CSc 453

Compilers and Systems Software

17 : The Java VM

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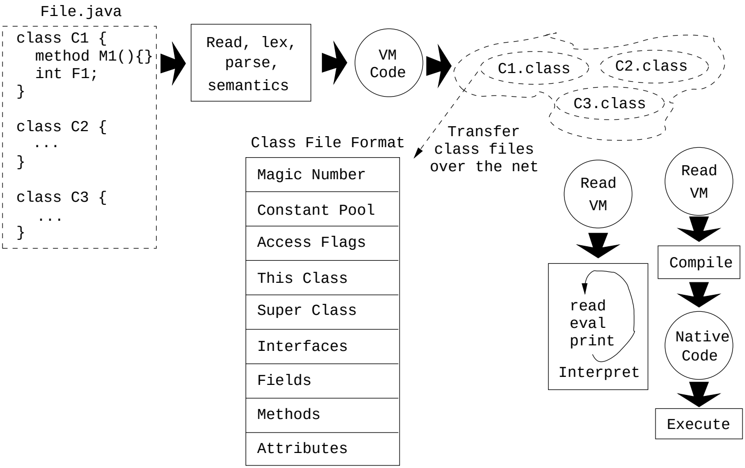
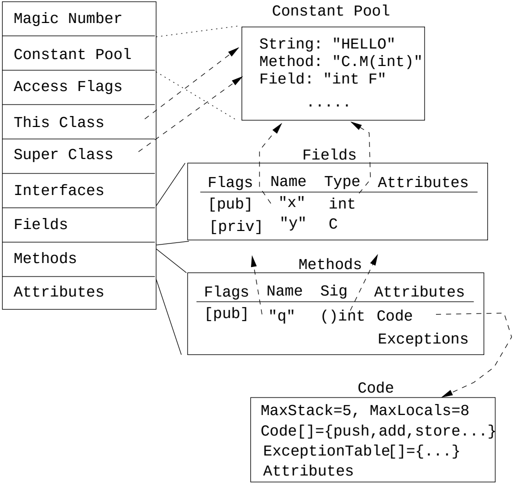
The Java Virtual Machine

- The Java VM has gone the "many complex instructions/large VM engine" way.
- Each Java source file may contain several Java classes. The Java compiler compiles each of these classes to a single Java *class file*.
- The Java class file stores all necessary data regarding the class. There is a symbol table (called the *Constant Pool*) which stores strings, large literal integers and floats, names and of all fields and methods.
- Each method is compiled to Java bytecode, a stack VM format.
- The class file is (almost) isomorphic to the source.


File.java
class C1 {
method M1(){}
int F1;
}
class C2 {
...
}
class C3 {
...
}
Read, lex,
parse,
semantics
VM
Code
C1.class
C2.class
C3.class
Transfer
class files
over the net
Class File Format
Magic Number
Constant Pool
Access Flags
This Class
Super Class
Interfaces
Fields
Methods
Attributes
Read
VM
read
eval
print
Interpret
Read
VM
Compile
Native
Code
Execute


Magic Number
Constant Pool
Access Flags
This Class
Super Class
Interfaces
Fields
Methods
Attributes
Constant Pool
String: "HELLO"
Method: "C.M(int)"
Field: "int F"
.....
Fields
Flags Name Type Attributes
[pub] "x" int
[priv] "y" C
Methods
Flags Name Sig Attributes
[pub] "q" ()int Code
Exceptions
Code
MaxStack=5, MaxLocals=8
Code[]={push,add,store...}
ExceptionTable[]={...}
Attributes

Java Byte Codes

- The Java bytecodes can manipulate data in these formats: integers (32-bits), longs (64-bits), floats (32-bits), doubles (64-bits), shorts (16-bits), bytes (8-bits), object references (32/64-bit pointers), and arrays.
- The bytecodes are 1 byte wide.
- Each method can have up to 256 local variables and formal parameters. The bytecode reference these by number.
- Actually, we can have up to 65536 local vars. There is a special `wide` instruction that modifies load and store instructions to reference the high-numbered locals. Hack.

Java Byte Codes. . .

- The Java stack is 32-bits wide. Longs and doubles hence take two stack entries.
- The bytecodes reference data from the class' constant pool. These references are 8 or 16 bits long. To push a reference to a literal string with constant pool # 4567, use `'ldc2 4567'`. If the # is 123, use `'ldc2 123'`.

Java Byte Codes...

$\texttt{int}_8$	An 8-bit integer value.
$\texttt{int}_{16}$	A 16-bit integer value.
$\texttt{int}_{32}$	A 32-bit integer value.
$\texttt{CP}_8$	An 8-bit constant pool index.
$\texttt{CP}_{16}$	A 16-bit constant pool index.
`FIdx`	An 8-bit local variable index.
$\texttt{FIdx}_{16}$	A 16-bit local variable index.
`CP[`i`]`	The i:th constant pool entry.
`Var[`i`]`	The i:th variable/formal parameter in the current method.

Opcode	Mnemonic	Args	Stack	Description
0	`nop`		$[] \Rightarrow []$	
1	`aconst_null`		$[] \Rightarrow [\mathsf{null}]$	Push null object
2	`iconst_m1`		$[] \Rightarrow [-1]$	Push -1
$3 \ldots 8$	`iconst_`n		$[] \Rightarrow [n]$	Push integer constant $n, 0 \leq n \leq 5$
$9 \ldots 10$	`lconst_`n		$[] \Rightarrow [n]$	Push long constant $n, 0 \leq n \leq 1$
$11 \ldots 13$	`fconst_`n		$[] \Rightarrow [n]$	Push float constant $n, 0 \leq n \leq 2$
$14 \ldots 15$	`dconst_`n		$[] \Rightarrow [n]$	Push double constant $n, 0 \leq n \leq 1$

Opcode	Mnemonic	Args	Stack	Description
16	`bipush`	n:$\mathtt{int}_8$	$[] \Rightarrow [n]$	Push 1-byte signed integer
17	`sipush`	n:$\mathtt{int}_{16}$	$[] \Rightarrow [n]$	Push 2-byte signed integer
18	`ldc1`	n:CP_8	$[] \Rightarrow [\mathrm{CP}[n]]$	Push item from constant pool
19	`ldc2`	n:CP_{16}	$[] \Rightarrow [\mathrm{CP}[n]]$	Push item from constant pool
20	`ldc2w`	n:CP_{16}	$[] \Rightarrow [\mathrm{CP}[n]]$	Push long/double from constant pool

Opcode	Mnemonic	Args	Stack
$21 \dots 25$	*X*`load`	n:`FIdx`	$[] \Rightarrow [\mathrm{Var}[n]]$
	$X \in$ {i,l,f,d,a}, Load int, long, float, double, object from local var.		
$26 \dots 29$	`iload_`n		$[] \Rightarrow [\mathrm{Var}[n]]$
	Load local integer var $n, 0 \leq n \leq 3$		
$30 \dots 33$	`lload_`n		$[] \Rightarrow [\mathrm{Var}[n]]$
	Load local long var $n, 0 \leq n \leq 4$		
$34 \dots 37$	`fload_`n		$[] \Rightarrow [\mathrm{Var}[n]]$
	Load local float var $n, 0 \leq n \leq 4$		
$38 \dots 41$	`dload_`n		$[] \Rightarrow [\mathrm{Var}[n]]$
	Load local double var $n, 0 \leq n \leq 4$		

Opcode	Mnemonic	Args	Stack
$42 \ldots 45$	`aload_`n		$[] \Rightarrow [\mathrm{Var}[n]]$
	Load local object var $n, 0 \leq n \leq 4$		
$46 \ldots 53$	X`load`		$[A, I] \Rightarrow [V]$
	$X \in$\{ia,la,fa,da,aa,ba, ca,sa\}. Push the value V (an int, long, etc.) stored at index I of array A.		
$54 \ldots 58$	X`store`	n:`FIdx`	$[\mathrm{Var}[n]] \Rightarrow []$
	$X \in$\{i,l,f,d,a\}, Store int, long, float, double, object to local var.		
$59 \ldots 62$	`istore_`n		$[\mathrm{Var}[n]] \Rightarrow []$
	Store to local integer var $n, 0 \leq n \leq 3$		
$63 \ldots 66$	`lstore_`n		$[\mathrm{Var}[n]] \Rightarrow []$
	Store to local long var $n, 0 \leq n \leq 4$		

Opcode	Mnemonic	Args	Stack
$67 \dots 70$	fstore_n		$[\mathrm{Var}[n]] \Rightarrow []$
	Store to local float var $n, 0 \leq n \leq 4$		
$71 \dots 74$	dstore_n		$[\mathrm{Var}[n]] \Rightarrow []$
	Store to local double var $n, 0 \leq n \leq 4$		
$75 \dots 78$	astore_n		$[\mathrm{Var}[n]] \Rightarrow []$
	Store to local object var $n, 0 \leq n \leq 4$		
$79 \dots 86$	Xstore		$[A, I, V] \Rightarrow []$
	$X \in$\{ia,la,fa,da,aa,ba,ca,sa\}. Store the value V (an int, long, etc.) at index I of array A.		
87	pop		$[A] \Rightarrow []$
	Pop top of stack.		

Opcode	Mnemonic	Stack	Description
88	`pop2`	$[A, B] \Rightarrow []$	Pop 2 elements.
89	`dup`	$[V] \Rightarrow [V, V]$	
	Duplicate top of stack.		
90	`dup_x1`	$[B, V] \Rightarrow [V, B, V]$	Duplicate.
91	`dup_x2`	$[B, C, V] \Rightarrow [V, B, C, V]$	Duplicate.
92	`dup2`	$[V, W] \Rightarrow [V, W, V, W]$	Duplicate.
93	`dup2_x1`	$[A, V, W] \Rightarrow [V, W, A, V, W]$	Duplicate.
94	`dup2_x2`	$[A, B, V, W] \Rightarrow [V, W, A, B, V, W]$	Duplicate.
95	`swap`	$[A, B] \Rightarrow [B, A]$	
	Swap top stack elements.		

Opcode	Mnemonic	Stack	Description
96 ... 99	X`add`	$[A, B] \Rightarrow [R]$	$X \in$ {i,l,d,f}. $R = A + B$
100 ... 103	X`sub`	$[A, B] \Rightarrow [R]$	$X \in$ {i,l,d,f}. $R = A - B$
104 ... 107	X`mul`	$[A, B] \Rightarrow [R]$	$X \in$ {i,l,d,f}. $R = A * B$
108 ... 111	X`div`	$[A, B] \Rightarrow [R]$	$X \in$ {i,l,d,f}. $R = A/B$
112 ... 115	X`mod`	$[A, B] \Rightarrow [R]$	$X \in$ {i,l,d,f}. $R = A\%B$
116 ... 119	X`neg`	$[A] \Rightarrow [R]$	$X \in$ {i,l,d,f}. $R = -A$
120 ... 121	X`shl`	$[A, B] \Rightarrow [R]$	$X \in$ {i,l}. $R = A << B$
122 ... 123	X`shl`	$[A, B] \Rightarrow [R]$	$X \in$ {i,l}. $R = A >> B$
124 ... 125	X`ushr`	$[A, B] \Rightarrow [R]$	$X \in$ {i,l}. $R = A >>> B$
126 ... 127	X`and`	$[A, B] \Rightarrow [R]$	$X \in$ {i,l}. $R = A \&\& B$
128 ... 129	X`or`	$[A, B] \Rightarrow [R]$	$X \in$ {i,l}. $R = A \vert\vert B$
130 ... 131	X`xor`	$[A, B] \Rightarrow [R]$	$X \in$ {i,l}. $R = A$ `xor` B

Opcode	Mnemonic	Args	Stack
$133 \ldots 144$	$X2Y\texttt{cnv}$		$[F] \Rightarrow [T]$
	Convert F from type X to T of type Y. $X \in$\{i,l,f,d\}, $Y \in$\{i,l,f,d\}.		
$145 \ldots 147$	$\texttt{i2}X$		$[F] \Rightarrow [T]$
	$X \in$\{b,c,s\}. Convert integer F to byte, char, or short.		
148,149,151	$X\texttt{cmp}$		$[A, B] \Rightarrow [V]$
	$X \in$\{l,f,d\}. $A > B \Rightarrow V = 1$, $A < B \Rightarrow V = -1$, $A = B \Rightarrow V = 0$. $A = \texttt{NaN} \vee B = \texttt{NaN} \Rightarrow V = -1$		
150,152	$X\texttt{cmp}$		$[A, B] \Rightarrow [V]$
	$X \in$\{f,d\}. $A > B \Rightarrow V = 1$, $A < B \Rightarrow V = -1$, $A = B \Rightarrow V = 0$. $A = \texttt{NaN} \vee B = \texttt{NaN} \Rightarrow V = 1$		
$153 \ldots 154$	$\texttt{if}\diamond$	L:$\texttt{int}_{16}$	$[A] \Rightarrow []$
	$\diamond$=\{eq,ne,lt,ge,gt,le\}. If $A \diamond 0$ goto $L + \texttt{pc}$.		

Opcode	Mnemonic	Args	Stack
159 ... 164	`if_icomp`$\diamond$	L:$\texttt{int}_{16}$	$[A, B] \Rightarrow []$
	$\diamond$=$\{$eq,ne,lt,ge,gt,le$\}$. If $A \diamond B$ goto $L + \mathtt{pc}$.		
165 ... 166	`if_acmp`$\diamond$	L:$\texttt{int}_{16}$	$[A, B] \Rightarrow []$
	$\diamond$=$\{$eq,ne$\}$. A, B are object refs. If $A \diamond B$ goto $L + \mathtt{pc}$.		
167	`goto`	I:$\texttt{int}_{16}$	$[] \Rightarrow []$
	Goto instruction I.		
168	`jsr`	I:$\texttt{int}_{16}$	$[] \Rightarrow []$
	Jump subroutine to instruction $I + \mathtt{pc}$.		
172 ... 177	X`return`		$[V] \Rightarrow []$
	$X \in \{$i,f,l,d,a,v$\}$. Return V.		
169	`ret`	L:$\texttt{FIdx}$	$[] \Rightarrow []$
	Return from subroutine. Address in local var L.		

Opcode	Mnemonic	Args	Stack
170	`tableswitch`	D:$\texttt{int}_{32}$,l, h:$\texttt{int}_{32}$,o^{h-l+1}	$[K] \Rightarrow []$
	Jump through the K:th offset. Else goto D.		
171	`lookupswitch`	D:$\texttt{int}_{32}$,n:$\texttt{int}_{32}$,$(m, o)^n$	$[K] \Rightarrow []$
	If, for one of the (m, o) pairs, $K = m$, then goto o. Else goto D.		
178	`getstatic`	F:$\texttt{CP}_{16}$	$[] \Rightarrow [V]$
	Push value V of static field F.		
180	`getfield`	F:$\texttt{CP}_{16}$	$[R] \Rightarrow [V]$
	Push value V of field F in object R.		
179	`putstatic`	F:$\texttt{CP}_{16}$	$[] \Rightarrow [V]$
	Store value V into static field F.		
181	`putfield`	F:$\texttt{CP}_{16}$	$[R, V] \Rightarrow []$
	Store value V into field F of object R.		

Opcode	Mnemonic	Args	Stack
182	`invokevirtual`	P:$\mathtt{CP}_{16}$	$[R, A_1, A_2, \ldots] \Rightarrow []$
	Call virtual menthod P, with arguments $A_1 \cdots A_n$, through object reference R.		
183	`invokespecial`	P:$\mathtt{CP}_{16}$	$[R, A_1, A_2, \ldots] \Rightarrow []$
	Call private/init/superclass menthod P, with arguments $A_1 \cdots A_n$, through object reference R.		
184	`invokestatic`	P:$\mathtt{CP}_{16}$	$[A_1, A_2, \ldots] \Rightarrow []$
	Call static menthod P with arguments $A_1 \cdots A_n$.		
185	`invokeinterface`	P:$\mathtt{CP}_{16}$,n:$\mathtt{int}_{16}$	$[R, A_1, A_2, \ldots] \Rightarrow []$
	Call interface menthod P, with n arguments $A_1 \cdots A_n$, through object reference R.		
187	`new`	T:$\mathtt{CP}_{16}$	$[] \Rightarrow [R]$
	Create a new object R of type T.		

Opcode	Mnemonic	Args	Stack
188	`newarray`	T:$\texttt{int}_8$	$[C] \Rightarrow [R]$
	Allocate new array R, element type T, C elements long.		
191	`athrow`		$[R] \Rightarrow [?]$
	Throw exception.		
193	`instanceof`	C:$\texttt{CP}_{16}$	$[R] \Rightarrow [V]$
	Push 1 if object R is an instance of class C. Else push 0.		
194	`monitorenter`		$[R] \Rightarrow []$
	Get lock for object R.		
195	`monitorexit`		$[R] \Rightarrow []$
	Release lock for object R.		
196	`wide`	C:$\texttt{int}_8$,I:$\texttt{FIdx}_{16}$	$[] \Rightarrow []$
	Perform opcode C on variable `Var`[I]. C is one of the load/store instructions.		

Opcode	Mnemonic	Args	Stack
197	`multianewarray`	T:CP$_{16}$,D:CP$_8$	$[d_1, d_2, \ldots] \Rightarrow [R]$
	Create new D-dimensional multidimensional array R. $d_1, d_2, \ldots$ are the dimension sizes.		
198	`ifnull`	L:int$_{16}$	$[V] \Rightarrow []$
	If $V =$ `null` goto L.		
199	`ifnonnull`	L:int$_{16}$	$[V] \Rightarrow []$
	If $V \neq$ `null` goto L.		
200	`goto_w`	I:int$_{32}$	$[] \Rightarrow []$
	Goto instruction I.		
201	`jsr_w`	I:int$_{32}$	$[] \Rightarrow []$
	Jump subroutine to instruction I.		

```
void spin() {
    int i; for (i = 0; i < 100; i++); // Empty loop body
```

$$\Downarrow$$

```
0    iconst_0      // Push int constant 0
1    istore_1      // Store into local 1 (i=0)
2    goto 8        // First time through don't increment
5    iinc 1 1      // Increment local 1 by 1(i++)
8    iload_1       // Push local 1 (i)
9    bipush 100    // Push int constant (100)
11   if_icmplt 5 // Compare, loop // if < (i < 100)
14   return        // Return void when done
```

```
double i;for (i = 0.0; i < 100.0; i++);  // Empty loop body
```

$\Downarrow$

```
0   dconst_0  // Push double constant 0.0
1   dstore_1  // Store into locals 1 and 2 (i = 0.0)
2   goto 9    // First time no incr
5   dload_1   // Push double
6   dconst_1  // Push double 1.o onto stack
7   dadd      // Add;
8   dstore_1  // Store result in locals 1 and 2
9   dload_1   // Push local
10  ldc2_w #4 // Double 100.000000
13  dcmpg
14  iflt 5    // Compare, loop if < (i < 100.000000)
17  return    // Return void when done
```

```
double doubleLocals(double d1, double d2) {
    return d1 + d2;
}
```

$$\Downarrow$$

```
0  dload_1 // First argument in locals 1 and 2
1  dload_3 // Second argument in locals 3 and 4
2  dadd    // Each also uses two words on stack
3  dreturn
```

```
int align2grain(int i, int grain) {
    return ((i + grain-1) & ~(grain-1));}
```

$$\Downarrow$$

```
0   iload_1
1   iload_2
2   iadd
3   iconst_1
4   isub
5   iload_2
6   iconst_1
7   isub
8   iconst_m1
9   ixor
10  iand
11  ireturn
```

```
void useManyNumeric() {
    int i = 100; int j = 1000000;
    long l1 = 1; long l2 = 0xffffffff; double d = 2.2; }
```

$$\Downarrow$$

```
0  bipush 100 // Push a small int
2  istore_1
3  ldc #1     // Integer 1000000; a larger int value uses l
5  istore_2
6  lconst_1   // A tiny long value
7  lstore_3
8  ldc2_w #6  // A long 0xffffffff. A long constant value.
11 lstore 5
13 ldc2_w #8  // Double 2.200000
16 dstore 7
```

```
void whileInt() {
    int i = 0;
    while (i < 100) i++;
}
```

$$\Downarrow$$

```
0    iconst_0
1    istore_1
2    goto 8
5    iinc 1 1
8    iload_1
9    bipush 100
11   if_icmplt 5
14   return
```

```
int lessThan100(double d) {
    if (d < 100.0) return 1; else  return -1; }
```

$$\Downarrow$$

```
0   dload_1
1   ldc2_w #4 // Double 100.000000
4   dcmpg     // Push 1 if d is NaN or d < 100.000000;
              // push 0 if d == 100.000000
5   ifge 10   // Branch on 0 or 1
8   iconst_1
9   ireturn
10  iconst_m1
11  ireturn
```

```
int add12and13() {return addTwo(12, 13);}
```

$$\Downarrow$$

```
0  aload_0           // Push this local 0 (this) onto stack
1  bipush 12         // Push int constant 12 onto stack
3  bipush 13         // Push int constant 13 onto stack
5  invokevirtual #4 // Method Example.addtwo(II)I
8  ireturn           // Return int on top of stack; it is
                     // the int result of addTwo()
```

```
Object create() {return new Object();}
```

$$\Downarrow$$

```
0  new #1           // Class java.lang.Object
3  dup
4  invokespecial #4 // Method java.lang.Object.<init>()V
7  areturn
```

```
void createBuffer() {
   int buf[]; int bsz = 100; int val=12;
   buf = new int[bsz]; buf[10]=val;  value = buf[11]; }
```

$\Downarrow$

```
0   bipush 100   // Push bsz
2   istore_2     // Store bsz in local 2
3   bipush 12    // Push val
5   istore_3     // Store val in local 3
6   iload_2      // Push bsz...
7   newarray int // and create new int array
9   astore_1     // Store new array in buf
10  aload_1      // Push buf
11  bipush 10    // Push constant 10
13  iload_3      // Push val
14  iastore      // Store val at buf[10]
15  aload_1      // Push buf
16  bipush 11    // Push constant 11
18  iaload       // Push value at buf[11]
19  istore_3     // ...and store it in value
20  return
```

```
int chooseNear(int i) {
switch(i){case 0:return 0; case 2:return 2; default:return
```

$\Downarrow$

```
0   iload_1      // Load local 1 (argument i)
1   tableswitch 0 to 2:
    0: 28        // If i is 0, continue at 28
    1: 32        // If i is 1, continue at 34
    2: 30        // If i is 2, continue at 32
    default:34   // Otherwise, continue at 34
28  iconst_0     // i was 0; push int 0...
29  ireturn      // ...and return it
30  iconst_2     // i was 2; push int 2...
31  ireturn      // ...and return it
32  iconst_m1    // otherwise push int -1...
33  ireturn      // ...and return it
```