JAM 16:
The Instruction Set
&
Sample Programs

CSE Dept. Univ. of Notre Dame
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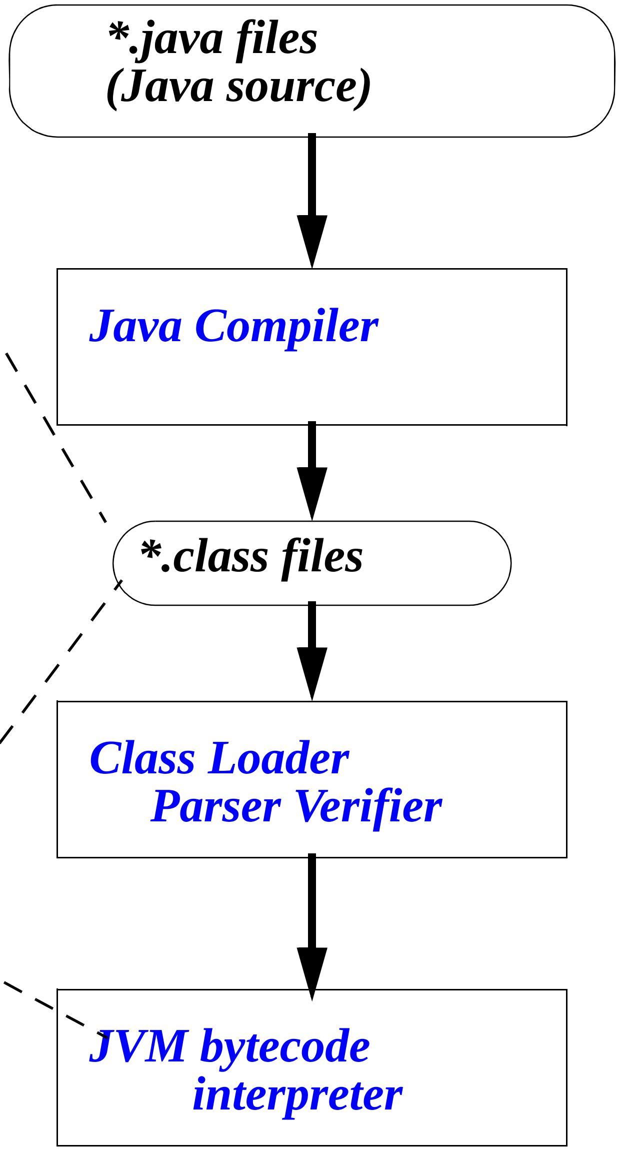
Java Terms

- **Java: "A simple, object-oriented, distributed, interpreted, robust, secure, architecture neutral, portable, high performance, and dynamic language." (Sun)**
- **Java Virtual Machine (JVM):**
  - **an Instruction Set Architecture into which Java programs are compiled**
  - **an interpreter which simulates this ISA (like XSPIM)**
- **JVM bytecodes: a sequence of bytes that define a JVM instruction**
- **Interpreter: software program that emulates at RTL level the execution of a program written in some ISA (usually different from that of the machine running the interpreted)**
  - **Java Interpreter: interprets programs constructed as JVM bytecodes**
- **Java Application: program written in Java that is executed like a program in any other language**
- **Java Applet:**
  - **(Small) program written in Java**
  - **Embedded in a web page**
  - **Loaded by, & interpreted in, web browser**

The Java Execution Model (non Applet)

.class file format:

- **Header information**
- **“Constant Pool”**
  - **Values of constants in the Java program**
- **“Interfaces”**
  - **Names of superclasses, interface methods, ...**
- **“Methods” (i.e. procedures)**
  - **One per method in original program**
  - **Storage requirements for execution**
  - **Compiled code in JVM “machine language”**



JVM = “Java Virtual Machine”

- **Instruction Set Architecture**
- **Easily interpreted by software**
- **Java chips under development**

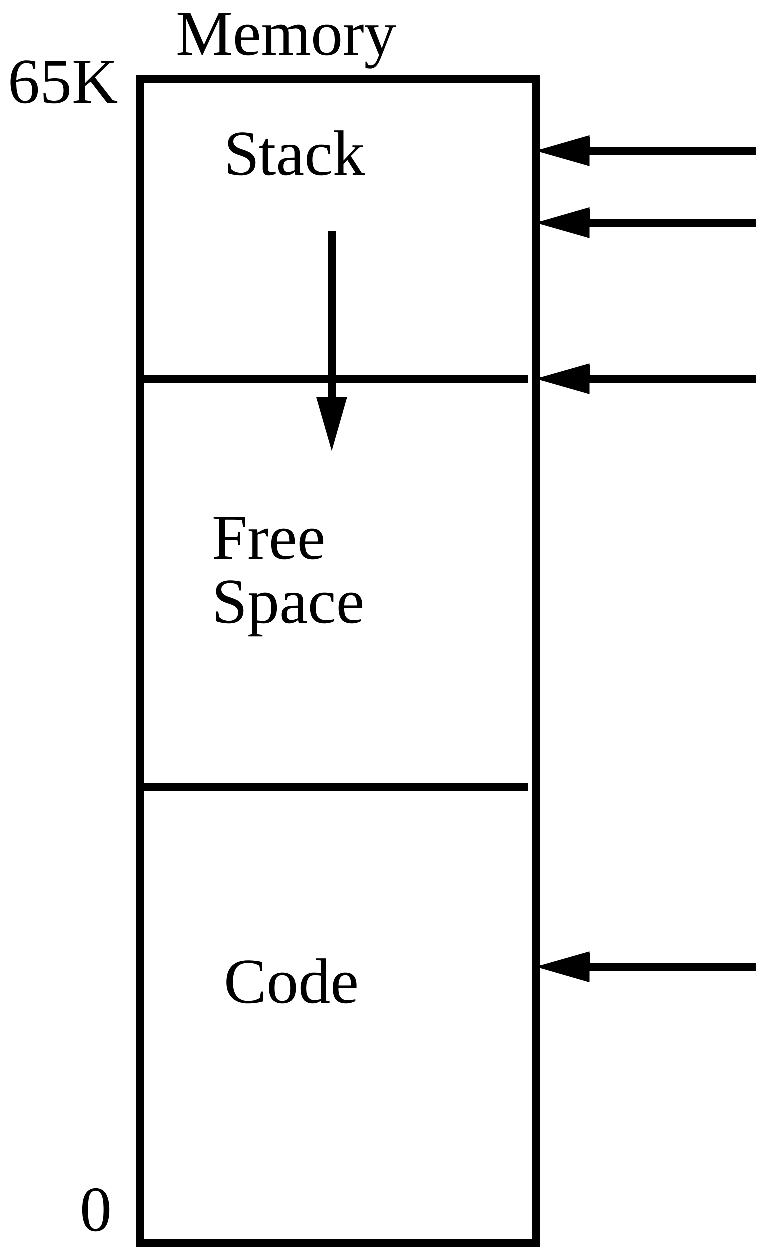
The Java Virtual Machine

- **Four 32 bit Programmer visible registers**
  - **pc: program counter = pointer to next bytecoded JVM instruction**
  - **optop: pointer to the top of a programmer-visible stack in memory**
  - **frame: pointer to memory area describing current method**
  - **vars: pointer to beginning of local variables for current method**
- **Heap: area in memory from which objects dynamically allocated**
- **Stack: area in memory referenced by optop, frame, vars registers**
  - **Separate stack allocated from heap at each method invocation**
  - **Holds arguments for, and results from, bytecode instructions**
  - **Holds arguments for, and results from, method invocations (local variables)**
  - **Holds state of each method invocation (its frame or environment)**
  - **Each stack word holds 32 bits (4 bytes)**
- **Bytecoded Instructions: one or more bytes that represent an instruction**
- **Support for operands of different sizes, 8, 16, 32 fixed, 32, 64 floating, strings, arrays, ...**

JAM-16

- JAM-16 = "Java Abstract Machine - 16 bit version"
  - Too hard to say JVM-16
- Similarities to JVM
  - Same four registers
  - Subset of same bytecodes
  - Still stack oriented
- Differences from JVM
  - No heap
  - Only single stack which holds multiple method areas
  - All registers, objects only 16 bits wide
  - No floating point, extended precision operations
  - 16 bit integer subset selected
  - All addresses only 16 bits; Memory space limited to 65K locations
  - Method call/return somewhat simplified
  - Only simple objects supported

JAM-16 Memory Model



vars=pointer to arguments and local variables

frame=pointer to state info for current method

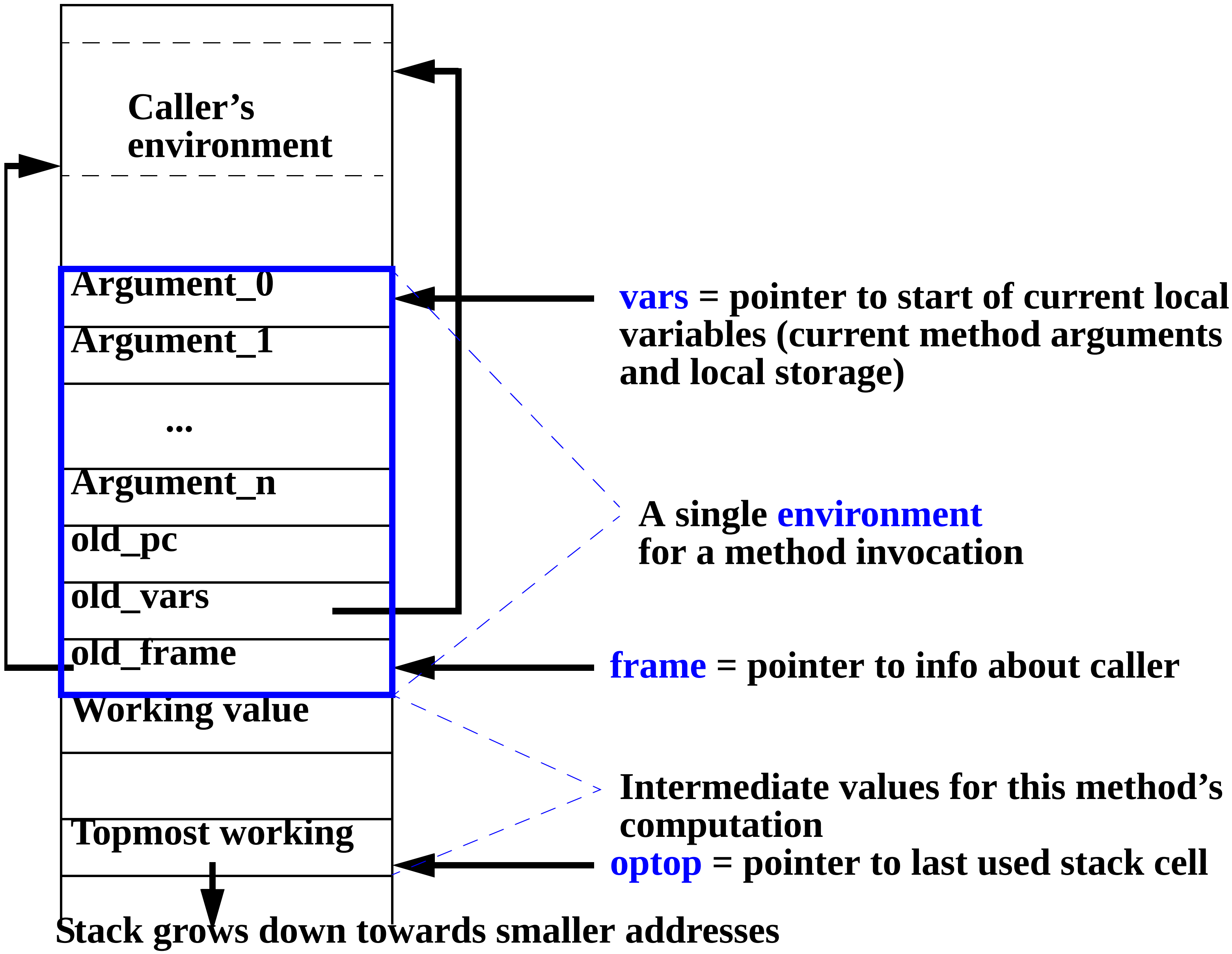
optop=pointer to top of stack

“Pushing” involves decrementing optop

“Popping” involves incrementing optop

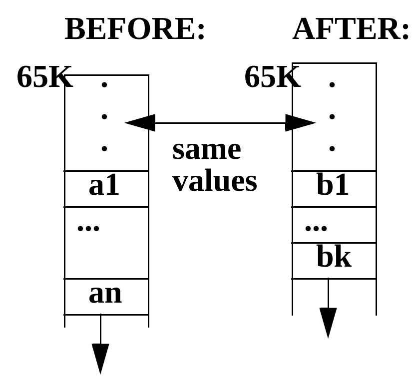
pc=pointer to next bytecoded instruction

JAM-16 Method Stack Environment



JAM-16 Instruction Descriptions

- Each instruction includes:
  - Bytecode (in binary and hexadecimal)
  - Mnemonic
  - Description: English, stack, RTL
  - Instructions of form “<mnemonic> #” mean a bytecoded instruction followed by an 8 bit integer *used for address or data)
- Mnemonic is followed by footnotes:
  - “1” => same opcode and semantics as JVM
  - “2” => operand value is only 8 bits
  - “3” => “#”(2nd byte) is 1, not 2, bytes long (JVM has 2 bytes)
  - “4” => same opcode , but slightly different semantics from JVM
  - “5” => new instruction not present in JVM
- “Stack notation” used in bytecode descriptions:
  - ..., a1, a2, ... an => ..., b1, b2, ... bk
  - Left of => is stack before instruction is executed
  - Right of => is stack after instruction is executed
  - top n values are replaced by k results



JAM-8: Basic Stack “Push” Operations

<table>
<tr><th>Bytecode</th><th>Mnemonic</th><th>English/Stack/RTL</th></tr>
<tr><td>00010000
0x10</td><td>bipush #
1</td><td>Push a one byte constant to stack
... => ..., #
optop--; M(optop)<-M(pc+1); pc<-pc+2</td></tr>
<tr><td>01011001
0x59</td><td>dup
1</td><td>Duplicate top element of stack
..., value => ..., value, value
M(optop-1)<-M(optop); optop-- || pc++</td></tr>
<tr><td>00010101
0x15</td><td>iload #
1,2</td><td>Push local variable # to stack
... => ..., Local_variable_#
M(optop-1)<-M(vars-#); optop--; pc<-pc+2</td></tr>
<tr><td>11111110
0xFE</td><td>rload
5</td><td>Load using top of stack as address
..., adr => ..., M(adr)
M(optop)<-M(M(optop)); pc++</td></tr>
<tr><td>00011001
0x19</td><td>aload #
4</td><td>Push address of local var # to stack
... => ..., vars-#
optop--; M(optop)<-vars-#; pc<-pc+2</td></tr>
</table>

Basic Stack "Pop" Operations

Bytecode	Mnemonic	Stack/RTL
00110110 0x36	istore # 1,2	Pop stack to local variable # ..., value => ... M(vars-#)<-M(optop++); pc<-pc+2
111111110x FF	rstore 5	Pop stack top to memory ..., adr, value => ... M(M(optop+1))<-M(optop); optop<-optop+2; pc++
01010111 0x57	pop 1	Pop top value off of stack and discard ..., value => ... optop++ || pc++

Basic Computational Operations

Bytecode	Mnemonic	Stack/RTL
01100000 **0x60**	**iadd** **1,2**	**Add top two elements on stack** **..., value1, value2 => result** **M(optop+1)<-M(optop+1)+M(optop); optop++; pc++**
01100100 **0x64**	**isub** **1,2**	**Subtract top two elements on stack** **..., value1, value2 => result** **M(optop+1)<-M(optop+1)-M(optop); optop++; pc++**
01111111 **0x7E**	**iand** **1,2**	**And top two elements on stack** **..., value1, value2 => result** **M(optop+1)<-M(optop+1) and M(optop); optop++; pc++**
10000000 **0x80**	**ior** **1,2**	**Or top two elements on stack** **..., value1, value2 => result** **M(optop+1)<-M(optop+1) or M(optop); optop++; pc++**
10000100 **0x84**	**iinc #1,#2** **1,2**	**Increment local variable #1 by #2** **... => ...** **M(vars-#1)<-M(vars-#1)+#2; pc<-pc+3**
01011111 **0x5F**	**swap** **1**	**Swap top two values** **..., value1, value2 => ..., value 2, value1** **temp<-M(optop); M(optop)<-M(optop+1);** **M(optop+1)<-temp; pc++**

Basic Transfer of Control

Bytecode	Mnemonic	Stack/RTL
10100111 0xA7	goto # 1,3	go to # ... => ... PC<-#
10011001 0x99	ifeq # 1,3	if top of stack=0 then go to # ..., value => ... if M(optop++)=0 then PC<-# else PC<-PC+2
10011010 0x9A	ifne # 1,3	if top of stack<>0 then go to # ..., value => ... if M(optop++)<>0 then PC<-# else PC<-PC+2;
10011011 0x9B	iflt # 1,3	if top of stack<0 then go to # ..., value => ... if M(optop++)<0 then PC<-# else PC<-PC+2;
10011100 0x9C	ifge # 1,3	if top of stack>=0 then go to # ..., value => ... if M(optop++)>=0 then PC<-# else PC<-PC+2;
11001010 0xCA	breakpoint 4	wait until external signal ... => ... when “go” goes from 0 to 1 then continue

Basic Method (Procedure) Invocation

Bytecode	Mnemonic	Stack/RTL
10101000 0xA8	**jsr # 1,3**	**Jump to subroutine at # ... => ..., return_address M(optop-1)<-PC+2;optop--||PC<-#**
10101001 0xA9	**ret 4**	**return from subroutine ..., return_address => ... pc<-M(optop++)**
10111000 0xB8	**invoke # 4**	**call new method ... => ..., “space,” old_pc, old_vars, old_frame optop<-optop-M(#); M(optop)<-pc+2; M(optop-1)<-vars; vars<-optop+M(#+1); M(optop-2)<-frame; frame<-optop-2; pc<-#+2; optop<-optop-2;**
10101100 0xAC	**ireturn 1,2**	**return value to calling method ..., value => “stack as of last invoke,” value M(vars)<-M(optop); optop<-vars; pc<-M(frame+2); vars<-M(frame+1); frame<-M(frame)**

JAM-16 at Reset

- **pc<-0; vars<-0; frame<-0; optop<-0**
- **Program execution starts at location 0**
- **First push of any value goes to location 65,535 (0xFF) - top of memory**
- **To allocate space for “global” variables, need an early “invoke”**

0: invoke 3 (Note: this uses the two numbers at 3 as constants to set up stack space)

2: breakpoint

3: n+1 (a magic constant) where n=amount of storage for global variables; see “invoke”

4: n

5: start of main program - can now reference local vars

Compilation

- **Constant value accessing: “bipush #” to place on stack**
- **Variable value accessing:**
  - **Local variable: “iload #” or “istore #” to move value to/from stack and “#” argument in current stack frame**
  - **Static/Global variable: “rload” or “rstore” use value on the stack as an address**
- **Expression evaluation: convert expression into “Reverse Polish”**
  - **Eg. A + (B and (C - D)) => A B C D - and +**
  - **Generate code from left to right: vars -> iloads, ops -> bytecodes**
  - **Eg. A B C D - and + => iload A; iload B; iload C; iload D; sub; and; add;**
- **“If <expr1> <comparator> <expr2> then <then_code> else <else_code>:**
  - **Assume <comparator> is = or !=**
  - **Compile <expr1> to leave value on stack**
  - **Compile <expr2> to leave value on stack**
  - **“sub”**
  - **“ifeq” or “ifne” # where # is address of start of else code**
  - **Compile <then_code>, followed by “goto #” where # is after <else>**
  - **Compile <else_code>**

Compilation (Continued)

- **while <expr1> <comparator> <expr2> do <while_body>**
  - **"goto" # where # is address of start of condition**
  - **Compile <while_body>**
  - **Compile <expr1>**
  - **Compile <expr2>**
  - **"ifeq" or "ifne" with #, where # is address of start of <while_body>**
- **Simple procedure call**
  - **"jsr #" to save pc on stack and go to #. frame, vars unchanged**
  - **In body of procedure, for return use "ret"**
- **Method/Function call with arguments/local definitions: foo(a0, ... an)**
  - **Compile each argument ai to leave value on stack, in order 0, ... n**
  - **"invoke #" where # is address of start of procedure**
- **Function/method body**
  - **At entry, first byte has value = # of extra local storage needed +1**
  - **Next is a byte with value = # arguments + # local storage**
  - **Following this is start of code for body of method**
  - **At completion, top of stack has return value, do "ireturn"**

Sample Program

```
char n, m;
char temp[10];
main()
{   initarray();
     m=total(1, 5, &temp[0]);
}

void initarray(void); // initialize global array temp
{   n=0;
    while (n != 10)
        {temp[n]=n;
        n++}
}

byte total(char n, char m, char *ptr);
char sum=0; char i; // Sum up elements of input array from n to m
{
    for (i=n; i != m; i++)
        sum=sum+*(ptr+i);
     return sum}
```

Sample Compilation

```
int n, m;
int temp[10];
    0: invoke 3 // initial call to establish storage for globals
    2: breakpoint // this is here to stop the machine if it runs amok
    3: 24 //space for n,m, and 10 array elts
         // note that n is local 0, m is local 2, temp starts at local 4
    4: 24 // magic constant needed by invoke
main (void)
initarray;
    5: jsr 18 // call initarray without building new context
m=total(1, 5, &temp[0]);
    7: bipush 1 // first argument
    9: bipush 5 // second argument
    11: aload 2 // third argument - address of temp[0]
    13: invoke 43 // call total with new frame
    15: istore 1 // save returned value in m
    17: breakpoint // our instruction to stop after main program is done
}
```

Sample Compilation (page 2)

```
void initarray(void);// start initarray next
{    n=0;
     18: bipush 0 // write 0 into n
     20: istore 0
while (n != 10)
     22: goto 35 // jump to the loop test
{temp[n]=n;
     24: aload 2 // compute address of temp[n]
     26: iload 0
     28: isub
     29: iload 0 // get value of n
     31: rstore // store n into temp(n)
n++} }
     32: iinc 0,1 // increment n by 1
     35: iload 0 // start of the loop test
     37: bipush 10
     39: isub
     40: ifne 24 // if loop continues, branch backwards to loop body
     42: ret // return from initarray
```

Sample Compilation (page 3)

```
byte total(char n, char m, char *ptr);
char sum=0; char i;
    43: 3 // 2 local variables
    44: 5 // 3 arguments + 2 local vars
    45: bipush 0 // initial value for sum
    47: istore 3 // store it in sum
for (i=n; i != m; i++) sum=sum+&(ptr+i);
    49: iload 0 // get the local n
    51: istore 4 // store in local i
    53: goto 69 // enter the test code
    55: iload 3 // get sum
    57: iload 2 // get pointer to array
    59: iload 4 // get i
    61: isub // compute address of array
    62: rload // get value of array location
    63: iadd // compute new sum
    64: istore 3 // and update sum
    66: iinc 4,1 // increment i by 1
    69: iload 4 // get i. start of loop test
    71: iload 1 // get m
    73: isub
    75: ifne 55 // return to loop start
return sum}
    77: iload 3
    79: ireturn
```

Layers in the ISA

"Simple 12" equivalent ISA

- **bipush**
- **rload**
- **rstore**
- **iadd**
- **isub**
- **iand**
- **ior**
- **goto**
- **ifeq**
- **iflt**

Minimal "Java" extensions

- **invoke**
- **ireturn**
- **aload**

"Java" enhancements

- **iload**
- **istore**

Basic computing enhancements:

- **jsr**
- **ret**

Additional enhancements

- **ifne**
- **ifgt**
- **swap**
- **dup**
- **pop**
- **iinc**

JAM-8