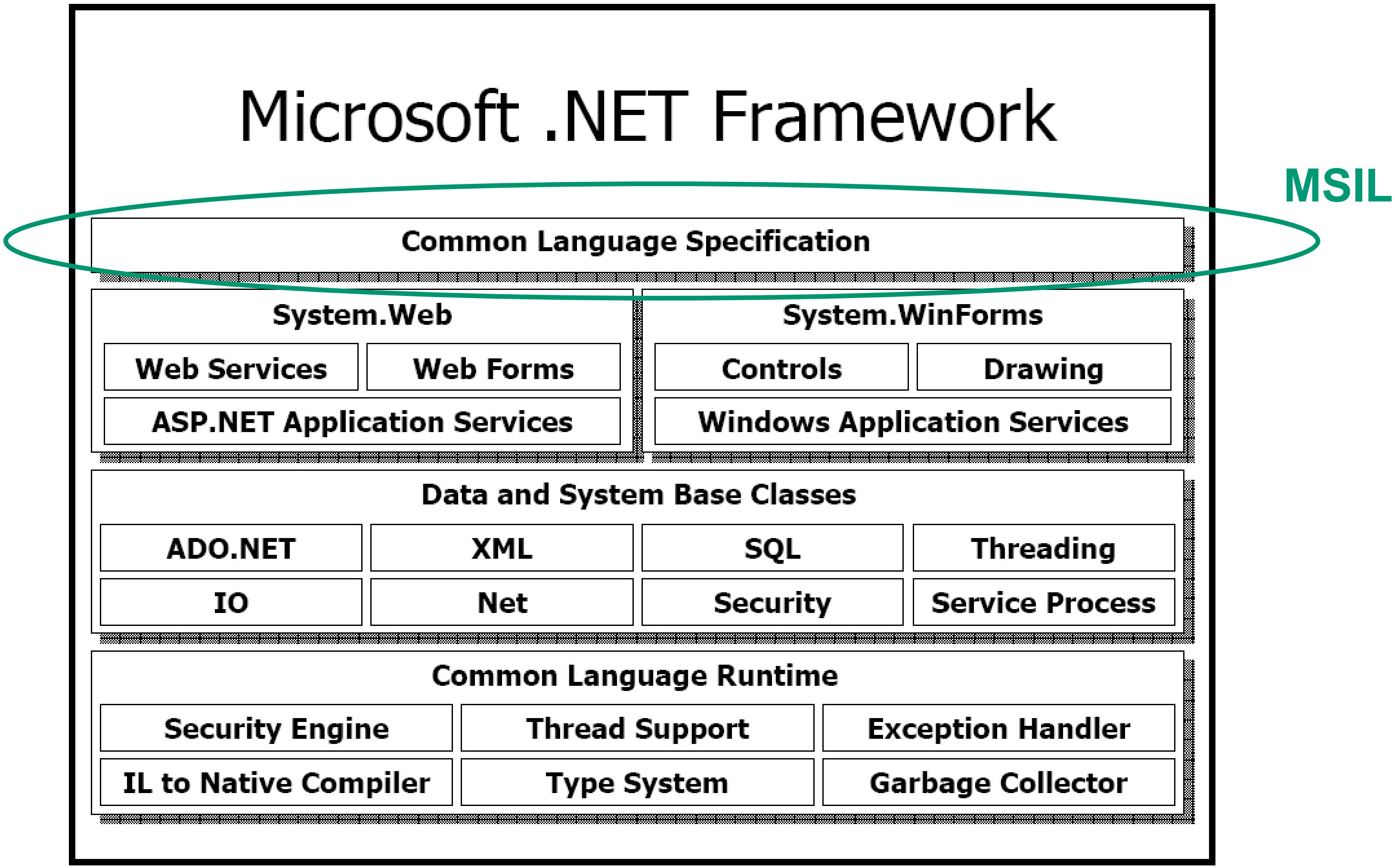


Microsoft .NET Common Language Interface

- .NET can be described as several things:
  - An application development framework with tons of windows-centric capabilities
  - A comprehensive communication and interoperation layer, involving XML, SOAP, COM, and other technologies
  - Microsoft’s answer to ~~Sun’s~~ Oracle’s Java / JVM
  - A cool virtual machine
  - A marketing term applied to things that Microsoft creates

- These are all correct!

Components of the .NET Framework



.NET Application Development

- .NET is made up of two parts:
  - CLI (Common Language Interface)
    - CLS (Common Language Specification)
    - CTS (Common Type System)
    - MSIL (Microsoft Intermediate Language)

  - VES (Virtual Execution System)
    - CLR (Common Language Runtime)
    - JIT compiler

- Some of these have counterparts in Java/JVM, while some do not

- .NET languages supported
  - New with .NET
    - C# (enhanced Java with lots of windows libs)
    - F# (functional language for scientific computing)
  - Existing
    - C++ (sort of) , VB, Managed Jscript (not JavaScript), IronPython, …
    - no Java in .NET

CLI – Microsoft Common Language Infrastructure

- Some properties of the CLI
  - Input: assemblies
    - roughly comparable to JAR files – collection of classes
    - binary or text form
      - Microsoft Intermediate Language (MSIL)

- No public interpreter (except Xamarin Mono), but well-defined virtual machine
  - Data memory
    - all storage locations have a known type and size
      - actual layout in memory can only be partially controlled
    - expression evaluation, method arguments, and locals are in logically distinct areas
      - each has a static size that is part of the method
      - no reuse of locals storage for locals with disjoint lifetimes
  - Instructions
    - types of values and frame safety are fully specified and checked

```
.method static int32 foo(int32 x) {
  .maxstack 1
  .locals (int32 z)
  ldarg x; stloc z; ret z
}
```

Example MSIL code

All assemblies can be fully type checked

```
.assembly PrintString {} /* Console.WriteLine("Hello, World)" */

.method static public void main() il managed

{

    .entrypoint // this function is the application entry point
    .maxstack 8

    // load string onto stack
    ldstr "Hello, World“

    // Call static System.Console.Writeline function
    call void [mscorlib]System.Console::WriteLine(class System.String)


    ret

}
```

What would it take to type-check mJAM code?

- What are the types of values resulting from the following operations?

```
LOADL  12324    ; what type?  int or address or bool?
LOAD   5[LB]    ; what type?  must know the types of the local vars
LOAD   -3[LB]   ; what type?  must know the types of the parameters
CALL   ADD      ; int if top two elts on stack are always int, else type error

LOAD   4[LB]    ; could be object address
LOADL  3        ; field index – could be arbitrary int expr
CALL   ADD      ; this is an uncontrolled address – type error
LOADI           ; what is the result type?
```

- Requirements
  - all objects, methods, and local variables must be typed
    - what about different type locals with disjoint lifetimes at the same offset?
  - operations must be type specific
  - use fieldref and arrayref instead of arithmetic on addresses

.NET vs JVM

- .NET Advantages
  - Designed to work with many source languages, rather than just one
    - C#, C++ (kinda), VB, Haskell, …
    - supports values of arbitrary size, function values, non-local reference, union types, integer arithmetic with overflow detection, etc.
  - More extensive class library than Java
    - e.g. record types, function types
  - Type system permits “escapes” for low-level programming

- .NET Disadvantages
  - Less emphasis on exception handling (?advantage perhaps)
  - Java is much more widely accepted and used, with a much larger installed user base
  - The CLR is very Windows-centric

Dynamic Compilation

- What is it?
  - compilation of virtual machine code to native machine code at start of execution
    - Examples
      - Virtual Execution System in Microsoft CLI
      - Open Runtime Platform (Intel)
- Why useful?
  - avoids premature commitment to execution platform
  - compile only what is needed
- Managed Runtime Environment
  - key feature is typed virtual machine code

Just-in-time Compilation (JIT)

- What is it?
  - fast compilation of virtual machine code to native machine code
    - typically on a method-by-method basis
    - use simple optimization strategy to limit compilation overheads
  - used selectively within virtual machine interpreter
    - rule of thumb
      - >80% of the time is spent in <20% of the program
      - recall 10x - 20x penalty for interpretation
    - cost-effectiveness
      - JIT is worthwhile if
        - » interpret-time(P) > compile-time(P,P') + native-execution(P')
      - HotSpot analysis: compile only "worthwhile" methods
        - » interpreter tracks time spent in each method
        - » invokes JIT compilation for the method when a threshold is reached
        - » substitutes compiled code for interpreted code

JIT Advantages

- Some aspects of the environment are fixed when JIT compiler runs
  - Allows the compiler to make assumptions that cannot be made by static compilers
    - The dynamic type of some values may be known
      - enables method inlining
    - The sizes of some arrays may be known
    - Array bound / null pointer checks
    - Dynamic method inlining

- Compiler can make probabilistic optimizations based on profiling information
  - Which loops run many iterations
  - Which conditions rarely are true

- Methods that are never executed are never compiled, reducing compilation time and executable size in memory

Compiling Java for high performance is difficult

- Distinguishing features of Java
  - many dynamic checks
    - array indexing, type casting
  - many heap allocated values and garbage collection
    - requires maintenance of accessibility, possible indirection for compacting GC
  - good software engineering practices lead to
    - small method bodies
      - hard to amortize method invocation overhead
    - virtual method invocation
      - makes it difficult to “inline” method bodies
  - dynamic class loading
    - can change assumptions
      - e.g. method p() always appears to call a particular instance of method q()
      - after loading a new class that is also a client of p(), this may no longer be true
- Native implementation of low-level libraries can be a big help

Strategies for JIT compilation

- Shared execution stack for
  - JVM
  - JIT-compiled code
  - native methods
- Streamlined representation of values
  - no indirection for (some) allocated objects
- optimizations
  - register allocation
  - method inlining
  - array access optimization
  - bounds check optimization
  - common subexpression elimination