

Virtual Machine

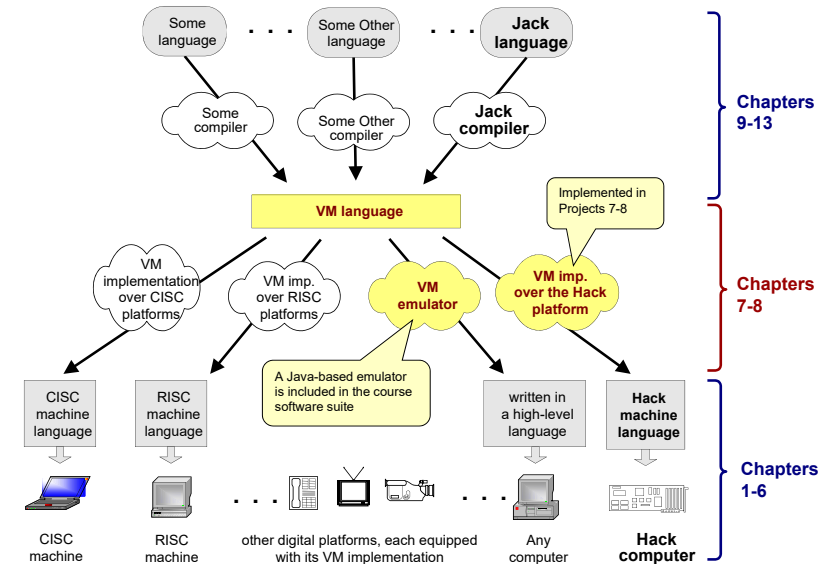
Part II: Program Control



Building a Modern Computer From First Principles

www.nand2tetris.org

The big picture



The VM language

Goal: Complete the specification and implementation of the VM model and language

Arithmetic / Boolean commands	Program flow commands
add	label (declaration)
sub	goto (label)
neg	if-goto (label)
eq	
gt	
lt	
and	
or	
not	
Memory access commands	Function calling commands
pop x (pop into x, which is a variable)	function (declaration)
push y (y being a variable or a constant)	call (a function)
	return (from a function)

Method: (a) specify the abstraction (model's constructs and commands)
(b) propose how to implement it over the Hack platform.

The compilation challenge

Source code (high-level language)

```
class Main {
    static int x;

    function void main() {
        // Inputs and multiplies two numbers
        var int a, b, c;
        let a = Keyboard.readInt("Enter a number");
        let b = Keyboard.readInt("Enter a number");
        let c = Keyboard.readInt("Enter a number");
        let x = solve(a,b,c);
        return;
    }

    // Solves a quadratic equation (sort of)
    function int solve(int a, int b, int c) {
        var int x;
        if (~(a = 0))
            x = (-b + sqrt(b*b - 4*a*c)) / (2*a);
        else
            x = -c/b;
        return x;
    }
}
```

Our ultimate goal:
Translate high-level programs into executable code.

Compiler

Target code

```
000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
0000000000010010
1110001100000001
0000000000010000
1111110000010000
0000000000010001
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111100000010000
0000000000000000
1111010011010000
0000000000010010
1110001100000001
0000000000010000
1111110000010000
0000000000010001
...
```

The compilation challenge / two-tier setting

Jack source code

```
if (~ (a = 0))
  x = (-b + sqrt(b*b - 4*a*c)) / (2*a)
else
  x = -c/b
```

Compiler

VM (pseudo) code

```
push a
push 0
eq
if-goto elseLabel
push b
neg
push b
push b
call mult
push 4
push a
call mult
push c
call mult
call sqrt
add
push 2
push a
call mult
div
pop x
goto contLabel
elseLabel:
push c
neg
push b
call div
pop x
contLabel:
```

VM translator

Machine code

```
0000000000000000
111011111001000
0000000000000001
1110101010001000
0000000000000000
1111110000010000
0000000000000000
111010011010000
0000000000010010
1110001100000001
0000000000010000
111110000010000
0000000000010001
0000000000010000
111011111001000
0000000000010010
1110101010001000
0000000000010000
111110000010000
0000000000000000
111010011010000
0000000000010010
1110001100000001
0000000000010000
111110000010000
0000000000010001
0000000000010010
1110001100000001
...
```

- ❑ We'll develop the compiler later in the course
- ❑ We now turn to describe how to complete the implementation of the VM language
- ❑ That is -- how to translate each VM command into assembly commands that perform the desired semantics.

The compilation challenge

Typical compiler's source code input:

```
// Computes x = (-b + sqrt(b^2 - 4*a*c)) / 2*a
if (~ (a = 0))
  x = (-b + sqrt(b * b - 4 * a * c)) / (2 * a)
else
  x = - c / b
```

program flow logic
(branching)

(this lecture)

Boolean
expressions

(previous lecture)

function call and
return logic

(this lecture)

arithmetic
expressions

(previous lecture)

How to translate such high-level code into machine language?

- In a two-tier compilation model, the overall translation challenge is broken between a *front-end* compilation stage and a subsequent *back-end* translation stage
- In our Hack-Jack platform, all the above sub-tasks (handling arithmetic / Boolean expressions and program flow / function calling commands) are done by the back-end, i.e. by the VM translator.

Lecture plan

Arithmetic / Boolean commands

```
add
sub
neg
eq
gt
lt
and
or
not
```

Memory access commands

```
pop x (pop into x, which is a variable)
push y (y being a variable or a constant)
```

Chapter 7

Program flow commands

```
label (declaration)
goto (label)
if-goto (label)
```

Function calling commands

```
function (declaration)
call (a function)
return (from a function)
```

Program flow commands in the VM language

VM code example:

```
function mult 1
  push constant 0
  pop local 0
label loop
  push argument 0
  push constant 0
  eq
  if-goto end
  push argument 0
  push 1
  sub
  pop argument 0
  push argument 1
  push local 0
  add
  pop local 0
  goto loop
label end
  push local 0
  return
```

In the VM language, the program flow abstraction is delivered using three commands:

```
label c // label declaration
goto c // unconditional jump to the
// VM command following the label c
if-goto c // pops the topmost stack element;
// if it's not zero, jumps to the
// VM command following the label c
```

How to translate these abstractions into assembly?

- ❑ Simple: label declarations and goto directives can be effected directly by assembly commands
- ❑ More to the point: given any one of these three VM commands, the VM Translator must emit one or more assembly commands that effects the same semantics on the Hack platform
- ❑ How to do it? see project 8.

Flow of control

pseudo code

```
if (cond)
  statement1
else
  statement2
```

VM code

```
~cond
if-goto elseLabel
statement1
goto contLabel
label elseLabel
statement2
label contLabel
```

Flow of control

pseudo code

```
while (cond)
  statement
...
```

VM code

```
label contLabel
~(cond)
if-goto exitLabel
statement
goto contLabel
label exitLabel
...
```

Lecture plan

Arithmetic / Boolean commands

```
add
sub
neg
eq
gt
lt
and
or
not
```

previous
lecture

Memory access commands

```
pop x (pop into x, which is a variable)
push y (y being a variable or a constant)
```

Program flow commands

```
label (declaration)
goto (label)
if-goto (label)
```

Function calling commands

```
function (declaration)
call (a function)
return (from a function)
```

Subroutines

```
// Compute  $x = (-b + \sqrt{b^2 - 4ac}) / 2a$ 
if ~(a = 0)
   $x = (-b + \text{sqrt}(b * b - 4 * a * c)) / (2 * a)$ 
else
   $x = -c / b$ 
```

Subroutines = a major programming artifact

- Basic idea: the given language can be extended at will by user-defined commands (aka *subroutines* / *functions* / *methods* ...)
- Important: the language's primitive commands and the user-defined commands have the same look-and-feel
- This transparent extensibility is the most important abstraction delivered by high-level programming languages
- The challenge: implement this abstraction, i.e. allow the program control to flow effortlessly between one subroutine to the other

Subroutines in the VM language

Calling code, aka "caller" (example)

```
...
// computes (7 + 2) * 3 - 5
push constant 7
push constant 2
add
push constant 3
call mult
push constant 5
sub
...
```

VM subroutine
call-and-return
commands

Called code, aka "callee" (example)

```
function mult 1
  push constant 0
  pop local 0 // result (local 0) = 0
  label loop
  push argument 0
  push constant 0
  eq
  if-goto end // if arg0==0, jump to end
  push argument 0
  push 1
  sub
  pop argument 0 // arg0--
  push argument 1
  push local 0
  add
  pop local 0 // result += arg1
  goto loop
label end
push local 0 // push result
return
```

Subroutines in the VM language

The invocation of the VM's primitive commands and subroutines follow exactly the same rules:

- ❑ The caller pushes the necessary argument(s) and calls the command / function for its effect
- ❑ The callee is responsible for removing the argument(s) from the stack, and for popping onto the stack the result of its execution.

What behind subroutines

The following scenario happens

- ❑ The caller pushes the necessary arguments and call callee
- ❑ The state of the caller is saved
- ❑ The space of callee's local variables is allocated
- ❑ The callee executes what it is supposed to do
- ❑ The callee removes all arguments and pushes the result to the stack
- ❑ The space of the callee is recycled
- ❑ The caller's state is reinstalled
- ❑ Jump back to where is called

Stack as the facility for subroutines

code

```
function a
  call b
  call c
  ...

function b
  call c
  call d
  ...

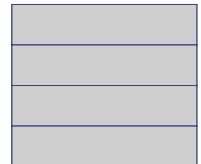
function c
  call d
  ...

function d
  ...
```

flow

```
start a
  start b
    start c
      start d
        end d
      end c
    end b
  start c
    start d
      end d
    end c
  end a
```

stack



Function commands in the VM language

```
function g nVars // here starts a function called g,
                  // which has nVars local variables

call g nArgs      // invoke function g for its effect;
                  // nArgs arguments have already been pushed
                  // onto the stack

return            // terminate execution and return control
                  // to the caller
```

Q: Why this particular syntax?

A: Because it simplifies the VM implementation (later).

Function call-and-return conventions

Calling function

```
function demo 3
...
push constant 7
push constant 2
add
push constant 3
call mult
...
```

called function aka "callee" (example)

```
function mult 1
  push constant 0
  pop local 0 // result (local 0) = 0
label loop
  ...          // rest of code omitted
label end
  push local 0 // push result
  return
```

Although not obvious in this example, every VM function has a private set of 5 memory segments (local, argument, this, that, pointer)

These resources exist as long as the function is running.

Function call-and-return conventions

Calling function

```
function demo 3
...
push constant 7
push constant 2
add
push constant 3
call mult
...
```

called function aka "callee" (example)

```
function mult 1
  push constant 0
  pop local 0 // result (local 0) = 0
label loop
  ...          // rest of code omitted
label end
  push local 0 // push result
  return
```

Call-and-return programming convention

- ❑ The caller must push the necessary argument(s), call the callee, and wait for it to return
- ❑ Before the callee terminates (returns), it must push a return value
- ❑ At the point of return, the callee's resources are recycled, the caller's state is re-instated, execution continues from the command just after the call
- ❑ **Caller's net effect:** the arguments were replaced by the return value (just like with primitive commands)

Function call-and-return conventions

Calling function

```
function demo 3
...
push constant 7
push constant 2
add
push constant 3
call mult
...
```

called function aka "callee" (example)

```
function mult 1
  push constant 0
  pop local 0 // result (local 0) = 0
label loop
  ...          // rest of code omitted
label end
  push local 0 // push result
  return
```

Behind the scene

- ❑ Recycling and re-instating subroutine resources and states is a major headache
- ❑ Some agent (either the VM or the compiler) should manage it behind the scene "like magic"
- ❑ In our implementation, the magic is VM / stack-based, and is considered a great CS gem.

The function-call-and-return protocol

```
function g nVars
call g nArgs
return
```

The caller's view:

- Before calling a function *g*, I must push onto the stack as many arguments as needed by *g*
- Next, I invoke the function using the command `call g nArgs`
- After *g* returns:
 - ❑ The arguments that I pushed before the call have disappeared from the stack, and a return value (that always exists) appears at the top of the stack
 - ❑ All my memory segments (local, argument, this, that, pointer) are the same as before the call.

Blue = VM function writer's responsibility

Black = black box magic, delivered by the VM implementation

Thus, the VM implementation writer must worry about the "black operations" only.

The function-call-and-return protocol

```
function g nVars
call g nArgs
return
```

The callee's (*g*'s) view:

- When I start executing, my argument segment has been initialized with actual argument values passed by the caller
- My local variables segment has been allocated and initialized to zero
- The static segment that I see has been set to the static segment of the VM file to which I belong, and the working stack that I see is empty
- Before exiting, I must push a value onto the stack and then use the command `return`.

Blue = VM function writer's responsibility

Black = black box magic, delivered by the VM implementation

Thus, the VM implementation writer must worry about the "black operations" only.

The function-call-and-return protocol: the VM implementation view

When function *f* calls function *g*, the VM implementation must:

- ❑ Save the return address within *f*'s code: the address of the command just after the `call`
- ❑ Save the virtual segments of *f*
- ❑ Allocate, and initialize to 0, as many local variables as needed by *g*
- ❑ Set the local and argument segment pointers of *g*
- ❑ Transfer control to *g*.

```
function g nVars
call g nArgs
return
```

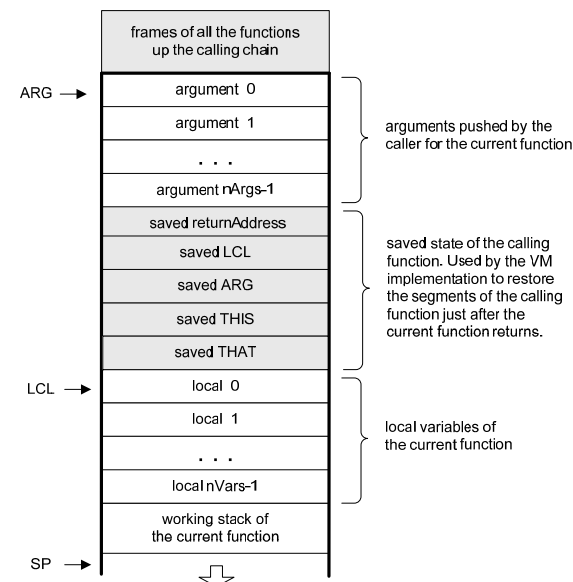
When *g* terminates and control should return to *f*, the VM implementation must:

- ❑ Clear *g*'s arguments and other junk from the stack
- ❑ Restore the virtual segments of *f*
- ❑ Transfer control back to *f* (jump to the saved return address).

Q: How should we make all this work "like magic"?

A: We'll use the stack cleverly.

The implementation of the VM's stack on the host Hack RAM



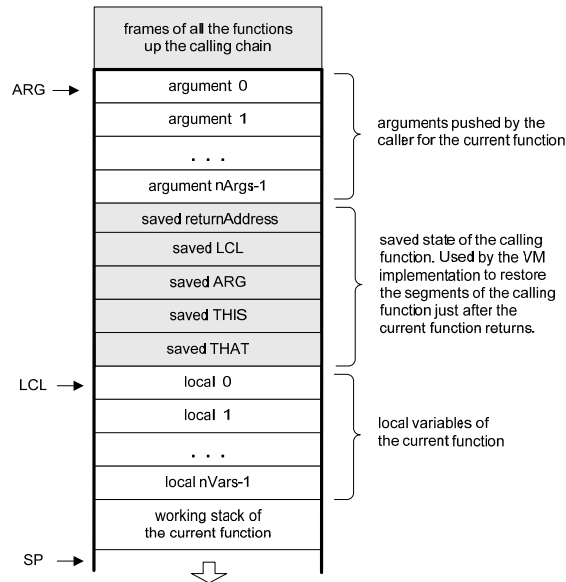
Global stack:

the entire RAM area dedicated for holding the stack

Working stack:

The stack that the current function sees

The implementation of the VM's stack on the host Hack RAM



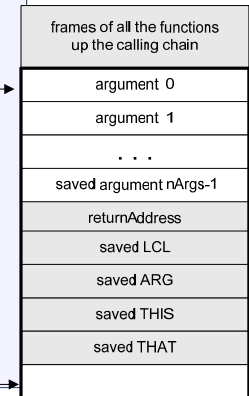
- At any point of time, only one function (the *current function*) is executing; other functions may be waiting up the calling chain
- Shaded areas: irrelevant to the current function
- The current function sees only the working stack, and has access only to its memory segments
- The rest of the stack holds the frozen states of all the functions up the calling hierarchy.

Implementing the `call g nArgs` command

`call g nArgs`

```
// In the course of implementing the code of f
// (the caller), we arrive to the command call g nArgs.
// we assume that nArgs arguments have been pushed
// onto the stack. What do we do next?
// We generate a symbol, let's call it returnAddress;
// Next, we effect the following logic:
push returnAddress // saves the return address
push LCL           // saves the LCL of f
push ARG           // saves the ARG of f
push THIS          // saves the THIS of f
push THAT          // saves the THAT of f
ARG = SP - nArgs - 5 // repositions SP for g
LCL = SP            // repositions LCL for g
goto g             // transfers control to g
returnAddress:      // the generated symbol
```

None of this code is executed yet ...
At this point we are just generating code (or simulating the VM code on some platform)



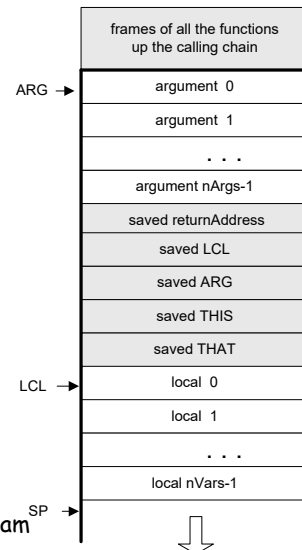
Implementation: If the VM is implemented as a program that translates VM code into assembly code, the translator must emit the above logic in assembly.

Implementing the `function g nVars` command

`function g nVars`

```
// to implement the command function g nVars,
// we effect the following logic:
```

```
g:
  repeat nVars times:
    push 0
```

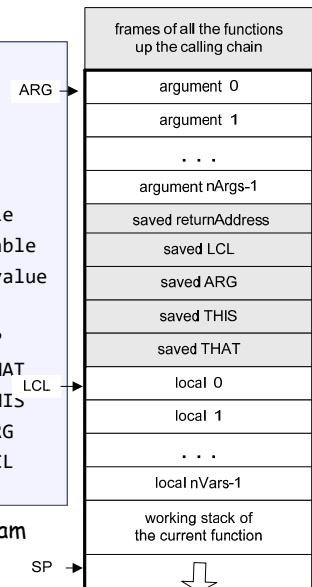


Implementation: If the VM is implemented as a program that translates VM code into assembly code, the translator must emit the above logic in assembly.

Implementing the `return` command

`return`

```
// In the course of implementing the code of g,
// we arrive to the command return.
// We assume that a return value has been pushed
// onto the stack.
// We effect the following logic:
frame = LCL // frame is a temp. variable
retAddr = *(frame-5) // retAddr is a temp. variable
*ARG = pop // repositions the return value
// for the caller
SP = ARG + 1 // restores the caller's SP
THAT = *(frame-1) // restores the caller's THAT
THIS = *(frame-2) // restores the caller's THIS
ARG = *(frame-3) // restores the caller's ARG
LCL = *(frame-4) // restores the caller's LCL
goto retAddr // goto returnAddress
```



Implementation: If the VM is implemented as a program that translates VM code into assembly code, the translator must emit the above logic in assembly.

Example: factorial

High-level code

```
function fact (n) {
  int result, j;
  result = 1;
  j = 1;
  while ((j=j+1) <= n) {
    result = result * j;
  }
  return result;
}
```

Pseudo code

```
...
loop:
  if ((j=j+1) > n) goto end
  result=result*j
  goto loop
end:
...
```

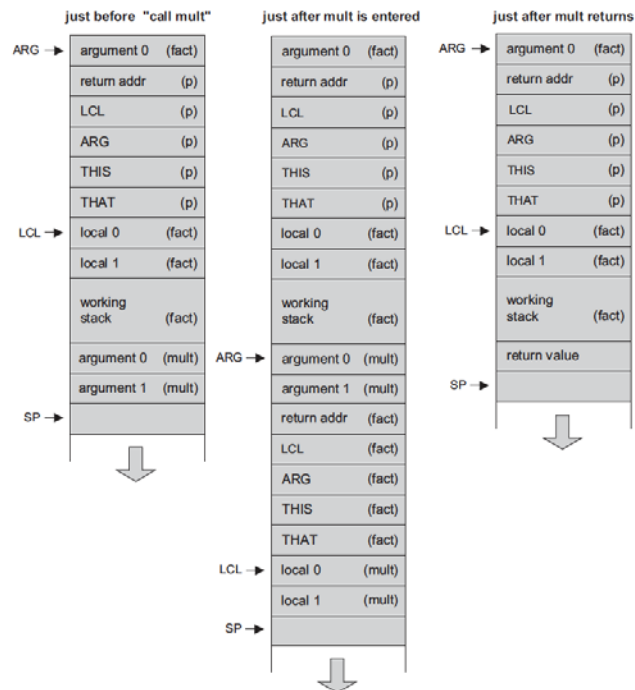
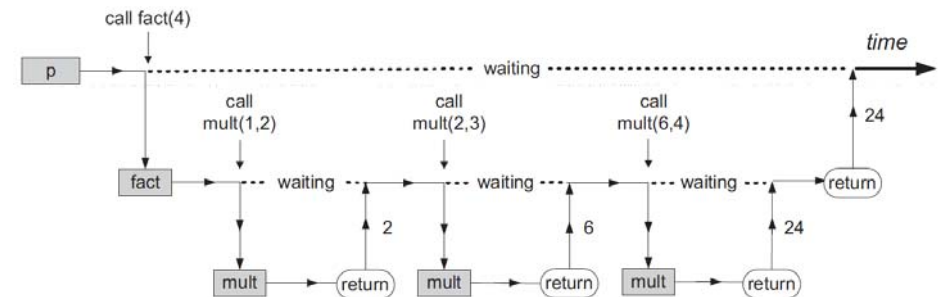
VM code (first approx.)

```
function fact(n)
  push 0
  pop result
  push 1
  pop j
  label loop
  push 1
  push j
  add
  pop j
  push n
  gt
  if-goto end
  push result
  push j
  mult
  pop result
  pop j
  goto loop
  label end
  push result
  return
```

VM code

```
function fact 2
  push constant 0
  pop local 0
  push constant 1
  pop local 1
  label loop
  push constant 1
  push local 1
  add
  pop local 1
  push argument 0
  gt
  if-goto end
  push local 0
  push local 1
  call mult 2
  pop local 0
  pop local 1
  goto loop
  label end
  push local 0
  return
```

```
function p
...
push constant 4
call fact 1
...
```



Example: factorial

High-level code

```
function fact (n) {
  int r;
  if (n!=1)
    r = n * fact(n-1);
  else
    r = 1;
  return r;
}
```

VM code (first approx.)

```
function fact(n)
  push n
  push 1
  eq
  if-goto else
  push n
  push 1
  sub
  fact
  push n
  mult
  pop r
  goto cont
  label else
  push 1
  pop r
  label cont
  push r
  return
```

Example: factorial

High-level code

```
function fact (n) {  
  int r;  
  if (n!=1)  
    r = n * fact(n-1);  
  else  
    r = 1;  
  return r;  
}
```

VM code (first approx.)

```
function fact(n)  
  push n  
  push 1  
  eq  
  if-goto else  
  push n  
  push 1  
  sub  
  fact  
  push n  
  mult  
  
  goto cont  
label else  
  push 1  
  
label cont  
  
  return
```

VM code

```
function fact 1  
  push argument 0  
  push constant 1  
  eq  
  if-goto else  
  push argument 0  
  push constant 1  
  sub  
  call fact 1  
  push argument 0  
  call mult 2  
  
  goto cont  
label else  
  push constant 1  
  
label cont  
  
  return
```

Calling stack for fact(4)

High-level code

```
function fact (n) {  
  int r;  
  if (n!=1)  
    r = n * fact(n-1);  
  else  
    r = 1;  
  return r;  
}
```

stack

frame fact(4)
frame fact(3)
frame fact(2)
frame fact(1)

Calling stack for fact(4)

High-level code

```
function fact (n) {  
  int r;  
  if (n!=1)  
    r = n * fact(n-1);  
  else  
    r = 1;  
  return r;  
}
```

stack

frame fact(4)
frame fact(3)
frame fact(2)
frame mult(2,1)

Calling stack for fact(4)

High-level code

```
function fact (n) {  
  int r;  
  if (n!=1)  
    r = n * fact(n-1);  
  else  
    r = 1;  
  return r;  
}
```

stack

frame fact(4)
frame fact(3)
frame mult(3,2)

Calling stack for fact(4)

High-level code

```
function fact (n) {  
  int r;  
  if (n!=1)  
    r = n * fact(n-1);  
  else  
    r = 1;  
  return r;  
}
```

stack

frame fact(4)
frame mult(4,6)

Bootstrapping

A high-level jack program (aka application) is a set of class files.

By a Jack convention, one class must be called Main, and this class must have at least one function, called main.

The contract: when we tell the computer to execute a Jack program, the function Main.main starts running

Implementation:

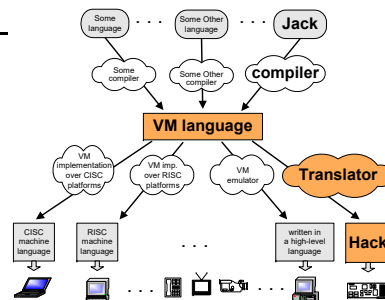
- After the program is compiled, each class file is translated into a .vm file
- The operating system is also implemented as a set of .vm files (aka "libraries") that co-exist alongside the program's .vm files
- One of the OS libraries, called Sys.vm, includes a method called init. The Sys.init function starts with some OS initialization code (we'll deal with this later, when we discuss the OS), then it does call Main.main
- Thus, to bootstrap, the VM implementation has to effect (e.g. in assembly), the following operations:

```
SP = 256      // initialize the stack pointer to 0x0100  
call Sys.init // call the function that calls Main.main
```

Perspective

Benefits of the VM approach

- Code transportability: compiling for different platforms requires replacing only the VM implementation
- Language inter-operability: code of multiple languages can be shared using the same VM
- Common software libraries
- Code mobility: Internet, cloud



Benefits of managed code:

- Security
- Array bounds, index checking, ...
- Add-on code
- Etc.

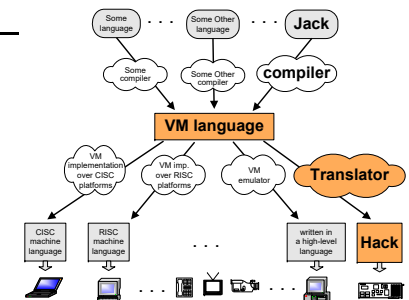
VM Cons

- Performance.

Perspective

- Some virtues of the modularity implied by the VM approach to program translation:

- Improvements in the VM implementation are shared by all compilers above it
- Every new digital device with a VM implementation gains immediate access to an existing software base
- New programming languages can be implemented easily using simple compilers



Benefits of managed code:

- Security
- Array bounds, index checking, ...
- Add-on code
- Etc.

VM Cons

- Performance.