CSCI 742 - Compiler Construction

Lecture 26
Introduction to Code Generation
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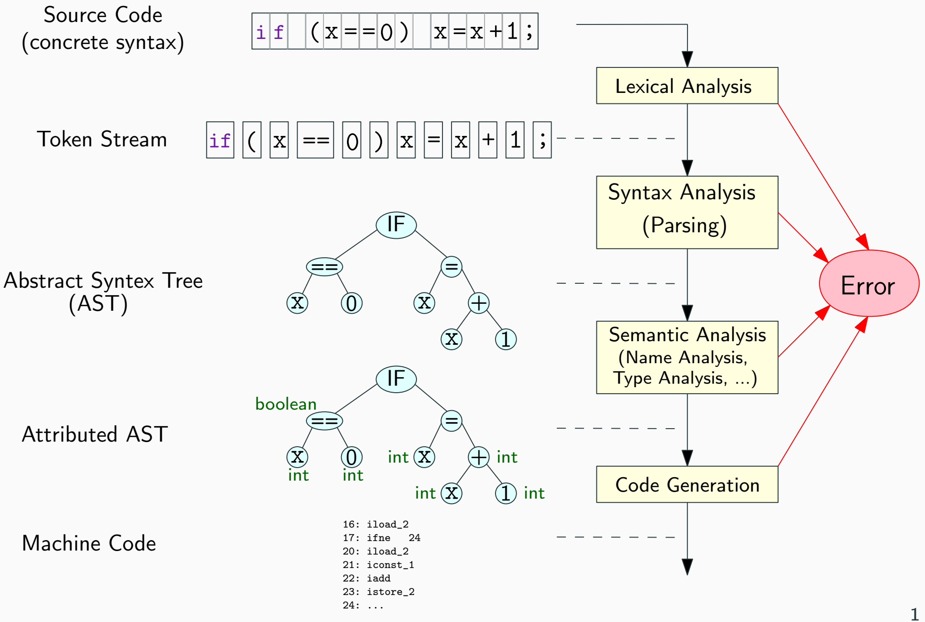
March 30, 2018

Compiler Phases



Code Generation Example

- Phase after type checking emits such bytecode instructions

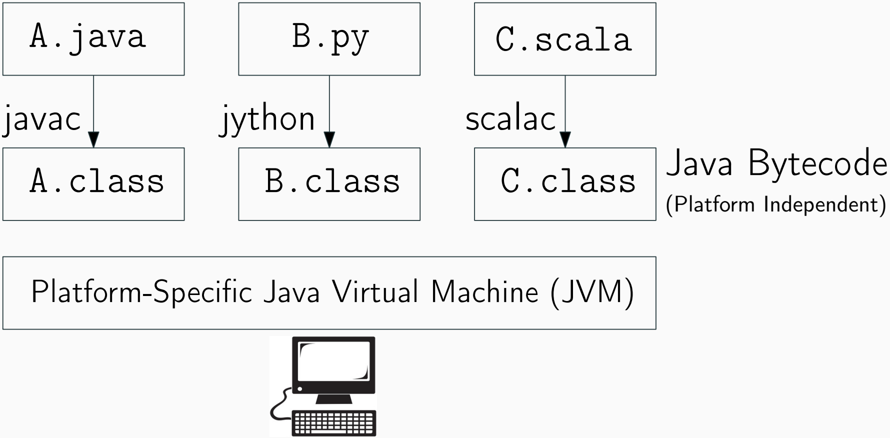
```
while (i > 0) {
  i += 2 * j + 1;
  j = j - 5;
  System.out.println(j);
}
```

```
javac Test.java
javap -c Test
```

```
 5: iload_1
 6: ifle           31
 9: iload_1
10: iconst_2
11: iload_2
12: imul
13: iconst_1
14: iadd
15: iadd
16: istore_1
17: iload_2
18: iconst_5
19: isub
20: istore_2
21: getstatic      #2 // System.out
24: iload_2
25: invokevirtual  #3 // println
28: goto           5
31: // ...
```

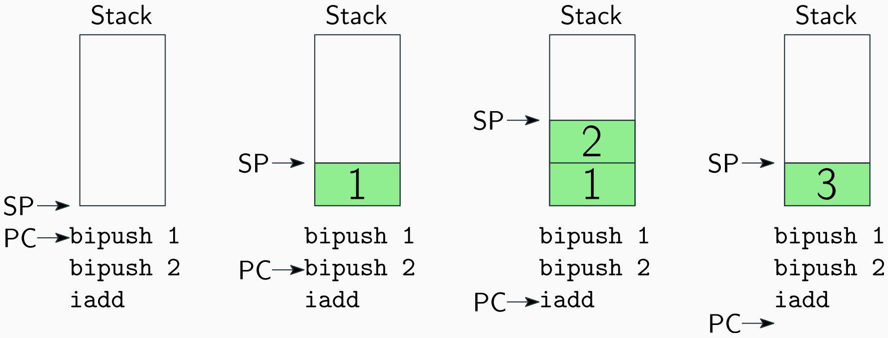
Java Virtual Machine (JVM)

- Programs are written in Java or other languages
- Compiler translates them to Java Bytecode
- Platform-specific Java Virtual Machine executes Java Bytecode



Java Virtual Machine (JVM)

- JVM is a stack machine: evaluation of expressions uses a stack (operand stack)
- Instructions fetch their arguments from the top of the operand stack
- Instructions store their results at the top of the operand stack



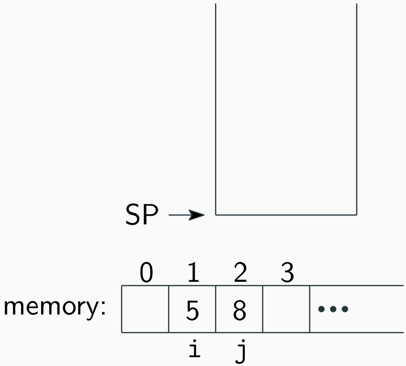
Why a Stack Machine

- A simple evaluation model: no variables or registers
- Each operation:
  - takes operands from top of stack
  - puts results back at top of stack
- Instruction "`add`" as opposed to "`add r1, r2`"
- Simpler compiler, more compact programs

Local Variables

- In memory space of a function there is an array V to store local variables and arguments
- `iload`: push the value of a local variable onto the stack
- `istore`: pop the value from the stack and store it in a local variable
- Initially the arguments $x_1, \cdots, x_n$ are stored in local variables array $V[1], \cdots, V[n]$
- $V[0]$ holds the reference to `this`
    - object on which the method is invoked

Stack Machine Execution Example



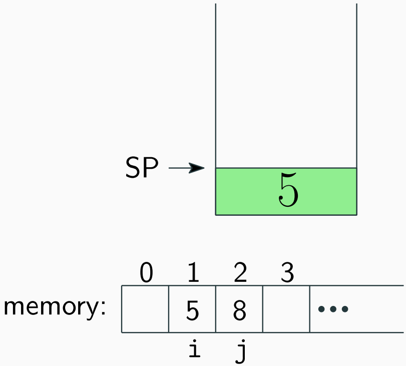
Java Bytecode

```
PC →  9: iload_1
```

```
 6: // ...
 9: iload_1
10: iconst_2
11: iload_2
12: imul
13: iconst_1
14: iadd
15: iadd
16: istore_1
17: // ...
```

Java Statement: `i += 2 * j + 1;`

Stack Machine Execution Example

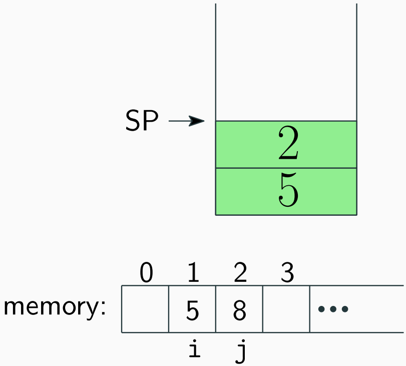


Java Bytecode

```
       6:  // ...
       9:  iload_1
PC →  10:  iconst_2
      11:  iload_2
      12:  imul
      13:  iconst_1
      14:  iadd
      15:  iadd
      16:  istore_1
      17:  // ...
```

Java Statement: `i += 2 * j + 1;`

Stack Machine Execution Example

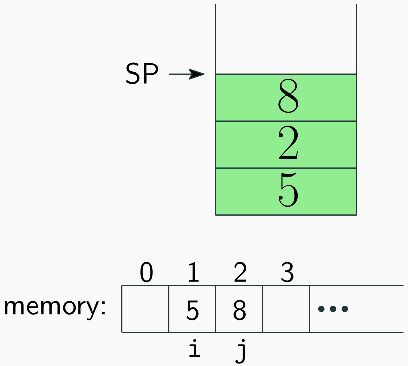


Java Bytecode

```
       6:  // ...
       9:  iload_1
      10:  iconst_2
PC →  11:  iload_2
      12:  imul
      13:  iconst_1
      14:  iadd
      15:  iadd
      16:  istore_1
      17:  // ...
```

Java Statement: `i += 2 * j + 1;`

Stack Machine Execution Example

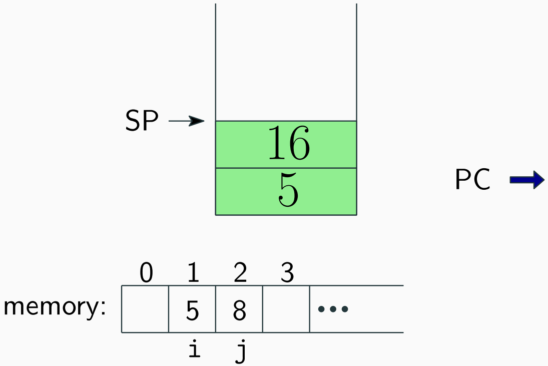


Java Bytecode

```
      6:  // ...
      9:  iload_1
     10:  iconst_2
     11:  iload_2
PC → 12:  imul
     13:  iconst_1
     14:  iadd
     15:  iadd
     16:  istore_1
     17:  // ...
```

Java Statement: `i += 2 * j + 1;`

Stack Machine Execution Example

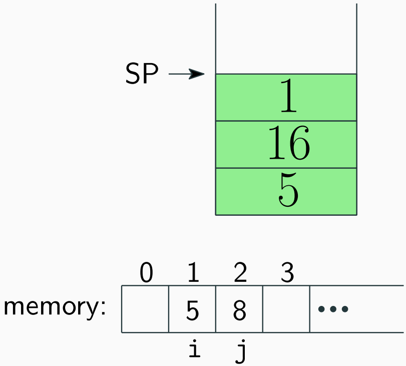


Java Bytecode

```
 6: // ...
 9: iload_1
10: iconst_2
11: iload_2
12: imul
13: iconst_1
14: iadd
15: iadd
16: istore_1
17: // ...
```

Java Statement: `i += 2 * j + 1;`

Stack Machine Execution Example



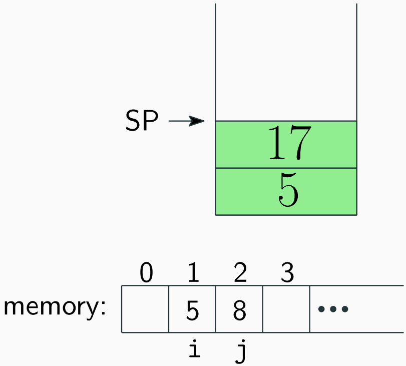
Java Bytecode

PC → 14

```
 6:  // ...
 9:  iload_1
10:  iconst_2
11:  iload_2
12:  imul
13:  iconst_1
14:  iadd
15:  iadd
16:  istore_1
17:  // ...
```

Java Statement: `i += 2 * j + 1;`

Stack Machine Execution Example



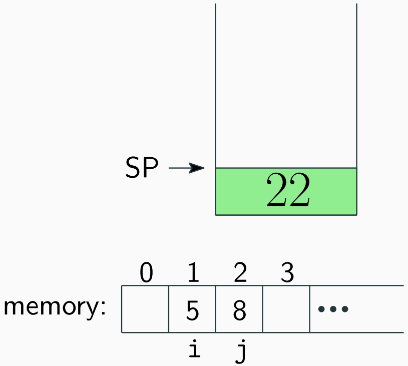
Java Bytecode

PC ➡

```
 6: // ...
 9: iload_1
10: iconst_2
11: iload_2
12: imul
13: iconst_1
14: iadd
15: iadd
16: istore_1
17: // ...
```

Java Statement: `i += 2 * j + 1;`

Stack Machine Execution Example



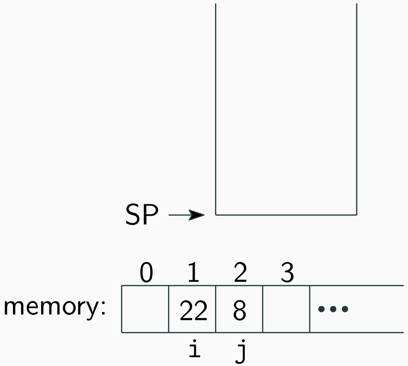
Java Bytecode

PC → 16

```
 6: // ...
 9: iload_1
10: iconst_2
11: iload_2
12: imul
13: iconst_1
14: iadd
15: iadd
16: istore_1
17: // ...
```

Java Statement: `i += 2 * j + 1;`

Stack Machine Execution Example



Java Bytecode

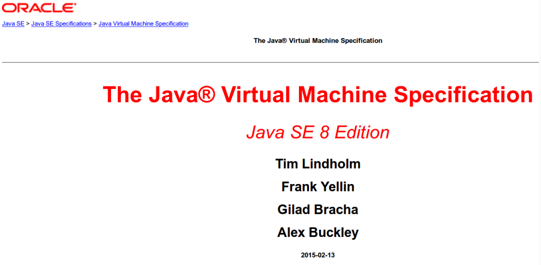
```
    6:  // ...
    9:  iload_1
   10:  iconst_2
   11:  iload_2
   12:  imul
   13:  iconst_1
   14:  iadd
   15:  iadd
   16:  istore_1
PC → 17:  // ...
```

Java Statement: `i += 2 * j + 1;`

Instructions in JVM

- Separate for each type, including
  - integer types (`iadd`, `imul`, `iload`, `istore`, `bipush`)
  - reference types (`aload`, `astore`)
- Why are they separate if not in e.g. x86?
  - Memory safety
  - Each reference points to a valid allocated object
- Conditionals and jumps
- Further high-level operations
  - array operations
  - object method and field access

Java Virtual Machine Specifications


ORACLE

Java SE > Java SE Specifications > Java Virtual Machine Specification

The Java® Virtual Machine Specification

The Java® Virtual Machine Specification

Java SE 8 Edition

Tim Lindholm

Frank Yellin

Gilad Bracha

Alex Buckley

2015-02-13

`http://docs.oracle.com/javase/specs/jvms/se8/html/index.html`

- Use `javac -g *.java` to compile
- Use `javap -c -l ClassName` to explore

Selected Instructions

`iload_x`	Loads the integer value of the local variable in slot `x` on the stack. $x \in \{0, 1, 2, 3\}$
`iload X`	Loads the value of the local variable pointed to by index `X` on the top of the stack.
`iconst_x`	Loads the integer constant `x` on the stack. `x`$\in \{0, 1, 2, 3, 4, 5\}$
`bipush X`	Like `iconst`, but for arbitrarily large `X`
`istore_x`	Stores the current value on top of the stack in the local variable in slot `x`$\in \{0, 1, 2, 3\}$
`istore X`	Stores the current value on top of the stack in the local variable indexed by `X`.
`ireturn`	Method return statement (note that the return value has to have been put on the top of the stack beforehand).
`iadd`	Pop two (integer) values from the stack, add them and put the result back on the stack.
`isub`	Pop two (integer) values from the stack, subtract them and put the result back on the stack.

Selected Instructions

`imult`	Pop two (integer) values from the stack, multiply them and put the result back on the stack.
`idiv`	Pop two (integer) values from the stack, divide them and put the result back on the stack.
`irem`	Pop two (integer) values from the stack, put the result of $x_1 \% x_2$ back on the stack.
`ineg`	Negate the value on the stack.
`iinc x, y`	Increment the variable in slot `x` by amount `y`.
`ior`	Bitwise OR for the two integer values on the stack.
`iand`	Bitwise AND for the two integer values on the stack.
`ixor`	Bitwise XOR for the two integer values on the stack.
`ifXX L`	Pop one value from the stack, compare it zero according to the operator XX. If the condition is satisfied, jump to the instruction given by label L. XX$\in$ {`eq, lt, le, ne,gt, ge, null, nonnull`}

Selected Instructions

`if_icmpXX L`	Pop two values from the stack and compare against each other. Rest as `ifXX L`.
`goto L`	Unconditional jump to instruction given by the label `L`.
`pop`	Discard word currently on top of the stack.
`dup`	Duplicate word currently on top of the stack.
`swap`	Swaps the two top values on the stack.
`aload_x`	Loads an object reference from slot `x`.
`aload X`	Loads an object reference from local variable indexed by `X`.
`iaload`	Loads onto the stack an integer from an array. The stack must contain the array reference and the index.
`iastore`	Stores an integer in an array. The stack must contain the array reference, the index and the value, in that order.

Example: Twice

```
class Expr1 {
  public static int twice(int x) {
    return x*2;
  }
}
```

```
> javac -g Expr1.java; javap -c -l Expr1
```

```
public static int twice(int);
Code:
  0: iload_0   // load int from var 0 to top of stack
  1: iconst_2 // push 2 on top of stack
  2: imul      // replace two topmost elements with their product
  3: ireturn   // return top of stack
```

Example: Area

```
class Expr2 {
 public static int cubeArea(int a,int b,int c) {
  return (a*b + b*c + a*c) * 2;
}}
```

```
> javac -g Expr2.java; javap -c -l Expr2
```

LocalVariableTable:

Start	Length	Slot	Name	Signature
0	14	0	a	I
0	14	1	b	I
0	14	2	c	I

- Start: start bytecode where the variable is visible
- Length: number of bytecode bytes during which the variable is visible

```
public static int
 cubeArea(int,int,int);
Code:
0: iload_0
1: iload_1
2: imul
3: iload_1
4: iload_2
5: imul
6: iadd
7: iload_0
8: iload_2
9: imul
10: iadd
11: iconst_2
12: imul
13: ireturn
```