

Virtual Machines & Interpretation Techniques

Advanced Compiler Techniques 2004
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Partially based on slides from
Kostas Sagonas (<http://user.it.uu.se/~kostas/Teaching/ACT-04/>) and
Pietro Taitelbaum (<http://www.cs.tufts.edu/~taitelba/VMDesign2003.html>)

Virtual Machines

- ◆ A virtual machine is an abstract computing architecture independent of any hardware.
- ◆ They are software machines that run on top of real hardware, providing an abstraction layer for language implementers.
 - ◆ There are other types of virtual machines intended to emulate some real hardware (e.g., VirtuTech-Simics, VMware, Transmeta), but they are not the focus of this course.

Characteristics of a VM

- ◆ A VM has its own instruction set independent of the host system.
- ◆ A VM usually has its own memory manager and can also provide its own concurrency primitives.
- ◆ Access to the host OS is usually limited and controlled by the VM.

Advantages of VMs

- ◆ A VM bridges the gap between the high level language and the low level aspects of a real machine.
- ◆ It is relatively easy to implement a VM, and it is easier to compile to a VM than to a real machine.
- ◆ A VM can be modified when experimenting with new languages.
- ◆ Portability is enhanced.
- ◆ Support for dynamic (down-)loading of software.
- ◆ VM code is usually smaller than real machine code.
- ◆ Safety features can be verified by the VM.
- ◆ Profiling and debugging are easy to implement.

Disadvantages of VMs

- ◆ Lower performance than with a native code compiler.
 - ◆ Overhead of interpretation.
 - ◆ Modern hardware is not designed for running interpreters.

Some VM History

- ◆ VMs have been built and studied since the late 1950s.
- ◆ The first Lisp implementations (1958) used virtual machines with garbage collection, sandboxing, reflection, and an interactive shell.
- ◆ Forth (early 70s) uses a very small and easy to implement VM with high level of reflection.
- ◆ Smalltalk (early 70s) is a very dynamic language where everything can be changed on the fly, the first truly interactive OO system.
- ◆ USCD Pascal (late 70s) popularized the idea of using pseudocode to improve portability.
- ◆ Self (late 80s) a prototype-based Smalltalk flavor with an implementation that pushed the limits of VM technology.
- ◆ Java (early 90s) made VMs popular and well known.

VM Design Choices

- ◆ When designing a VM one has some design choices similar to the choices when designing intermediate code for a compiler:
 - ◆ Should the machine be used on several different physical architectures and operating systems? (JVM)
 - ◆ Should the machine be used for several different source languages? (CLI/CLR (.NET))
- ◆ Some design choices are similar to those of the compiler backend:
 - ◆ Is performance more important than portability?
 - ◆ Is reliability more important than performance?
 - ◆ Is (smaller) size more important than performance?
- ◆ And some design choices are similar to when designing an OS:
 - ◆ How to implement memory management, concurrency, IO...
 - ◆ Is low memory consumption, scalability, or security more important than performance?

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VM Components

- ◆ The components of a VM vary depending on several factors:
 - ◆ Is the language (environment) interactive?
 - ◆ Does the language support reflection and or dynamic loading?
 - ◆ Is performance paramount?
 - ◆ Is concurrency support required?
 - ◆ Is sandboxing required?
- ◆ In this lecture we will only talk about the interpreter of the VM.

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VM Implementation

- ◆ Virtual machines are usually written in “portable” (in the sense that compilers for most architectures already exists) programming languages such as C or C++.
- ◆ For performance critical components assembly language can be used.
- ◆ Some VMs (Lisp, Forth, Smalltalk) are largely written in the language itself.
- ◆ Many VMs are written specifically for gcc, for reasons that will become clear in later slides.

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Interpreters

- ◆ Language runtime systems often uses two kinds of interpreters:
 1. Command-line interpreter.
 - ◆ Reads and parses instructions in source form.
 - ◆ Used in interactive systems.
 2. Instruction interpreter.
 - ◆ Reads and executes instructions in some intermediate form such as bytecode.

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Implementing Interpreters

- ◆ There are several ways to implement an interpreter.
 - ◆ Pattern (or string) based interpretation.
 - ◆ Interpreting source code (strings) directly is inefficient since most of the time is spent in lexical analysis.
 - ◆ A better alternative is to compile the source into e.g., an abstract syntax tree and then do the interpretation over that tree. (Jumps and calls are expensive.)
 - ◆ Token-based interpretation.
 - ◆ Compiling the code into a linear representation of instructions, where each instruction is represented by a token, e.g., bytecode.
 - ◆ Address-based interpretation.
 - ◆ Compiling the code into a linear representation where each instruction is represented by the address that implements the instruction.
 - ◆ There are several variants: Indirect threaded code, direct threaded code and subroutine threading.

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Taxonomy of Interpreters

```

graph TD
    Interpreters --> Pattern-based
    Interpreters --> Token-based
    Interpreters --> Address-based
    Pattern-based --> String-based
    Pattern-based --> Tree-based
    Token-based --> Bytecode
    Address-based --> Indirect_threaded_code[Indirect threaded code]
    Address-based --> Direct_threaded_code[Direct threaded code]
    Address-based --> Subroutine_threaded_code[Subroutine threaded code]
  
```

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Implementing Interpreters

- ◆ We will now look at some details of how to implement an interpreter.
- ◆ We will start with a complete but simple string based interpreter for a very simple language. Then extend the language and the interpreter to show the different ways to implement interpreters.

Virtual Machines: Implementation

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Interpreting while Parsing (String-based Interpretation)

- ◆ For some really simple languages the interpretation can be done during parsing.
- ◆ We can e.g., implement a simple calculator directly in a parser generator.
- ◆ A parser generator is a program that takes a description of a grammar and generates a program that can parse the grammar.
- ◆ We will use CUP a parser generator for Java:
 - ◆ <http://www.cs.princeton.edu/~appel/modern/java/CUP/>
 - ◆ I will not go into the details of CUP.

String-based Interpretation

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A Calculator Language

- ◆ Grammar:
 - Expr ::= Expr MINUS Term
 | Expr PLUS Term
 | Term
 - Term ::= Term TIMES Factor
 | Term DIV Factor
 | Factor
 - Factor ::= NUMBER | LPAR Expr RPAR

String-based Interpretation

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Simple Interpreter .cup

```
terminal PLUS, MINUS, TIMES, DIV, LPAR, RPAR;
terminal Integer NUMBER;

non terminal Program;
non terminal Integer Expression, Term, Factor;

precedence left PLUS, MINUS;
precedence left TIMES, DIV;

start with Program;
```

String-based Interpretation

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Interpreter .cup

```
Program ::= Expression:e
  { : System.out.println(e.intValue()); ; }
  ;
Expression ::= Expression:e PLUS Term:t
  { : RESULT = new Integer(e.intValue() +
    t.intValue()); ; }
  | Expression:e MINUS Term:t
  { : RESULT = new Integer(e.intValue() -
    t.intValue()); ; }
  | Term:t
  { : RESULT = t; ; }
```

String-based Interpretation

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Interpreter .cup

```
Term ::= Term:t TIMES Factor:f
  { : RESULT = new Integer(t.intValue() *
    f.intValue()); ; }
  | Term:t DIV Factor:f
  { : RESULT = new Integer(t.intValue() /
    f.intValue()); ; }
  | Factor:f
  { : RESULT = f; ; }
Factor ::= NUMLIT:n { : RESULT = n; ; }
  | LPAR Expression:e RPAR
  { : RESULT = e; ; }
```

String-based Interpretation

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Control Flow

- ◆ This approach works fine for simple expressions.
- ◆ Control flow constructs such as 'if' and 'while' are harder to handle.
- ◆ For 'while' we would need to "reparse" the statement that is to be repeated.
- ◆ Let us extend the language with control flow, variables, and boolean values.

String-based Interpretation

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Tree-based (pattern-based) Interpretation

- ◆ By representing the code by a data structure we can "reexecute" the same piece of code several times.
- ◆ This will lead to a slightly more complicated interpreter, which will require at least two passes over the code.
- ◆ The code will first be parsed and stored in the internal representation, then the interpretation will be performed.
- ◆ We can use an abstract syntax tree for representing the code.

Pattern-based Interpretation

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Design choices

- ◆ How is the program represented?
 - ◆ As an Abstract Syntax Tree (AST) with the class `Tree`.
- ◆ How is data represented?
 - ◆ We have different types of values, integers and Booleans.
 - ◆ The value of each expression is either an `IntValue` or a `BoolValue`, subclasses of `Value`.
- ◆ How are variables represented?
 - ◆ With a symbol table where each symbol can have a value.

Pattern-based Interpretation

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The Implementation

- ◆ The Interpreter itself can be implemented by a Visitor on the AST.

- ◆ We need a Value class:

```
class Value {
  static class IntValue extends Value {
    int i;
    public IntValue(int i) { this.i = i; }
  }
  static class BoolValue extends Value {
    boolean b;
    public BoolValue(boolean b) { this.b = b; }
  }
}
```

Pattern-based Interpretation

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Interpreting Expressions

```
public void caseOp(Op tree) {
  switch (tree.op) {
  case TRUE:
    result = new BoolVal(true);
    break;
  case FALSE:
    result = new BoolVal(false);
    break;
  case PLUS:
    IntValue lval = (IntValue) interpret(tree.left);
    IntValue rval = (IntValue) interpret(tree.right);
    result = new IntValue(lval.i + rval.i);
    break;
  ...
}
```

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Semantic Analysis Needed

- ◆ This assumes that types are correct.
 - ◆ We could either have a prepass that does the type analysis.
 - ◆ Or we could do the type checking at the same time as interpreting.

Pattern-based Interpretation

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Analyzing While Interpreting

```
public void caseOp(Op tree) {
    switch (tree.op) {
    case PLUS:
        Value lval = interpret(tree.left);
        Value rval = interpret(tree.right);
        if ((lval instanceof IntValue) &&
            (rval instanceof IntValue)) {
            result = new IntValue(
                ((IntValue)lval).i +
                ((IntValue)rval).i);
        } else error();
        break;
    ...
}
```

Pattern-based Interpretation

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Control Flow

- ◆ Now we can try to interpret a control flow construct.
- ◆ It turns out to be very easy, since we are writing our interpreter in Java which supports the same control flow constructs.
- ◆ It becomes a bit complicated if the type analysis has to be done at the same time.

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While (assuming type analysis)

```
public void caseWhile(While tree){
    while(((BoolValue)
        interpret(tree.cond)).b) {
        interpret(tree.body);
    }
}
```

Pattern-based Interpretation

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Interpreting While, While Analyzing

```
public void caseWhile(While tree) {
    Value cond=interpret(tree.cond);
    while((cond instanceof BoolValue)
        && ((BoolValue) cond).b) {
        interpret(tree.body);
        cond=interpret(tree.cond);
    }
}
```

Pattern-based Interpretation

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Variables

- ◆ We need to keep track of the values of variables somehow. A simple solution is to store these values with the symbols in the symbol table.
- ◆ If we interpret an assignment we store the value in the symbol.
- ◆ If we interpret an identifier we read the value from the symbol.

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Functions

- ◆ These techniques can handle simple languages without functions or more than one scope.
- ◆ In order to handle functions and especially recursive functions and local scopes we will need an *environment*.

Pattern-based Interpretation

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Environments

- ◆ In an *environment* we store all values of parameters (arguments) and local variables of a function for one specific call.
- ◆ We create a new environment when we call a function or enter a local scope.
 - ◆ We store actual arguments of the call in the environment.
 - ◆ We initialize local variables.
 - ◆ After returning from a function, or leaving the local scope, the environment is not needed any more.
- ◆ The environment can be implemented as an array of values, the position in the array of an identifier can be stored in the symbol table.


```
class Environment {
    Environment outer; // For nested scope.
    Value[] values;
}
```
- ◆ An environment is similar to how scopes are handled in the compiler.
- ◆ When compiling to native code the environment is stored on the stack as activation records.

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Function Calls

```
void caseFuncall {
    // call interpreter recursively on
    // function arguments:
    Arguments args = interpret_args(tree.args);

    // Create a new Environment(currentEnv):
    currentEnv = new Environment(currentEnv);

    // Store the arguments in the new environment.
    insert_args(args, currentEnv);

    // Call the interpreter recursively on the
    // body of the called function, using the new
    // environment.
    result = interpret(find_code(tree.funName));

    // Restore the environment.
    currentEnv = currentEnv.outer;
}
```

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Disadvantages with Tree-based Interpreters

- ◆ The tree representation has to be created somehow each time we want to run the program.
 - ◆ Parsing the source code each time is time consuming.
 - ◆ Storing the whole tree is space consuming.
- ◆ The tree representation uses a lot of space at runtime, which is infeasible for large programs.
- ◆ Using the stack of the host language adds to the space need at runtime.

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Token-based Interpreters

- ◆ By compiling the program to a special instruction set of a virtual machine, and by adding tables that maps function names to offsets in the instruction sequence, some of the interpretation overhead can be reduced.
- ◆ Most VM instruction sets uses small integers to represent everything in the instruction stream (opcodes, registers, stack slots, functions, constants, etc.).
- ◆ By implementing the interpreter in C we can gain some speed, it also allows us to do nasty pointer tricks.

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Token-based Interpreters

- ◆ The fundamental instruction unit is the *token*.
- ◆ A token is a predefined numeric value that represents a certain instruction.
 - ◆ E.g., BREAK=0, LOADLITERAL = 1, ADD=2.
- ◆ The most common case is *bytecode*:
 - ◆ The token with is 8 bits.
 - ◆ The total instruction set is limited to 256 tokens.

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Basic Structure of a Token-based Interpreter

```
byte *pc = &program[0];
while(TRUE) {
    byte opcode = pc[0];
    switch(opcode) {
        -
        case LOADLITERAL:
            destReg = pc[1];
            value = getTwoBytes(&pc[2]);
            regs[destReg] = value;
            pc += 4;
            break;

        case JUMP:
            jumpAddress = getFourBytes(&pc[1]);
            pc = &program[jumpAddress];
            break;
    }
}
```

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Alignment

- Most modern machines loads data at least one word at the time (usually 4 bytes). By making sure that instructions are aligned on word offsets we get better performance.

opcode
addr0
addr1
addr2
addr3

opcode

addr0
addr1
addr2
addr3

Note: The padding is done by the loader, no extra space is needed in the external representation.

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Token-based Interpreter with Aligned Instructions

```

byte *pc = &program[0];
while(TRUE) {
  byte opcode = pc[0];
  switch(opcode) {
    -
    case LOADLITERAL:
      destReg = pc[1];
      value = getTwoBytes(&pc[2]);
      regs[destReg] = value;
      pc += 4;
      break;

    case JUMP:
      jumpAddress = getFourBytes(&pc[4]);
      pc = &program[jumpAddress];
      break;
  }
}
    
```

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Token-based Interpreter with Abstract Encoding

```

byte *pc = &program[0];
while(TRUE) {
  byte opcode = pc[0];
  switch(opcode) {
    -
    case LOADLITERAL:
      destReg = pc[LOADLITERAL_ARG1];
      value = getTwoBytes(&pc[LOADLITERAL_ARG2]);
      regs[destReg] = value;
      pc += LOADLITERAL_SIZE;
      break;

    case JUMP:
      jumpAddress = getFourBytes(&pc[JUMP_ARG1]);
      pc = &program[jumpAddress];
      break;
  }
}
    
```

```

#define LOADLITERAL_SIZE 4
#define JUMP_SIZE 8
#define LOADLITERAL_ARG1 1
#define LOADLITERAL_ARG2 2
#define JUMP_ARG1 4
        
```

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Token-based Interpreter with Abstract Control

```

byte *pc = &program[0];
while(TRUE) {
  loop:
  byte opcode = pc[0];
  switch(opcode) {
    -
    case LOADLITERAL:
      destReg = pc[LOADLITERAL_ARG1];
      value = getTwoBytes(&pc[LOADLITERAL_ARG2]);
      regs[destReg] = value;
      pc += LOADLITERAL_SIZE;
      NEXT;

    case JUMP:
      jumpAddress = getFourBytes(&pc[JUMP_ARG1]);
      pc = &program[jumpAddress];
      NEXT;
  }
}
    
```

```

#define NEXT goto loop
        
```

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Indirectly Threaded Interpreter

- In an indirectly threaded interpreter we do not switch on the tokens. Instead we use the tokens as indices into a table containing the addresses of the instruction implementations.
- The term threaded code refers to a code representation where every instruction is implicitly a function call to the next instruction.
- A threaded interpreter can be very efficiently implemented in assembler.
- In GNU C (gcc) we can use labels as values and take the address of a label with `&&labelname`.
- We can actually write the interpreter in such a way that it uses indirectly threaded code if compiled with gcc and a switch for compatibility.

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Indirectly Threaded Interpreter

```

byte *pc = &program[0];
while(TRUE) {
  loop:
  byte opcode = pc[0];
  switch(opcode) {
    -
    case LOADLITERAL:
      loadlitteral_label:
      destReg = pc[LOADLITERAL_ARG1];
      value = getTwoBytes(&pc[LOADLITERAL_ARG2]);
      regs[destReg] = value;
      pc += LOADLITERAL_SIZE;
      NEXT;

    case JUMP:
      jump_label:
      jumpAddress = getFourBytes(&pc[JUMP_ARG1]);
      pc = &program[jumpAddress];
      NEXT;
  }
}
    
```

```

static void *label_tab[] {
  &&loadlitteral_label;
  &&jump_label;
}
#define NEXT \
goto **(&void **)(label_tab[pc])
        
```

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Directly Threaded Interpreter

- ◆ In a directly threaded interpreter we do not use tokens at all during runtime.
- ◆ Instead the loader replaces each token with the address of the implementation of the instruction.
- ◆ This means the opcodes will take one word or four bytes at runtime, slightly increasing the code size.

Directly Threaded Code

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Directly Threaded Interpreter

```

byte *pc = &program[0];
while(TRUE) {
loop:
byte opcode = pc[0];
switch(opcode) {
...
case LOADLITERAL:
loadlitteral_label:
destReg = pc[LOADLITERAL_ARG1];
value = getTwoBytes(&pc[LOADLITERAL_ARG2]);
regs[destReg] = value;
pc += LOADLITERAL_SIZE;
NEXT:
...
case JUMP:
jump_label:
jumpAddress = getFourBytes(&pc[JUMP_ARG1]);
pc = &program[jumpAddress];
NEXT:
...
}
}

```

```

static void *label_tab[] {
...
&&loadlitteral_label;
&&jump_label;
}
#define NEXT \
goto **(void **) (pc)

```

Directly Threaded Code

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Subroutine Threaded Interpreter

- ◆ The only portable way to implement a threaded interpreter in C is to use subroutine threaded code.
- ◆ Each instruction is implemented as a function and at the end of each instruction the next function is called.

Subroutine Threaded Code

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Subroutine Threaded Interpreter (with tail-calls)

```

byte *pc = &program[0];
NEXT:
...

void loadlitteral(void) {
destReg = pc[LOADLITERAL_ARG1];
value = getTwoBytes(&pc[LOADLITERAL_ARG2]);
regs[destReg] = value;
pc += LOADLITERAL_SIZE;
NEXT:
}

void jump(void) {
jumpAddress = getFourBytes(&pc[JUMP_ARG1]);
pc = &program[jumpAddress];
NEXT:
}

```

```

static void *label_tab[] {
...
&&loadlitteral;
&&jump;
}
#define NEXT ((void (*)())pc)()

```

Subroutine Threaded Code

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Subroutine Threaded Interpreter

```

byte *pc = &program[0];
while (TRUE) NEXT;

```

```

static void *label_tab[] {
...
&&loadlitteral;
&&jump;
}
#define NEXT ((void (*)())*pc)()

```

```

void loadlitteral(void) {
destReg = pc[LOADLITERAL_ARG1];
value = getTwoBytes(&pc[LOADLITERAL_ARG2]);
regs[destReg] = value;
pc += LOADLITERAL_SIZE;
}

void jump(void) {
jumpAddress = getFourBytes(&pc[JUMP_ARG1]);
pc = &program[jumpAddress];
}

```

Subroutine Threaded Code

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Subroutine Threaded Interpreter

```

(void (*)()) pc = &program[0];
while (TRUE) *pc++;

```

```

#define LOADLITERAL_SIZE 1
#define JUMP_SIZE 1
#define LOADLITERAL_ARG1 0
#define LOADLITERAL_ARG2 1
#define JUMP_ARG1 0

```

```

void loadlitteral(void) {
destReg = ((int *)pc)[LOADLITERAL_ARG1];
value = getTwoBytes(&pc[LOADLITERAL_ARG2]);
regs[destReg] = value;
pc += LOADLITERAL_SIZE;
}

void jump(void) {
jumpAddress = getFourBytes(&pc[JUMP_ARG1]);
pc = &program[jumpAddress];
}

```

Subroutine Threaded Code

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Virtual Machines: Instruction Set

Stack-based vs. Register-based VM

- ◆ A VM can either be *stack-based* or *register-based*.
 - ◆ In a stack-based machine most operands are on the stack. The stack can grow as needed.
 - ◆ In a register-based machine most operands are in (virtual) registers. The number of registers is limited.
- ◆ Most VMs are stack-based.
 - ◆ Stack machines are simpler to implement.
 - ◆ Stack machines are easier to compile to.
 - ◆ Less encoding/decoding to find the right register.
 - ◆ Virtual registers are no faster than stack slots.

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Virtual Machines: Tuning

Interpreter Tuning

- ◆ Common interpreter optimizations include:
 - ◆ Writing the interpreter loop and key instructions in assembler.
 - ◆ Keeping important variables in hardware registers (pc, stack-top, heap-top). (GNU C allow global register variables.)
 - ◆ Top of stack caching.
 - ◆ Splitting the most used instruction into a separate interpreter loop.

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Virtual Machines: Tuning

Interpreter Tuning

- ◆ More advanced interpreter optimizations includes:
 - ◆ Instruction merging: A common sequence of VM instructions is replaced by a single instruction.
 - ◆ Reduced interpretation overhead.
 - ◆ Enhances code locality.
 - ◆ More compact bytecode.
 - ◆ Gives C compiler bigger code block to optimize.
 - ◆ Instruction specialization: A special case VM instruction is created, typically with some arguments hard-coded.
 - ◆ Eliminates argument decoding cost.
 - ◆ More compact bytecode.
 - ◆ Reduces register pressure.

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JIT Compilation

Just-in-time Compilation

- ◆ Native code is still faster than code interpreted in VMs. To get the best performance native code compilation is necessary. But bytecode is a nice format to distribute portable code.
- ◆ Solution: *dynamic compilation* or *just-in-time (JIT)* compilation.
- ◆ Native code takes more space than virtual machine code (4-8x). Don't compile everything to native code (some code is never executed).
- ◆ Compilation takes time, dynamic compilation has to be fast. No time for advanced optimization (unless the bytecode compiler has inserted hints in the bytecode).

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JIT Compilation

JIT - What to Compile

- ◆ Only compile a method if the total execution time is reduced.
- ◆ How do we know this?
- ◆ Use the past to predict the future:
 - ◆ Use profiling to detect what and when to compile. There are two basic approaches:
 - ◆ Invocation counters.
 - ◆ Sample based profiling.

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JIT Compilation

Invocation Counters

- ◆ Associate a counter with each function.
- ◆ When a function is called increment the counter.
- ◆ If the counter reaches a limit compile the function. Reset or use decay to only compile high-frequency functions.
- ◆ Hard to predict behavior, no control over time spent in compiler.

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Sample Based Profiling

- ◆ Measure time spent in interpreter, compiler, and in compiled code.
- ◆ Harder to implement.
- ◆ Gives better picture of the hot-spots.

JIT Integration

- ◆ Integrating a JIT system where native code can coexist with interpreted code in the VM is not trivial.
- ◆ Context switches between native and interpreted code has to be fast. (They can occur at function calls, returns, and when exceptions are thrown.)
- ◆ Ensuring proper tail-calls with a mixed execution environment is also tricky.

Summary

- ◆ Virtual machines provides an abstraction from real hardware and make programming language implementation easier and languages more portable.
- ◆ A direct threaded interpreter gives the best performance.
- ◆ Virtual machines have been used for half a century but research didn't really take off until the JVM came along.