CSCI 742 - Compiler Construction

Lecture 28

Introduction to Code Generation

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Compiler Phases

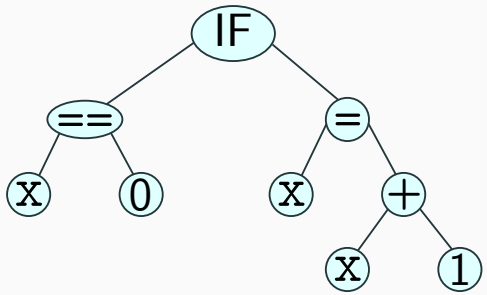
Source Code
(concrete syntax)

```
if (x==0) x=x+1;
```

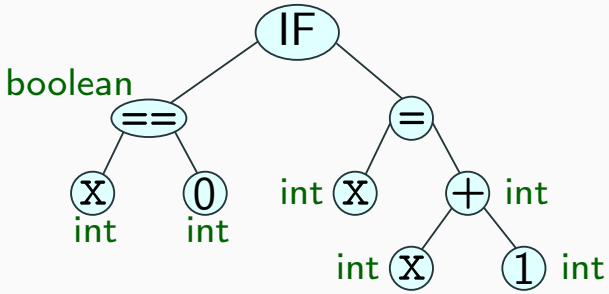
Token Stream

```
if ( x == 0 ) x = x + 1 ;
```

Abstract Syntex Tree
(AST)



Attributed AST



Machine Code

```
16: iload_2
17: ifne   24
20: iload_2
21: iconst_1
22: iadd
23: istore_2
24: ...
```

Lexical Analysis

Syntax Analysis
(Parsing)

Semantic Analysis
(Name Analysis,
Type Analysis, ...)

Code Generation

Error

Code Generation Example

- Phase after type checking emits such bytecode instructions

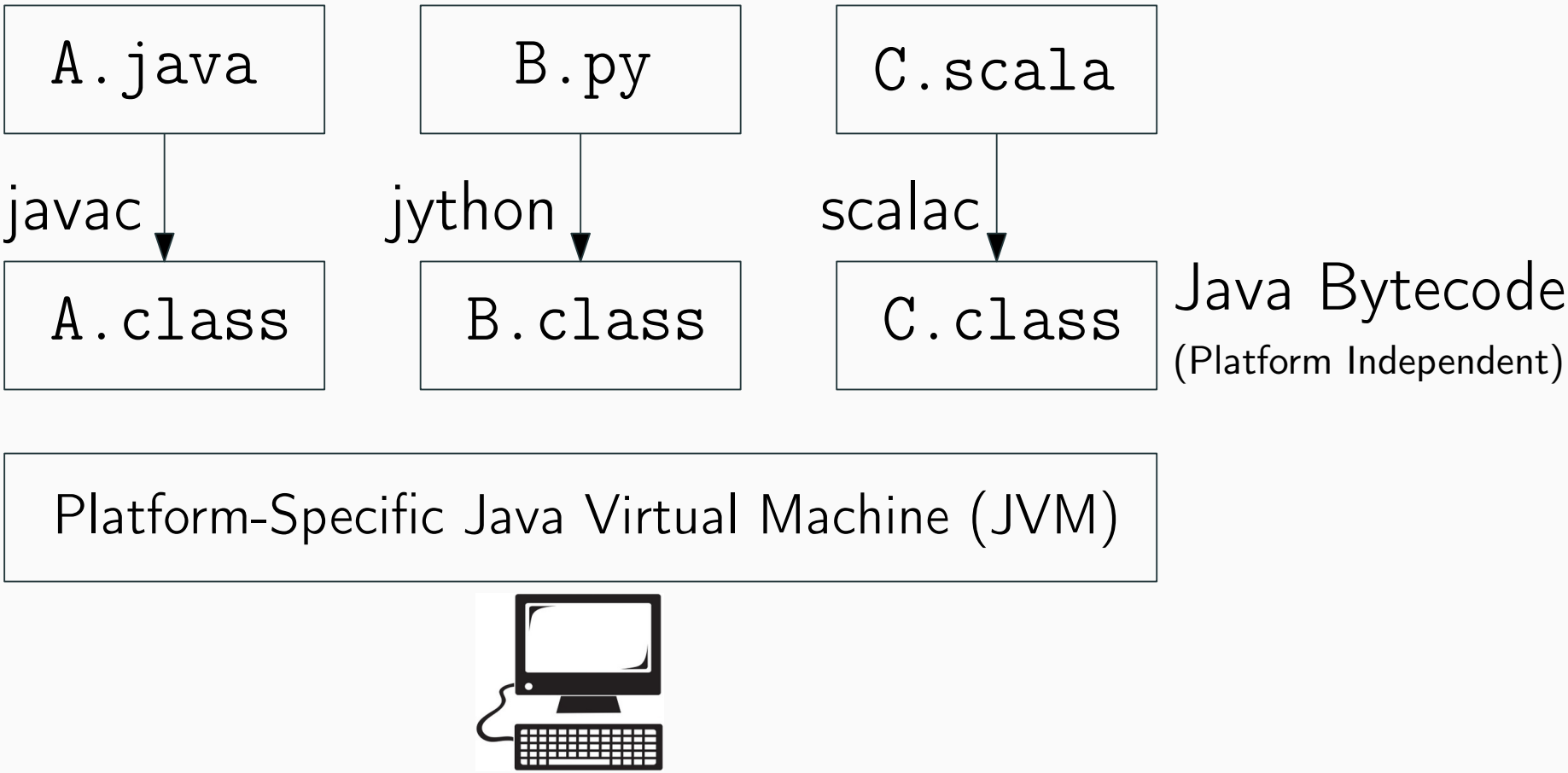
```
while (i > 0) {
  i += 2 * j + 1;
  j = j - 5;
  System.out.println(j);
}
```

```
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: // ...
```

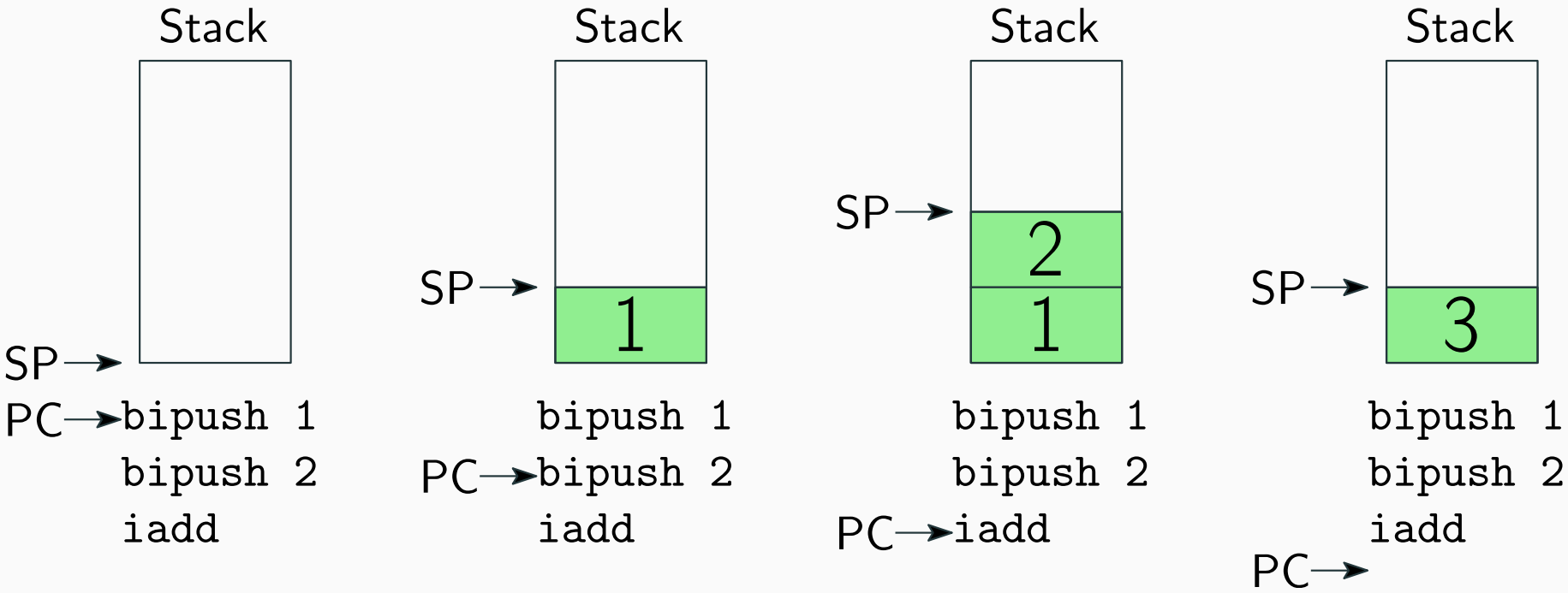
Java Virtual Machine (JVM)

- 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)

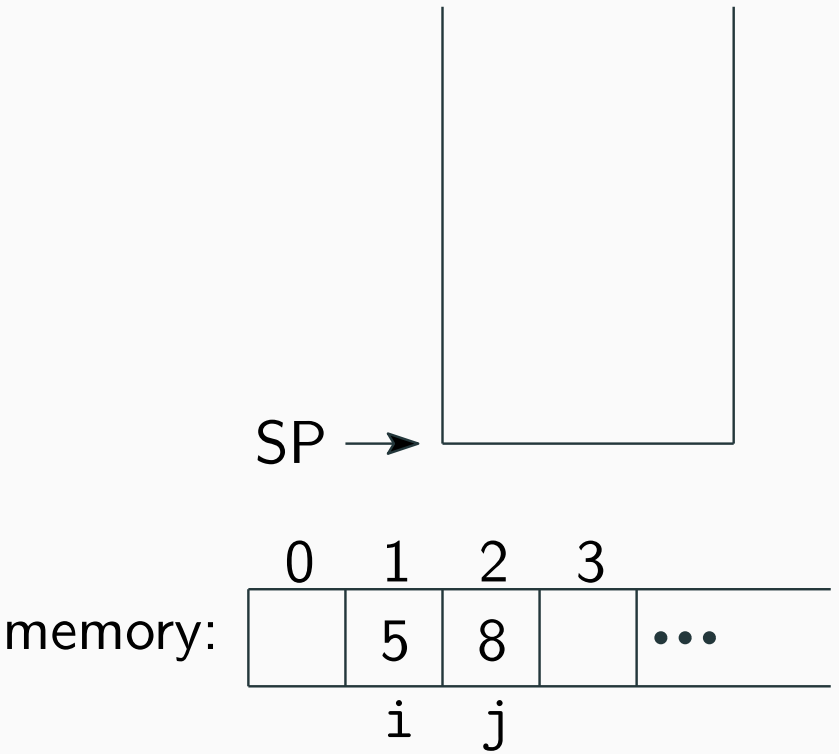
- JVM is a stack machine: evaluation of expressions uses a stack (operand stack)
- Instructions fetch their arguments from the top of the operand stack
- Instructions store their results at the top of the operand stack



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

Stack Machine Execution Example



Java Bytecode

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PC →

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

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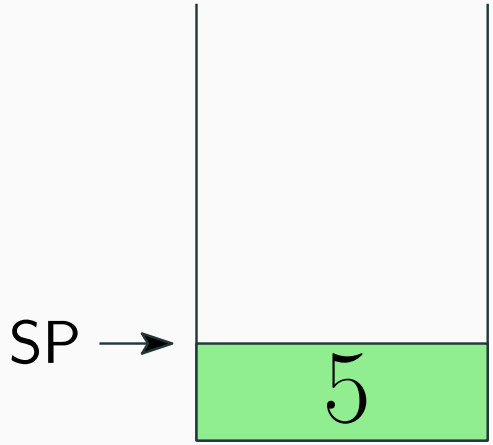

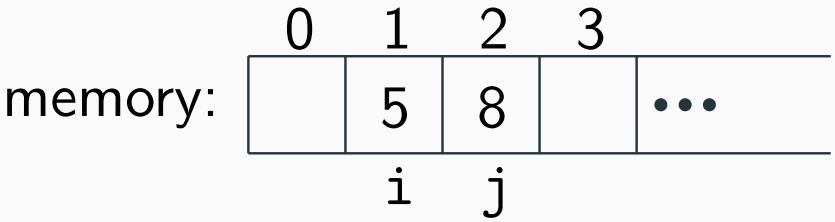

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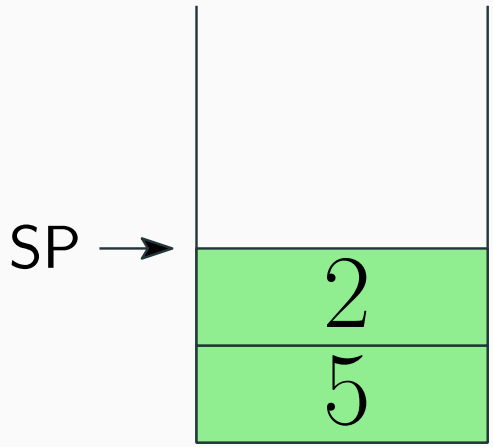

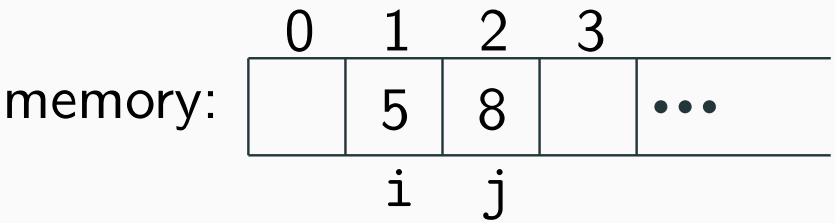

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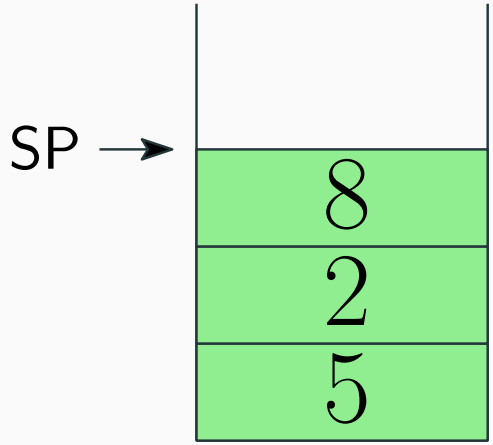

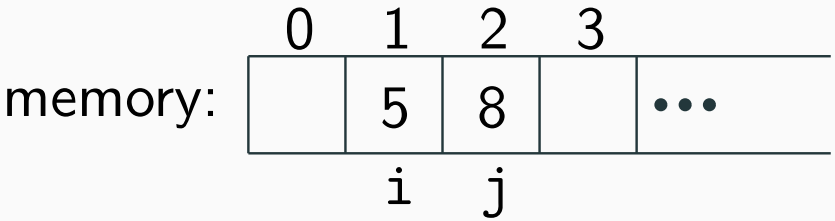

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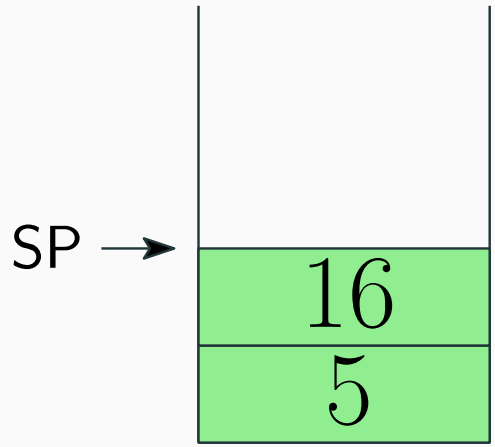

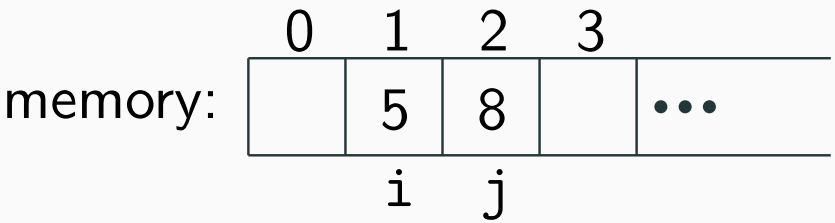

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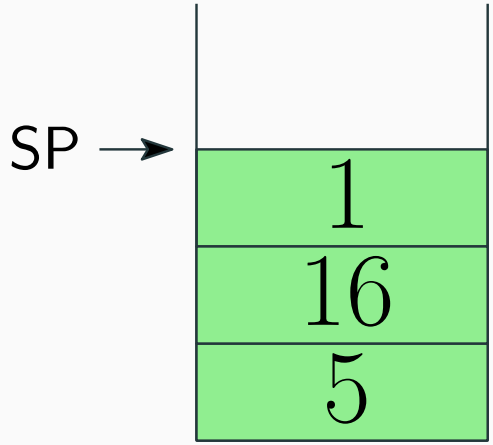

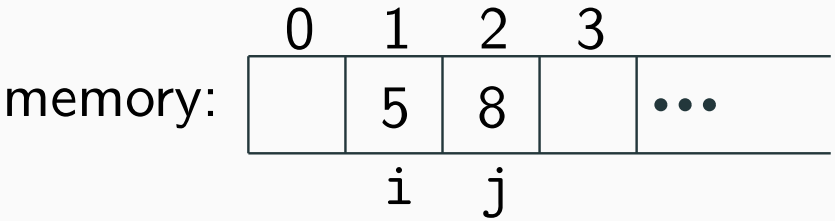

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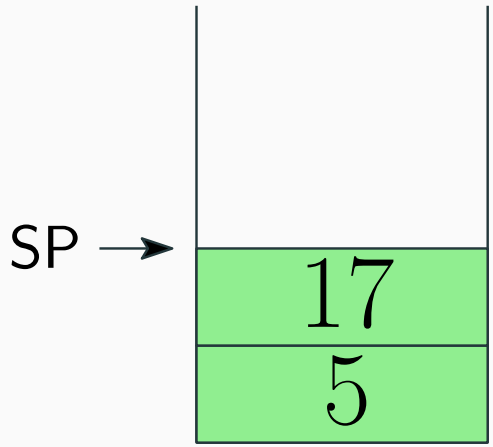

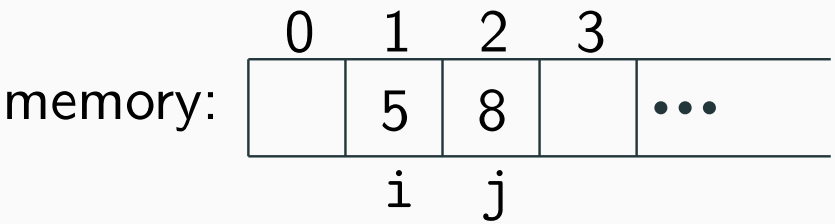

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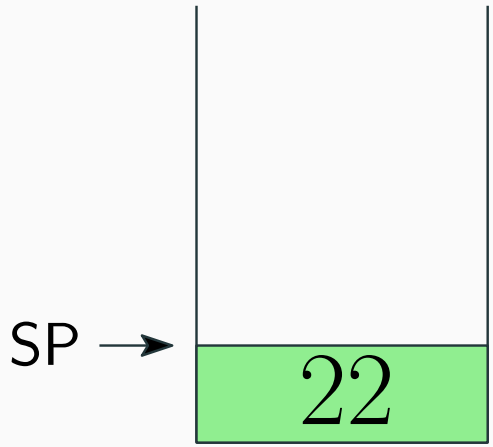

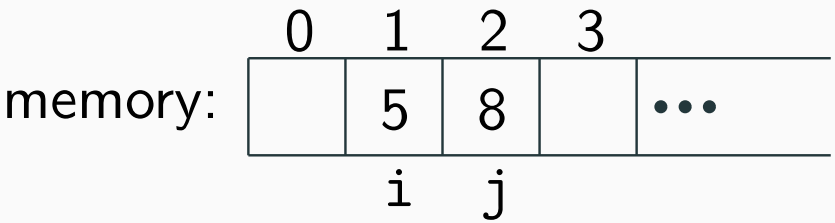

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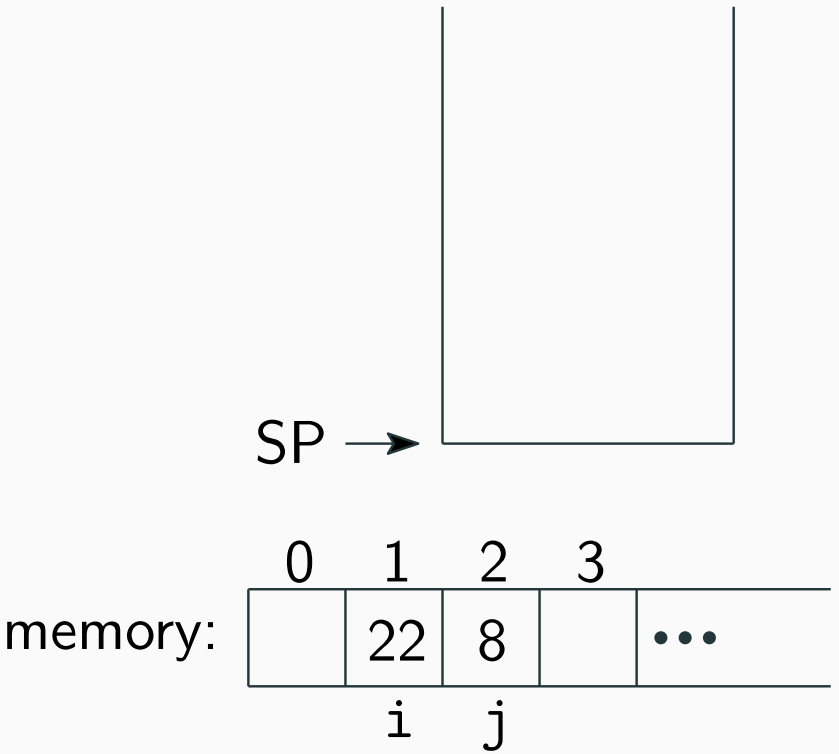

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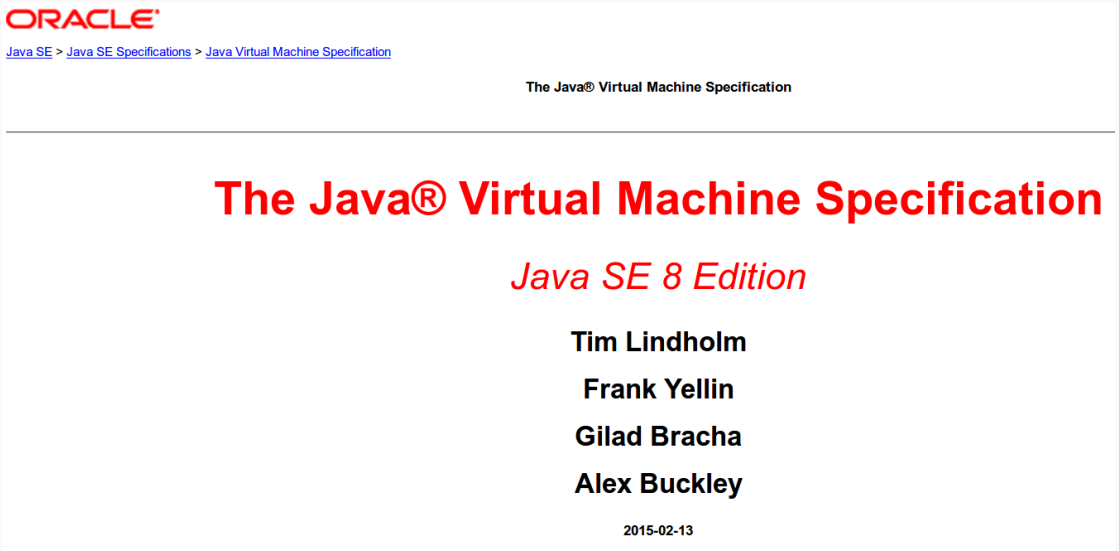
Instructions in JVM

- 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

```
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
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10: iadd
11: iconst_2
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13: ireturn
```