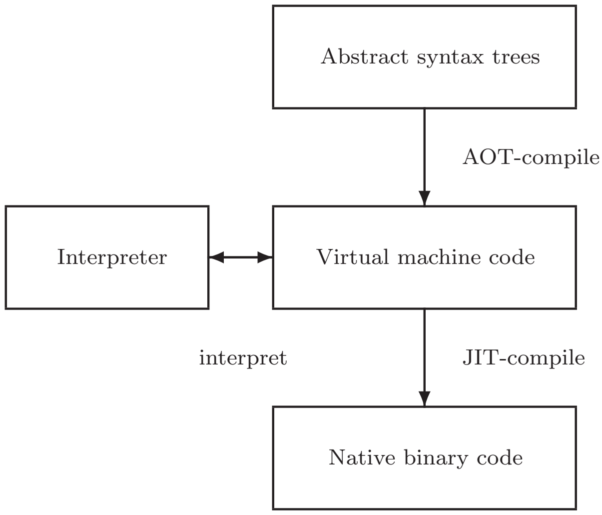
Virtual machines

Compilation and execution modes of Virtual machines:



Compilers traditionally compiled to machine code ahead-of-time (AOT).

Example:

- `gcc` translates into RTL (Register Transfer Language), optimizes RTL, and then compiles RTL into native code.

Advantages:

- can exploit many details of the underlying architecture; and
- intermediate languages like RTL facilitate production of code generators for many target architectures.

Disadvantage:

- a code generator must be built for each target architecture.

Interpreting virtual machine code.

Examples:

- P-code for early Pascal interpreters;
- Postscript for display devices; and
- Java bytecode for the Java Virtual Machine.

Advantages:

- easy to generate the code;
- the code is architecture independent; and
- bytecode can be more compact.

Disadvantage:

- poor performance due to interpretative overhead (typically 5-20 $\times$ slower).
  Reasons:
  - Every instruction considered in isolation,
  - confuses branch prediction,
  - ...and many more.

VirtualRISC is a simple RISC machine with:

- memory;
- registers;
- condition codes; and
- execution unit.

In this model we ignore:

- caches;
- pipelines;
- branch prediction units; and
- advanced features.

VirtualRISC memory:

- a stack
  (used for function call frames);
- a heap
  (used for dynamically allocated memory);
- a global pool
  (used to store global variables); and
- a code segment
  (used to store VirtualRISC instructions).

VirtualRISC registers:

- unbounded number of general purpose registers;
- the stack pointer (`sp`) which points to the top of the stack;
- the frame pointer (`fp`) which points to the current stack frame; and
- the program counter (`pc`) which points to the current instruction.

VirtualRISC condition codes:

- stores the result of last instruction that can set condition codes (used for branching).

VirtualRISC execution unit:

- reads the VirtualRISC instruction at the current `pc`, decodes the instruction and executes it;
- this may change the state of the machine (memory, registers, condition codes);
- the `pc` is automatically incremented after executing an instruction; but
- function calls and branches explicitly change the `pc`.

Memory/register instructions:

```
st Ri,[Rj]          [Rj] := Ri
st Ri,[Rj+C]        [Rj+C] := Ri

ld [Ri],Rj          Rj := [Ri]
ld [Ri+C],Rj        Rj := [Ri+C]
```

Register/register instructions:

```
mov Ri,Rj           Rj := Ri
add Ri,Rj,Rk        Rk := Ri + Rj
sub Ri,Rj,Rk        Rk := Ri - Rj
mul Ri,Rj,Rk        Rk := Ri * Rj
div Ri,Rj,Rk        Rk := Ri / Rj
...
```

Constants may be used in place of register values: `mov 5,R1`.

Instructions that set the condition codes:

```
cmp Ri,Rj
```

Instructions to branch:

```
b L
bg L
bge L
bl L
ble L
bne L
```

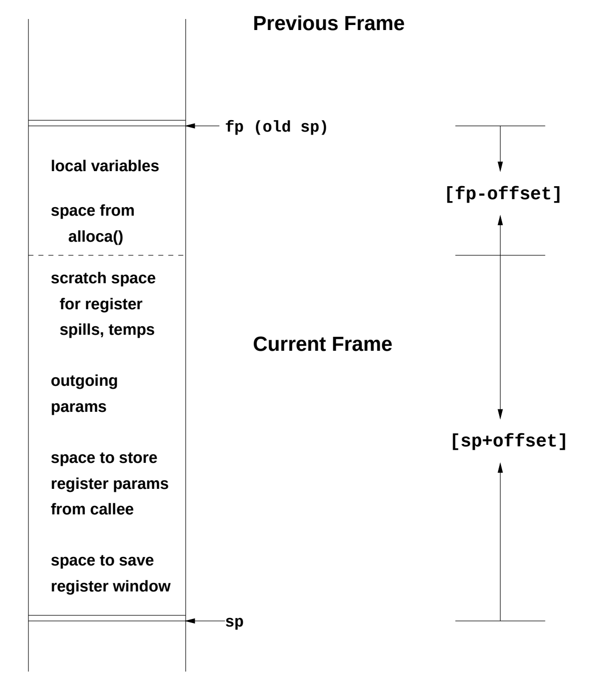
To express: `if R1 <= 9 goto L1`

we code:

```
cmp R1,9
ble L1
```


Other instructions:

```
save sp,-C,sp       save registers,
                    allocating C bytes
                    on the stack
call L              R15:=pc; pc:=L
restore             restore registers
ret                 pc:=R15+8
nop                 do nothing
```

Stack frames:

- stores function activations;
- `sp` and `fp` point to stack frames;
- when a function is called a new stack frame is created:
  `push fp; fp := sp; sp := sp + C;`
- when a function returns, the top stack frame is popped:
  `sp := fp; fp = pop;`
- local variables are stored relative to `fp`;
- the figure shows additional features of the SPARC architecture.

A simple C function:

```
int fact(int n)
{ int i, sum;
  sum = 1;
  i = 2;
  while (i <= n)
    { sum = sum * i;
      i = i + 1;
    }
  return sum;
}
```


Corresponding VirtualRISC code:

```
_fact:
  save sp,-112,sp   // save stack frame
  st R0,[fp+68]     // save input arg n in frame of CALLER
  mov 1,R0          // R0 := 1
  st R0,[fp-16]     // [fp-16] is location for sum
  mov 2,R0          // RO := 2
  st R0,[fp-12]    // [fp-12] is location for i
L3:
  ld [fp-12],R0     // load i into R0
  ld [fp+68],R1     // load n into R1
  cmp R0,R1         // compare R0 to R1
  ble L5            // if R0 <= R1 goto L5
  b L4              // goto L4
L5:
  ld [fp-16],R0     // load sum into R0
  ld [fp-12],R1     // load i into R1
  mul R0,R1,R0      // R0 := R0 * R1
  st R0,[fp-16]     // store R0 into sum
  ld [fp-12],R0     // load i into R0
  add R0,1,R1       // R1 := R0 + 1
  st R1,[fp-12]     // store R1 into i
  b L3              // goto L3
L4:
  ld [fp-16],R0     // put return value of sum into R0
  restore           // restore register window
  ret               // return from function
```


Java Virtual Machine has:

- memory;
- registers;
- condition codes; and
- execution unit.

Java Virtual Machine memory:

- a stack
  (used for function call frames);
- a heap
  (used for dynamically allocated memory);
- a constant pool
  (used for constant data that can be shared); and
- a code segment
  (used to store JVM instructions of currently loaded class files).

Java Virtual Machine registers:

- no general purpose registers;
- the stack pointer (`sp`) which points to the top of the stack;
- the local stack pointer (`lsp`) which points to a location in the current stack frame; and
- the program counter (`pc`) which points to the current instruction.

Java Virtual Machine condition codes:

- stores the result of last instruction that can set condition codes (used for branching).

Java Virtual Machine execution unit:

- reads the Java Virtual Machine instruction at the current `pc`, decodes the instruction and executes it;
- this may change the state of the machine (memory, registers, condition codes);
- the `pc` is automatically incremented after executing an instruction; but
- method calls and branches explicitly change the `pc`.

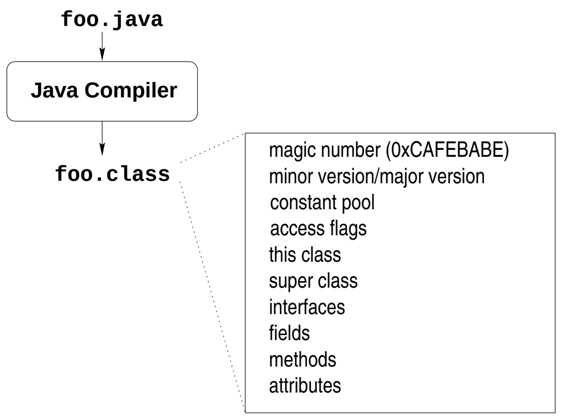
Java Virtual Machine stack frames have space for:

- a reference to the current object (`this`);
- the method arguments;
- the local variables; and
- a local stack used for intermediate results.

The number of local slots and the maximum size of the local stack are fixed at compile-time.

Java compilers translate source code to class files.

Class files include the bytecode instructions for each method.



A simple Java method:

```
public int Abs(int x)
{ if (x < 0)
    return(x * -1);
  else
    return(x);
}
```

Corresponding bytecode (in Jasmin syntax):

```
.method public Abs(I)I // one int argument, returns an int
.limit stack 2         // has stack with 2 locations
.limit locals 2        // has space for 2 locals

                       // --locals--  --stack---
                       // [ o -3 ]     [  *  * ]
  iload_1              // [ o -3 ]     [ -3  * ]
  ifge Label1          // [ o -3 ]     [  *  * ]
  iload_1              // [ o -3 ]     [ -3  * ]
  iconst_m1            // [ o -3 ]     [ -3 -1 ]
  imul                 // [ o -3 ]     [  3  * ]
  ireturn              // [ o -3 ]     [  *  * ]
Label1:
  iload_1
  ireturn
.end method
```

Comments show trace of `o.Abs(-3)`.

A sketch of a bytecode interpreter:

```
pc = code.start;
while(true)
  {  npc = pc + instruction_length(code[pc]);
     switch (opcode(code[pc]))
       {  case ILOAD_1: push(local[1]);
                        break;
          case ILOAD:   push(local[code[pc+1]]);
                        break;
          case ISTORE:  t = pop();
                        local[code[pc+1]] = t;
                        break;
          case IADD:    t1 = pop();  t2 = pop();
                        push(t1 + t2);
                        break;
          case IFEQ:    t = pop();
                        if (t == 0) npc = code[pc+1];
                        break;
          ...
       }
     pc = npc;
  }
```


Unary arithmetic operations:

```
ineg      [...:i] -> [...:-i]
i2c       [...:i] -> [...:i%65536]
```

Binary arithmetic operations:

```
iadd      [...:i1:i2] -> [...:i1+i2]
isub      [...:i1:i2] -> [...:i1-i2]
imul      [...:i1:i2] -> [...:i1*i2]
idiv      [...:i1:i2] -> [...:i1/i2]
irem      [...:i1:t2] -> [...:i1%i2]
```

Direct operations:

```
iinc k a  [...]  -> [...]
          local[k]=local[k]+a
```

Nullary branch operations:

```
goto L        [...]  -> [...]
              branch always
```

Unary branch operations:

```
ifeq L        [...:i] -> [...]
              branch if i == 0
ifne L        [...:i] -> [...]
              branch if i != 0

ifnull L      [...:o] -> [...]
              branch if o == null
ifnonnull L   [...:o] -> [...]
              branch if o != null
```


Binary branch operations:

```
if_icmpeq L   [...:i1:i2] -> [...]
              branch if i1 == i2
if_icmpne L   [...:i1:i2] -> [...]
              branch if i1 != i2
if_icmpgt L   [...:i1:i2] -> [...]
              branch if i1 > i2
if_icmplt L   [...:i1:i2] -> [...]
              branch if i1 < i2
if_icmple L   [...:i1:i2] -> [...]
              branch if i1 <= i2
if_icmpge L   [...:i1:i2] -> [...]
              branch if i1 >= i2

if_acmpeq L   [...:o1:o2] -> [...]
              branch if o1 == o2
if_acmpne L   [...:o1:o2] -> [...]
              branch if o1 != o2
```


Constant loading operations:

```
iconst_0      [...]  -> [...:0]
iconst_1      [...]  -> [...:1]
iconst_2      [...]  -> [...:2]
iconst_3      [...]  -> [...:3]
iconst_4      [...]  -> [...:4]
iconst_5      [...]  -> [...:5]

aconst_null   [...]  -> [...:null]

ldc_int i     [...]  -> [...:i]
ldc_string s  [...]  -> [...:String(s)]
```


Locals operations:

```
iload k         [...]  -> [...:local[k]]
istore k        [...:i] -> [...]
                local[k]=i

aload k         [...]  -> [...:local[k]]
astore k        [...:o] -> [...]
                local[k]=o
```

Field operations:

```
getfield f sig  [...:o] -> [...:o.f]
putfield f sig  [...:o:v] -> [...]
                o.f=v
```

Stack operations:

```
dup         [...:v1] -> [...:v1:v1]
pop         [...:v1] -> [...]
swap        [...:v1:v2] -> [...:v2:v1]
nop         [...]  -> [...]
```


Class operations:

```
new C           [...]  -> [...:o]

instance_of C   [...:o] -> [...:i]
                if (o==null) i=0
                else i=(C<=type(o))

checkcast C     [...:o] -> [...:o]
                if (o!=null && !C<=type(o))
                throw ClassCastException
```


Method operations:

```
invokevirtual m sig
     [...:o:a_1:...:a_n] -> [...]

//overloading already resolved:
// signature of m is known!
entry=lookupHierarchy(m,sig,class(o));
block=block(entry);
push stack frame of size
     block.locals+block.stacksize;
local[0]=o; //local points to
local[1]=a_1; //beginning of frame
...
local[n]=a_n;
pc=block.code;
```


Method operations:

```
invokespecial m sig
     [...:o:a_1:...:a_n] -> [...]

//overloading already resolved:
// signature of m is known!
entry=lookupClassOnly(m,sig,class(o));
block=block(entry);
push stack frame of size
     block.locals+block.stacksize;
local[0]=o; //local points to
local[1]=a_1; //beginning of frame
...
local[n]=a_n;
pc=block.code;
```

For which method calls is `invokespecial` used?

Method operations:

```
ireturn     [...:<frame>:i] -> [...:i]
            pop stack frame,
            push i onto frame of caller

areturn     [...:<frame>:o] -> [...:o]
            pop stack frame,
            push o onto frame of caller

return      [...:<frame>] -> [...]
            pop stack frame
```

Those operations also release locks in `synchronized` methods.

A Java method:

```
public boolean member(Object item)
{ if (first.equals(item))
    return true;
  else if (rest == null)
    return false;
  else
    return rest.member(item);
}
```


Corresponding bytecode (in Jasmin syntax):

```
.method public member(Ljava/lang/Object;)Z
.limit locals 2           // local[0] = o
                          // local[1] = item
.limit stack 2            // initial stack [ * * ]
aload_0                   // [ o * ]
getfield Cons/first Ljava/lang/Object;
                          // [ o.first *]
aload_1                   // [ o.first item]
invokevirtual java/lang/Object/equals(Ljava/lang/Object;)Z
                          // [ b * ] for some boolean b
ifeq else_1               // [ * * ]
iconst_1                  // [ 1 * ]
ireturn                   // [ * * ]
else_1:
aload_0                   // [ o * ]
getfield Cons/rest LCons; // [ o.rest * ]
aconst_null               // [ o.rest null]
if_acmpne else_2          // [ * * ]
iconst_0                  // [ 0 * ]
ireturn                   // [ * * ]
else_2:
aload_0                   // [ o * ]
getfield Cons/rest LCons; // [ o.rest * ]
aload_1                   // [ o.rest item ]
invokevirtual Cons/member(Ljava/lang/Object;)Z
                          // [ b * ] for some boolean b
ireturn                   // [ * * ]
.end method
```


Bytecode verification:

- bytecode cannot be trusted to be well-formed and well-behaved;
- before executing any bytecode, it should be verified, especially if that bytecode is received over the network;
- verification is performed partly at class loading time, and partly at run-time; and
- at load time, dataflow analysis is used to approximate the number and type of values in locals and on the stack.

Interesting properties of verified bytecode:

- each instruction must be executed with the correct number and types of arguments on the stack, and in locals (on all execution paths);
- at any program point, the stack is the same size along all execution paths;
- every method must have enough locals to hold the receiver object (except static methods) and the method's arguments; and
- no local variable can be accessed before it has been assigned a value.

Java class loading and execution model:

- when a method is invoked, a `ClassLoader` finds the correct class and checks that it contains an appropriate method;
- if the method has not yet been loaded, then it is verified (remote classes);
- after loading and verification, the method body is interpreted.
- If the method becomes executed multiple times, the bytecode for that method is translated to native code.
- If the method becomes hot, the native code is optimized.

The last two steps are very involved and companies like Sun and IBM have a thousand people working on optimizing these steps.

⇒ good for you! (why not 1001 people?)

Split-verification in Java 6+:

- Bytecode verification is easy but still polynomial, i.e. sometimes slow, and
- this can be exploited in denial-of-service attacks: `http://www.bodden.de/research/javados/`
- Java 6 (version 50.0 bytecodes) introduced `StackMapTable` attributes to make verification linear.
  - Java compilers know the type of locals at compile time.
  - Java 6 compilers store these types in the bytecode using `StackMapTable` attributes.
  - Speeds up construction of the "proof tree" ⇒ also called "Proof-Carrying Code"
- Java 7 (version 51.0 bytecodes) JVMs will enforce presence of these attributes.

Future use of Java bytecode:

- the JOOS compiler will produce Java bytecode in Jasmin format; and
- the JOOS peephole optimizer transforms bytecode into more efficient bytecode.

Future use of VirtualRISC:

- Java bytecode can be converted into machine code at run-time using a JIT (Just-In-Time) compiler;
- we will study some examples of converting Java bytecode into a language similar to VirtualRISC;
- we will study some simple, standard optimizations on VirtualRISC.