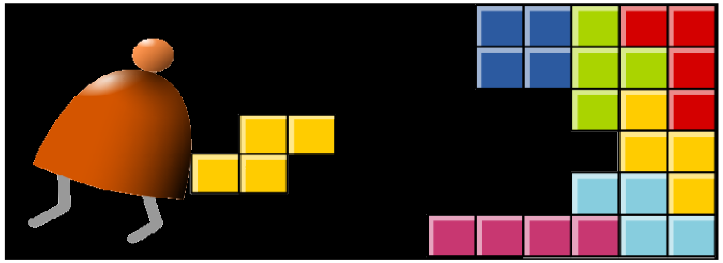
Virtual Machine II:
Program Control



Building a Modern Computer From First Principles

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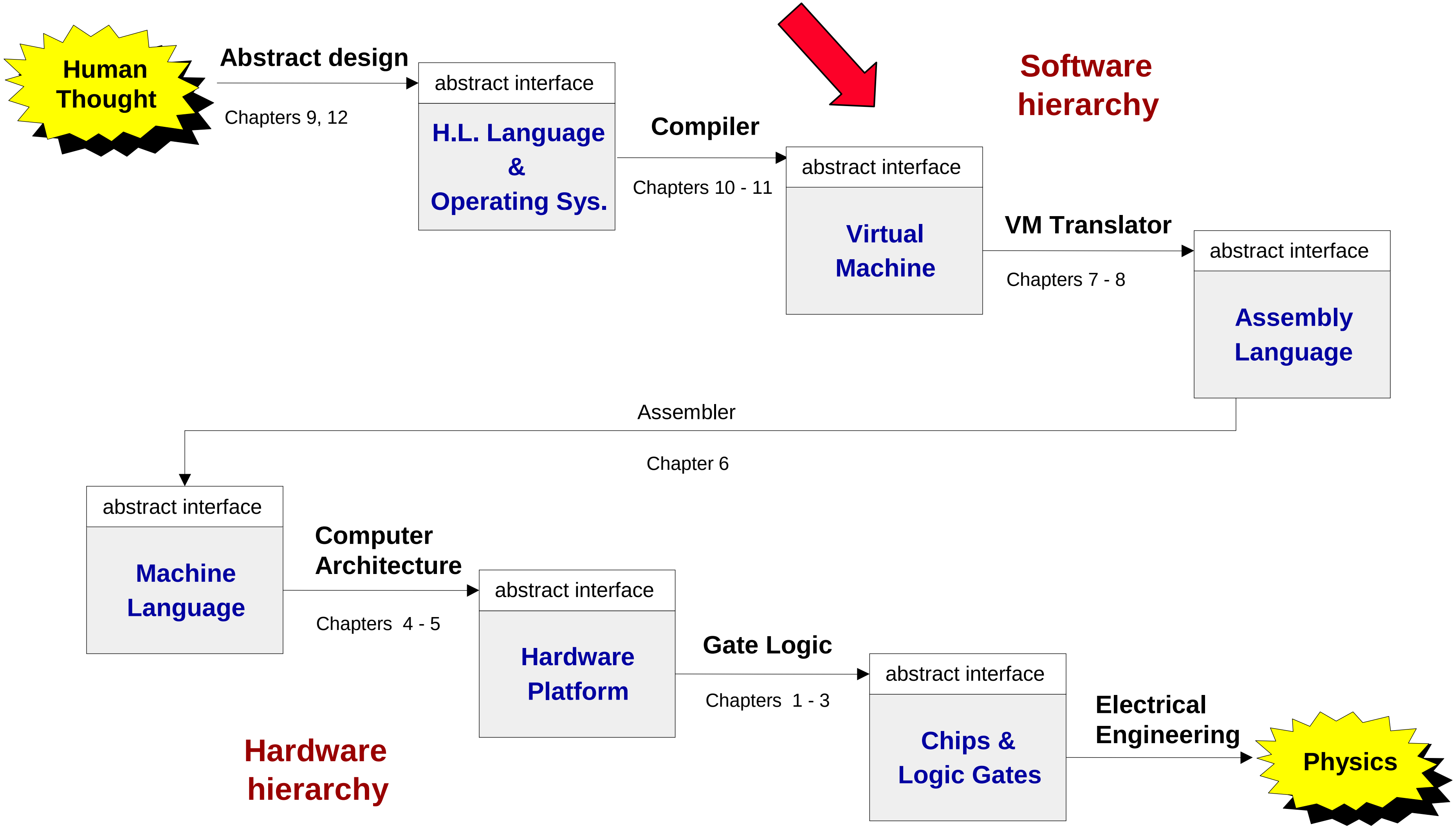
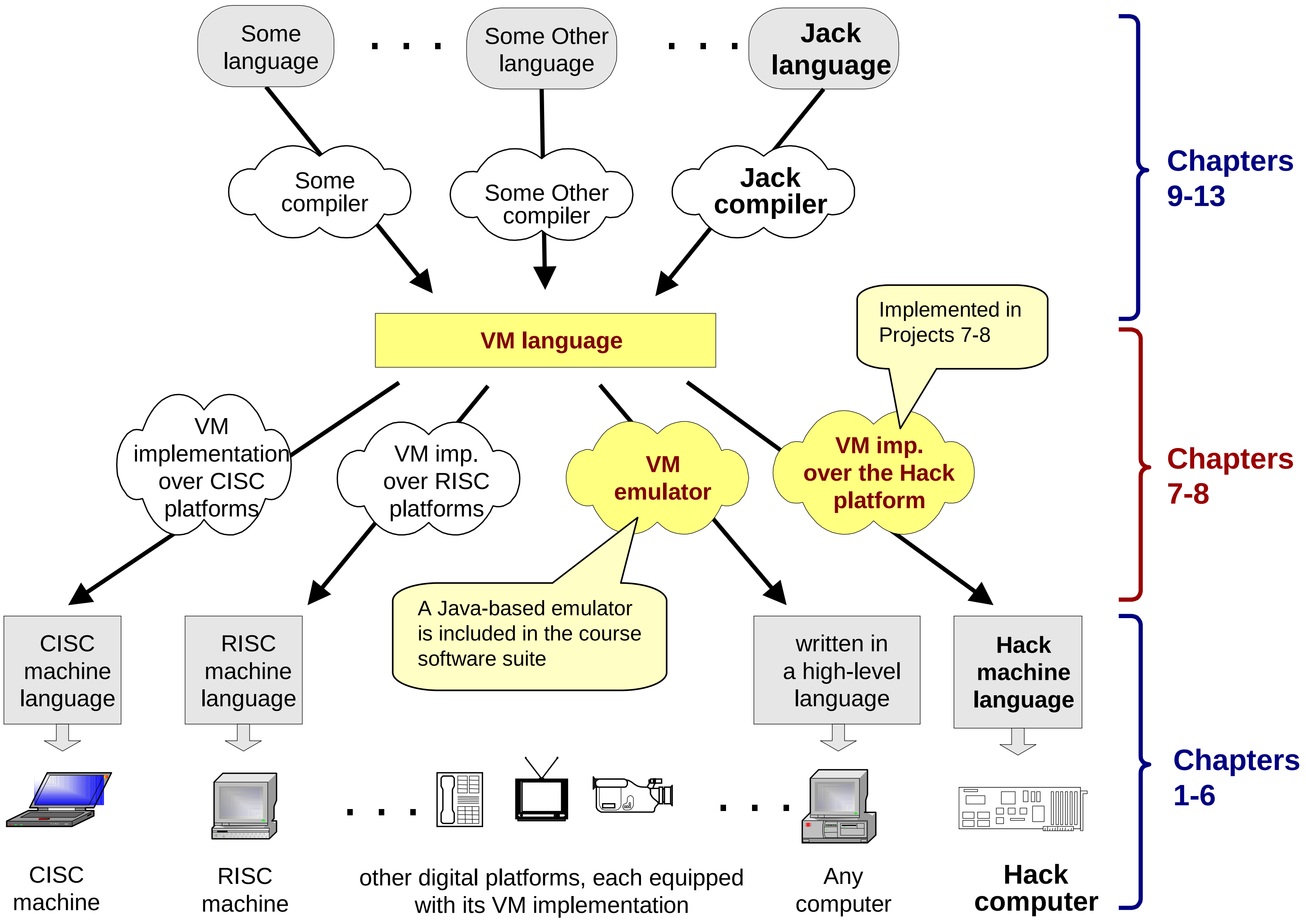
Where we are at:



The big picture



Lecture plan

Goal: Specify and implement a VM model and language

Arithmetic / Boolean commands

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

Previous lecture

Memory access commands

```
pop  segment i
push segment i
```

Program flow commands

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

This lecture

Function calling commands

`function`	(declaration)
`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.

Program structure and translation (on the Hack-Jack platform)

Jack source code (example):

```
class Foo {
  static int x1, x2, x3;
  method int f1(int x) {
    var int a, b;
    ...
  }
  method void f2(int x, int y) {
    var int a, b, c;
    ...
  }
  function int f3(int u) {
    var int x;
    ...
  }
}
```

```
class Bar {
  static int y1, y2;
  function void f1(int u, int v) {
    ...
  }
  method void f2(int x) {
    var int a1, a2;
    ...
  }
}
```

In general

Jack source code:

```
class Foo {
  static staticsList;
  method f1(argsList) {
    var localsList;
    ...
  }
  method f2(argsList) {
    var localsList;
    ...
  }
  function f3(argsList) {
    var localsList;
    ...
  }
}
```

```
class Bar {
  static staticsList;
  function f1(argsList){
    ...
  }
  method f2(argsList) {
    var localsList;
    ...
  }
}
```

Program structure and translation (on the Hack-Jack platform)

Jack source code:

```
class Foo {
   static staticsList;
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      var localsList;
      ...
   }
   method f2(argsList) {
      var localsList;
      ...
   }
   function f3(argsList) {
      var localsList;
      ...
   }
}
```
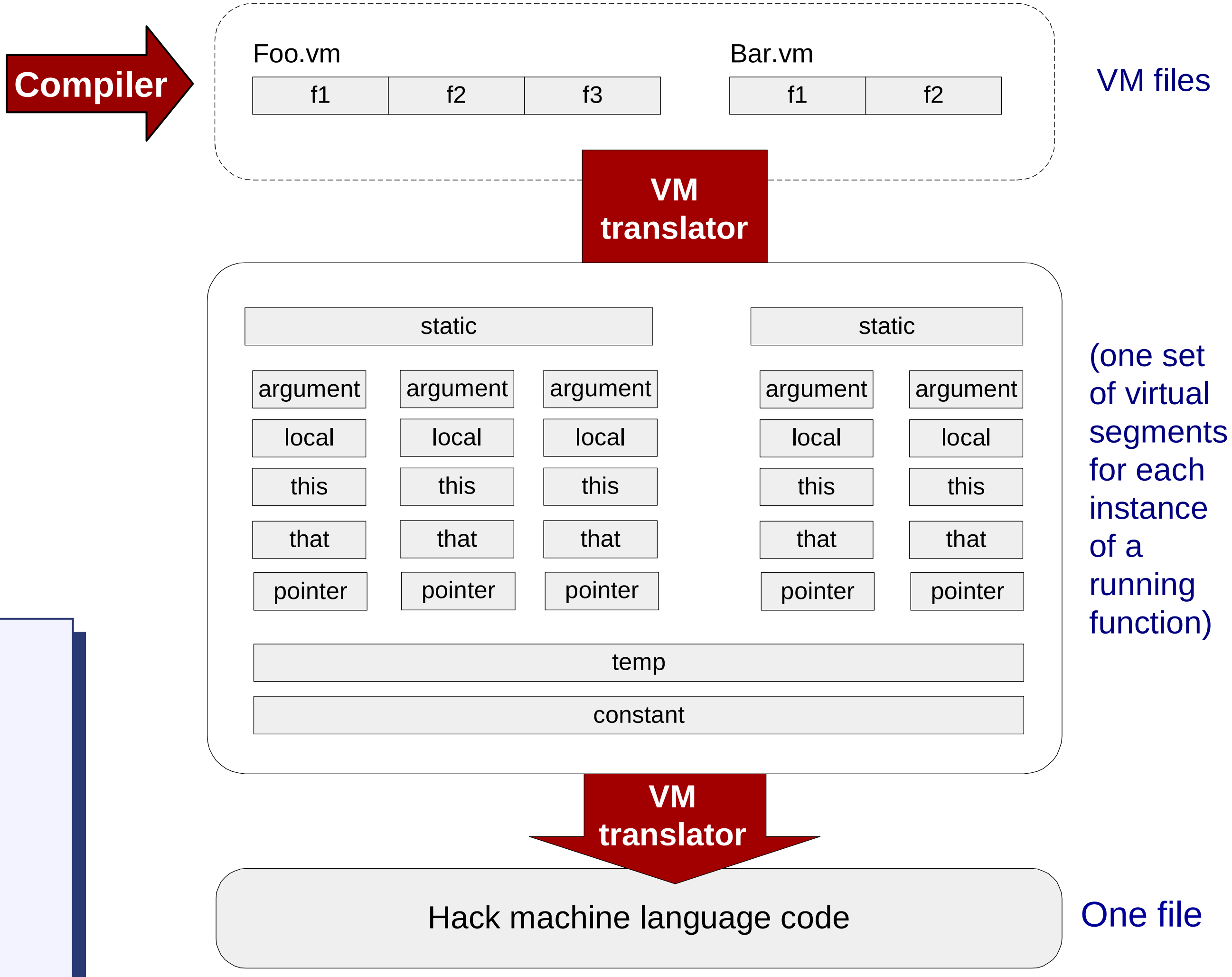

```
class Bar {
   static staticsList;
   function f1(argsList){
      ...
   }
   method f2(argsList) {
      var localsList;
      ...
   }
}
```

Following compilation:



The challenge ahead

$$x = (-b + \sqrt{b^2 - 4\cdot a\cdot c})/2a$$

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

To translate such high-level code to VM code, we have to know how to handle:

- Arithmetic operations (last lecture)
- Boolean operations (last lecture)
- Program flow (this lecture, *easy*)
- Subroutines (this lecture, *less easy*)

In the Jack/Hack platform: all these abstractions are handled by the VM level (rather than by the compiler).

Program flow commands in the VM language

- **`label`** *c*
- **`goto`** *c*
- **`if-goto`** *c* // pops the topmost stack element;
  // If it's not zero, jumps

Implementation (by translation to assembly):

Simple. Label declarations and goto directives can be effected directly by assembly commands.

Example:

```
function mult 2
  push   constant 0
  pop    local 0
  push   argument 1
  pop    local 1
label    loop
  push   local 1
  push   constant 0
  eq
  if-goto end
  push   local 0
  push   argument 0
  add
  pop    local 0
  push   local 1
  push   constant 1
  sub
  pop    local 1
  goto   loop
label    end
  push   local 0
  return
```

Subroutines

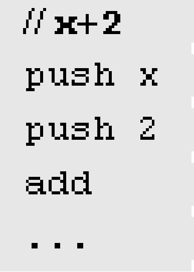
```
if ~(a = 0)
   x = (-b + sqrt(power(b,2) – 4 * a * c)) / (2 * a)
else
   x = - c / b
```

<u>Subroutines = a major programming artifact</u>

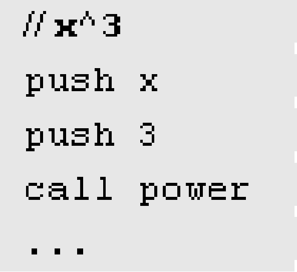
- Basic idea: the given language can be extended at will by user-defined commands (AKA *subroutines* / *functions* / *methods* ...)
- Important: the primitive commands and the user-defined commands have the same look-and-feel
- This transparent extensibility is the most important abstraction delivered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

"A well-designed system consists of a collection of black box modules, each executing its effect like magic"
(Steven Pinker, *How The Mind Works*)

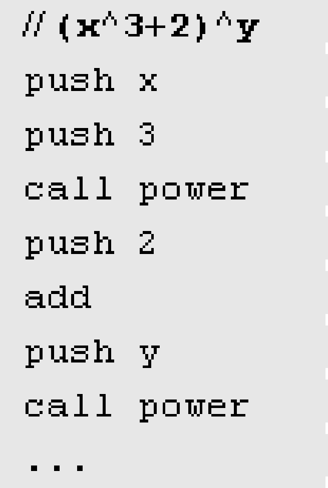
Subroutines usage at the VM level (pseudo code)



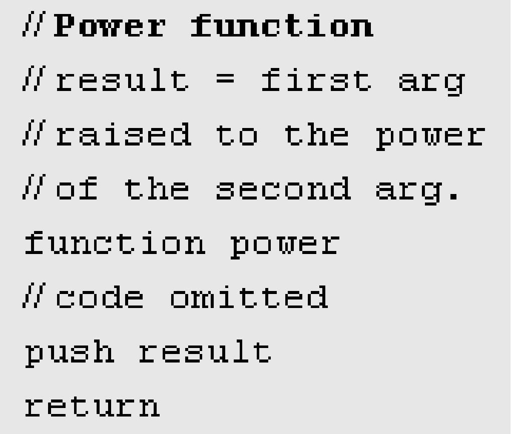
```
//x+2
push x
push 2
add
...
```



```
//x^3
push x
push 3
call power
...
```



```
//(x^3+2)^y
push x
push 3
call power
push 2
add
push y
call power
...
```



```
//Power function
//result = first arg
//raised to the power
//of the second arg.
function power
//code omitted
push result
return
```

Call-and-return convention

- The caller pushes the arguments, calls the callee, then waits for it to return
- Before the callee terminates (returns), the callee must push a return value
- At the point of return, the callee's resources are recycled, and the caller's state is re-instated
- **Caller's net effect:** the arguments were replaced by the return value (just like with primitive operations)

Behind the scene

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

Subroutine 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 been pushed onto the stack)

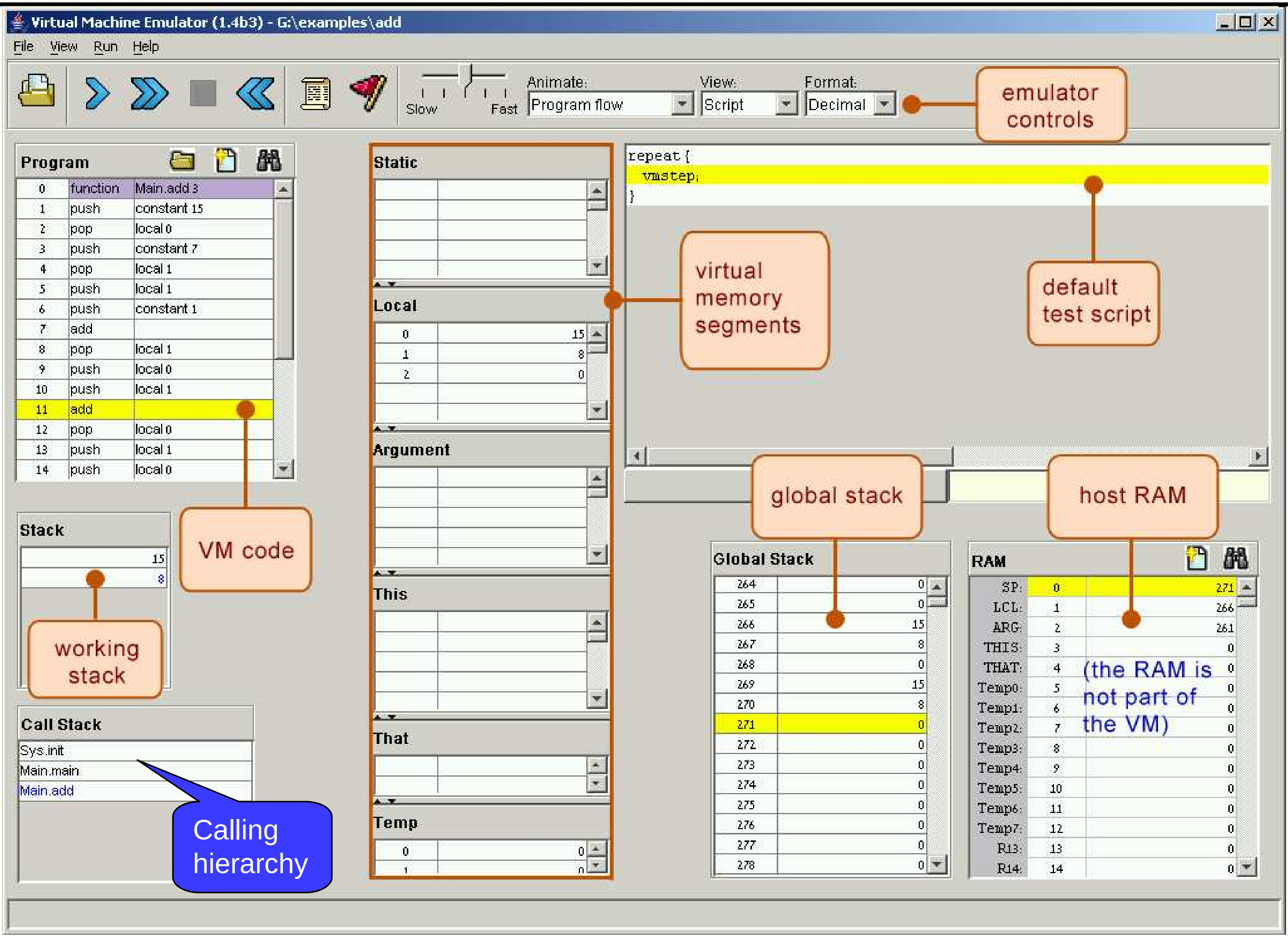
- `Return`

  (Terminate execution and return control to the calling function)

Q: Why this particular syntax?

A: Because it simplifies the VM implementation (later)

Aside: The VM emulator (Java-based, included in the course software suite)



Program

0	function	Main.add 3
1	push	constant 15
2	pop	local 0
3	push	constant 7
4	pop	local 1
5	push	local 1
6	push	constant 1
7	add	
8	pop	local 1
9	push	local 0
10	push	local 1
11	add	
12	pop	local 0
13	push	local 1
14	push	local 0

Stack

15
8

Call Stack

Sys.init
Main.main
Main.add

Local

0	15
1	8
2	0

Temp

0	0
1	0

```
repeat {
  vmstep;
}
```

Global Stack

264	0
265	0
266	15
267	8
268	0
269	15
270	8
271	0
272	0
273	0
274	0
275	0
276	0
277	0
278	0

RAM

SP:	0	271
LCL:	1	266
ARG:	2	261
THIS:	3	0
THAT:	4	0
Temp0:	5	0
Temp1:	6	0
Temp2:	7	0
Temp3:	8	0
Temp4:	9	0
Temp5:	10	0
Temp6:	11	0
Temp7:	12	0
R13:	13	0
R14:	14	0

emulator controls

virtual memory segments

default test script

VM code

working stack

Calling hierarchy

global stack

host RAM

(the RAM is not part of the VM)

The function-call-and-return protocol

- `function` *g nVars*
- `call` *g nArgs*
- `return`

The caller's view:

- Before calling the function, I must push as many arguments as needed onto the stack
- Next, I invoke the function using the `call` command
- After the called function 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 (**argument**, **local**, **static**, …) are the same as before the call.

Blue = function writer's responsibility

Black = black box magic, supplied by the VM implementation

In other words, we have to worry about the "black operations" only.

The callee'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 the function, I must push a value onto the stack and then RETURN.

VM implementation view of the function-call-and-return protocol

- **function** *g nVars*
- **call** *g nArgs*
- **return**

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

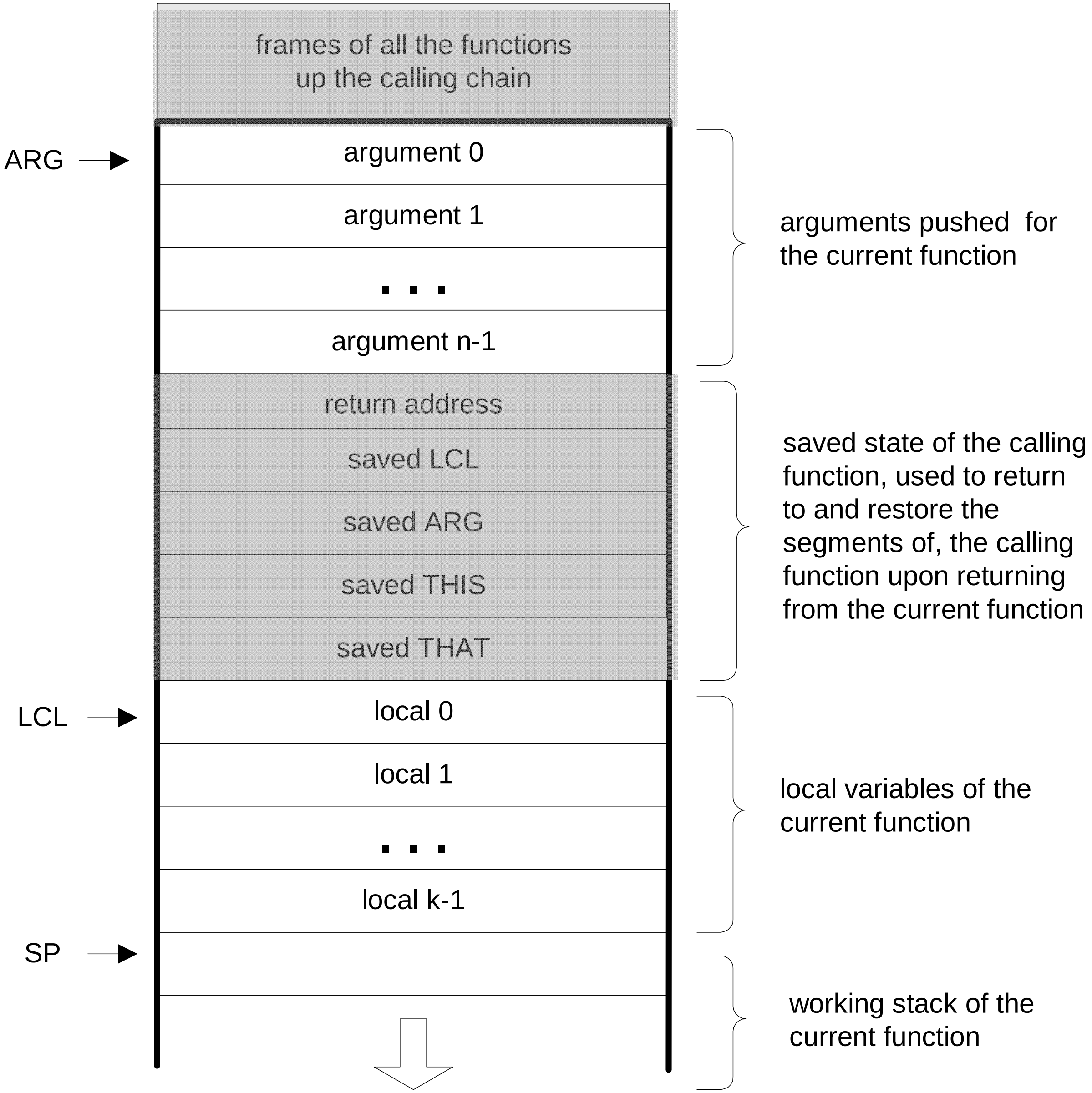
- Save the return address
- Save the virtual segments of *f*
- Allocate, and initialize to 0, as many local variables as needed by *g*
- Set the local and argument segment pointers of *g*
- Transfer control to *g*.

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).

Next: How we make this happen.
Basically, we will do everything on the stack.

The VM implementation storage housekeeping = the stack


frames of all the functions up the calling chain
ARG
argument 0
argument 1
. . .
argument n-1
arguments pushed for the current function
return address
saved LCL
saved ARG
saved THIS
saved THAT
saved state of the calling function, used to return to and restore the segments of, the calling function upon returning from the current function
LCL
local 0
local 1
. . .
local k-1
local variables of the current function
SP
working stack of the current function

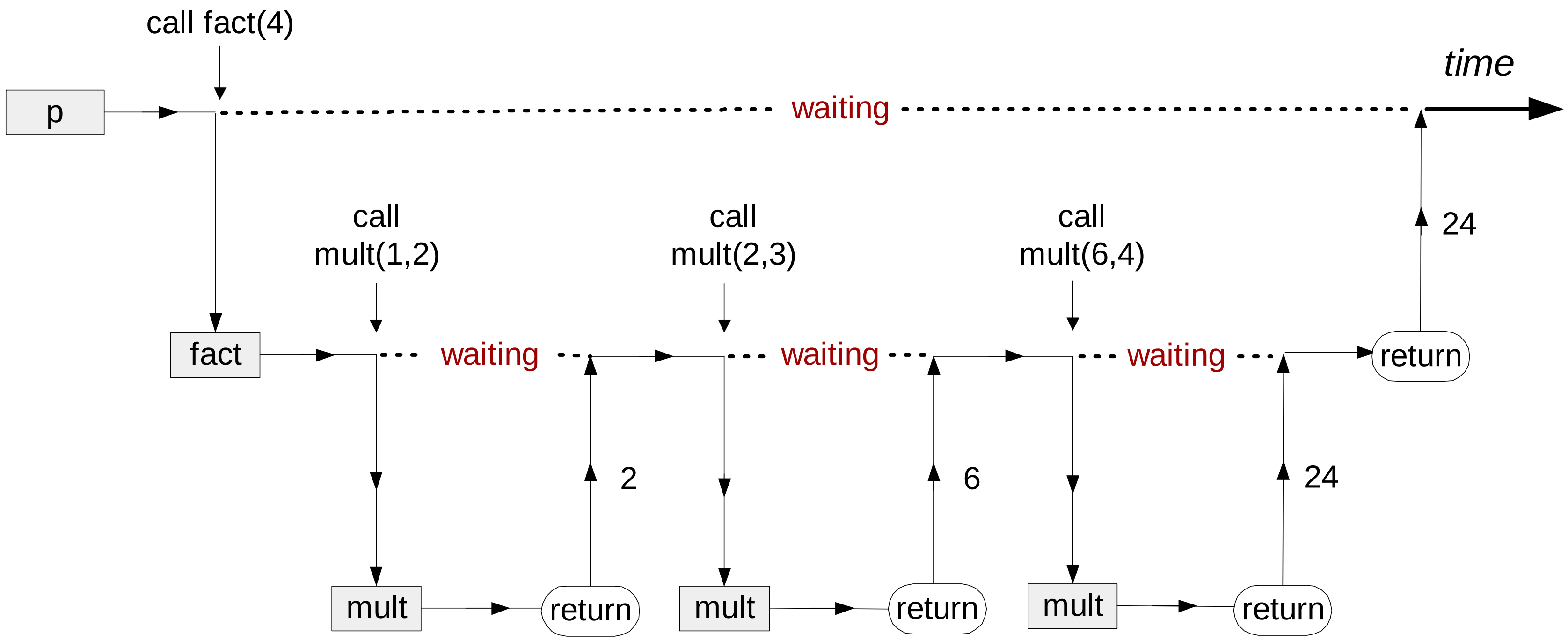
- At any point of time, some functions are waiting, and only the current function is running
- Shaded areas: irrelevant to the current function
- The current function sees only the top of the stack (AKA *working stack*)
- The rest of the stack holds the frozen states of all the functions up the calling hierarchy
- On the left: the Hack VM implementation
- Other VM models are similar but differ in the implementation details.

Example: a typical calling scenario

```
function p(...) {
...
   ... fact(4) ...
}
```

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

```
function mult(x,y) {
    vars sum,j;
    sum=0; j=y;
    while j>0 {
      sum=sum+x;
      j=j+1;
    }
    return sum;
}
```

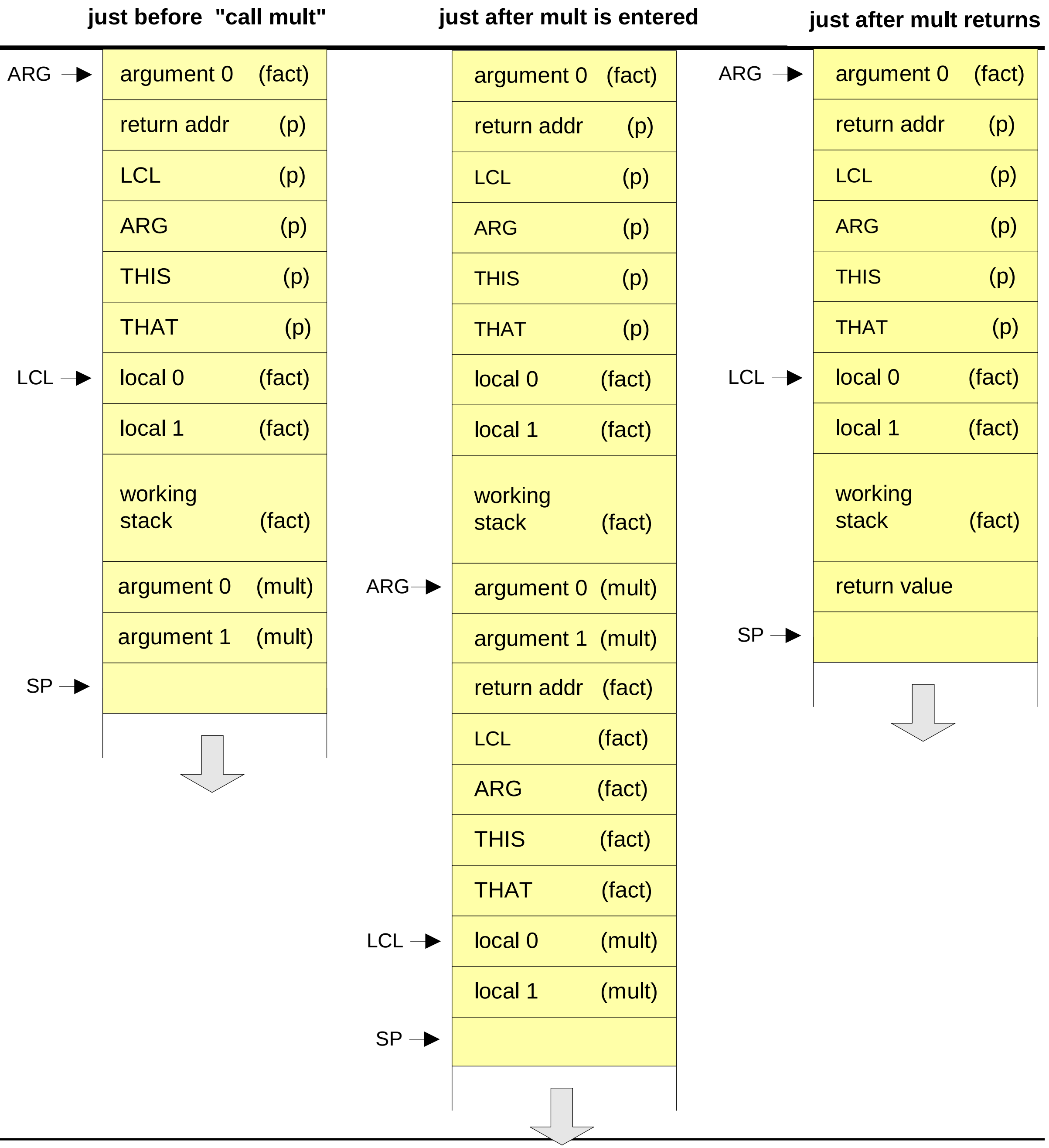


Behind the scene:

```
function p(...) {
...
   ... fact(4) ...
}
```

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

```
function mult(x,y) {
    vars sum,j;
    sum=0; j=y;
    while j>0 {
      sum=sum+x;
      j=j+1;
    }
    return sum;
}
```



just before "call mult"

ARG →	argument 0	(fact)
	return addr	(p)
	LCL	(p)
	ARG	(p)
	THIS	(p)
	THAT	(p)
LCL →	local 0	(fact)
	local 1	(fact)
	working stack	(fact)
	argument 0	(mult)
	argument 1	(mult)
SP →		

just after mult is entered

	argument 0	(fact)
	return addr	(p)
	LCL	(p)
	ARG	(p)
	THIS	(p)
	THAT	(p)
	local 0	(fact)
	local 1	(fact)
	working stack	(fact)
ARG →	argument 0	(mult)
	argument 1	(mult)
	return addr	(fact)
	LCL	(fact)
	ARG	(fact)
	THIS	(fact)
	THAT	(fact)
LCL →	local 0	(mult)
	local 1	(mult)
SP →		

just after mult returns

ARG →	argument 0	(fact)
	return addr	(p)
	LCL	(p)
	ARG	(p)
	THIS	(p)
	THAT	(p)
LCL →	local 0	(fact)
	local 1	(fact)
	working stack	(fact)
	return value	
SP →		

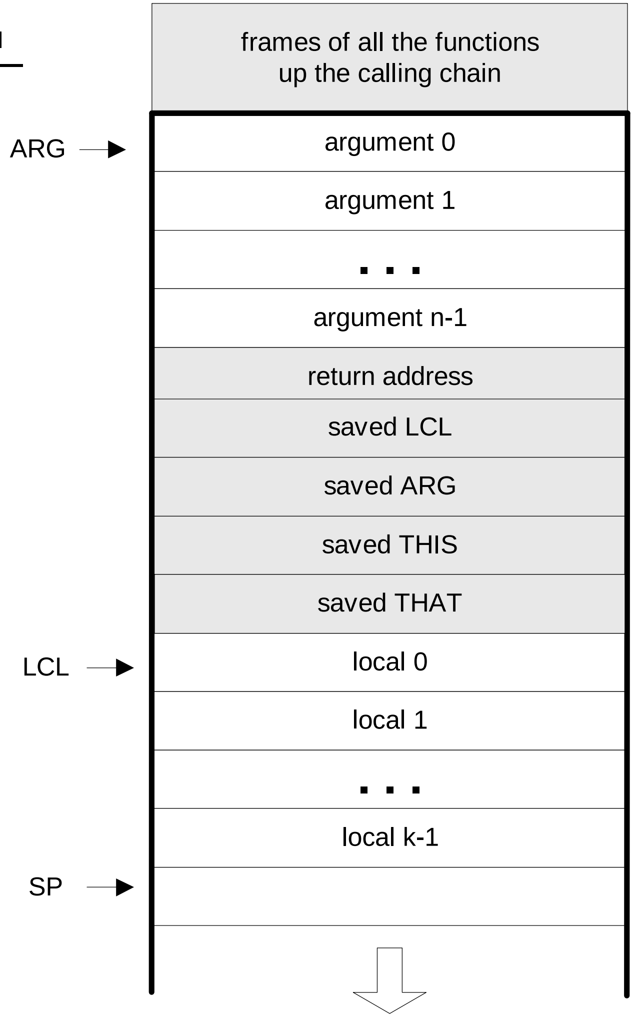
Implementing the `call f n` command

`call f n`

(calling a function `f` after `n` arguments have been pushed onto the stack)

```
   push return-address  // (Using the label declared below)
   push LCL             // Save LCL of the calling function
   push ARG             // Save ARG of the calling function
   push THIS            // Save THIS  of the calling function
   push THAT            // Save THAT of the calling function
   ARG = SP-n-5         // Reposition ARG (n = number of args)
   LCL = SP             // Reposition LCL
   goto f               // Transfer control
(return-address)        // Declare a label for the return-address
```

- If the VM is implemented as a program that translates VM code to assembly code, the translator should generate the above logic in assembly.



frames of all the functions
up the calling chain

ARG → argument 0

argument 1

. . .

argument n-1

return address

saved LCL

saved ARG

saved THIS

saved THAT

LCL → local 0

local 1

. . .

local k-1

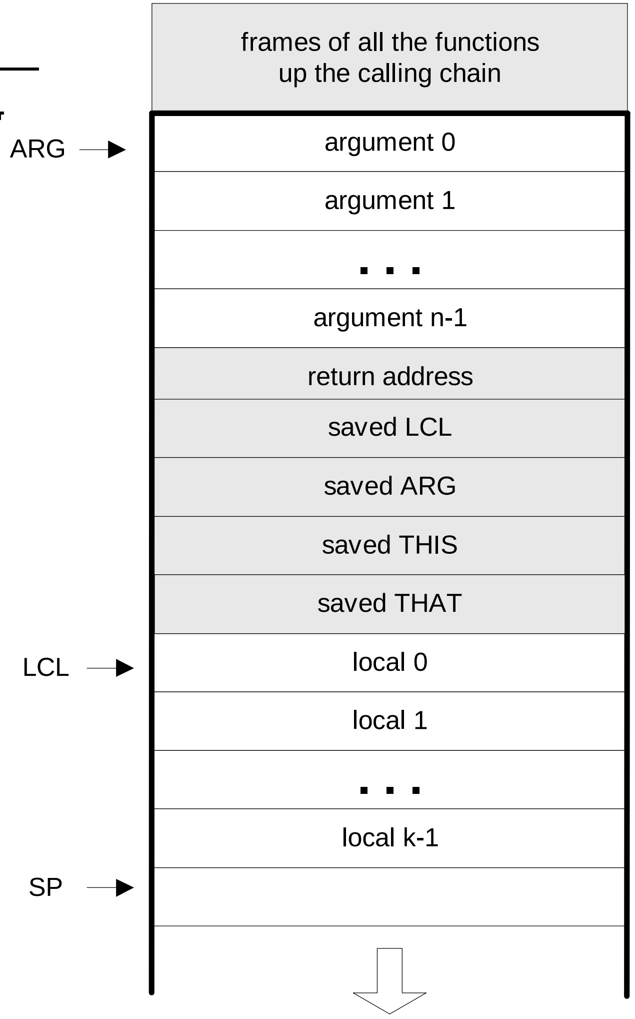
SP →

Implementing the `function f k` command

`function f k`

(declaring a function `f` that has `k` local variables)

```
(f)                      // Declare a label for the function entry
   repeat k times:       // k = number of local variables
   PUSH 0                // Initialize all of them to 0
```



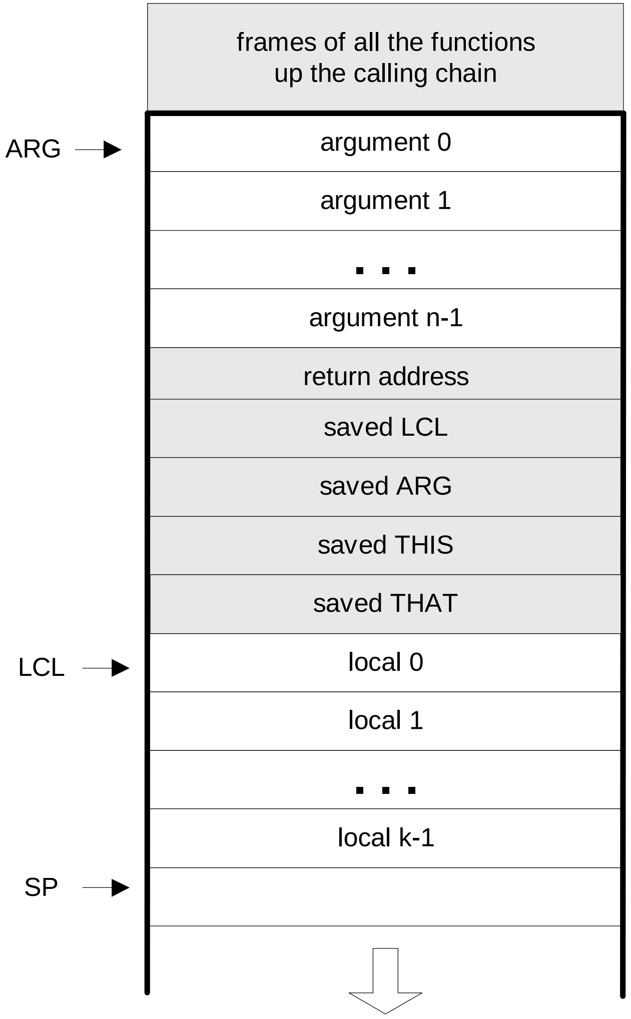
- If the VM is implemented as a program that translates VM code to assembly code, the translator should generate the above logic in assembly.

Implementing the `return` command

`return`

(from a function)

```
FRAME=LCL          // FRAME is a temporary variable
RET=*(FRAME-5)     // Put the return-address in a temp. variable
*ARG=pop()         // Reposition the return value for the caller
SP=ARG+1           // Restore SP of the caller
THAT=*(FRAME-1)    // Restore THAT of the caller
THIS=*(FRAME-2)    // Restore THIS of the caller
ARG=*(FRAME-3)     // Restore ARG  of the caller
LCL=*(FRAME-4)     // Restore LCL of the caller
goto RET           // Goto return-address (in the caller's code)
```



- If the VM is implemented as a program that translates VM code to assembly code, the translator should generate the above logic in assembly.

One more detail: 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 the program, the function **`Main.main`** starts running

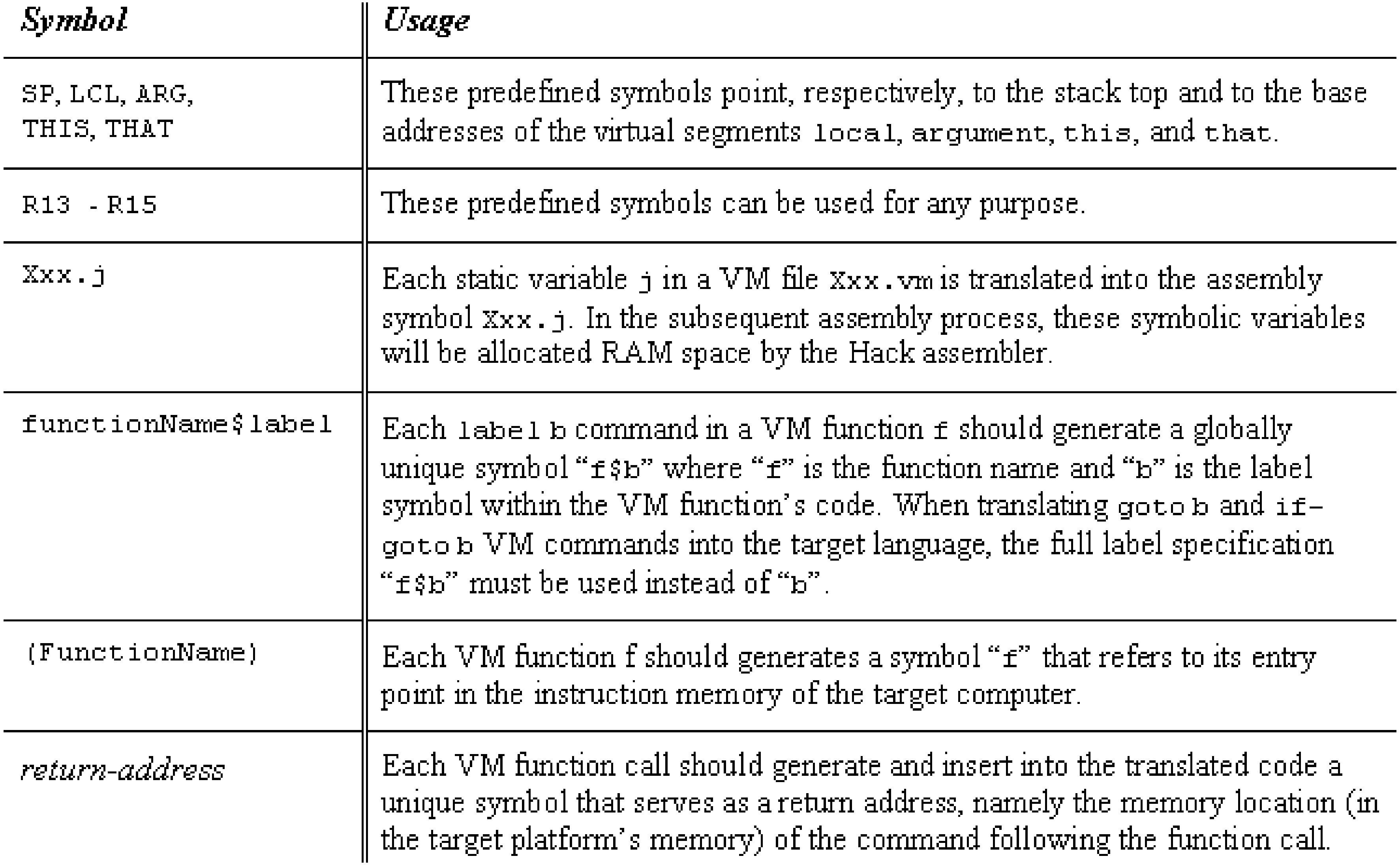
Implementation:

- After the program is compiled, each class file is translated into a **`.vm`** file
- From the host platform's standpoint, the operating system is also a set of **`.vm`** files (AKA "libraries") that co-exist alongside the user's **`.vm`** files
- One of the OS libraries is called **`Sys`**, which 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`** *f* and enters an infinite loop; If the application was written in the Jack language, then by convention **`call`** *f* should be **`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   // the initialization function
```

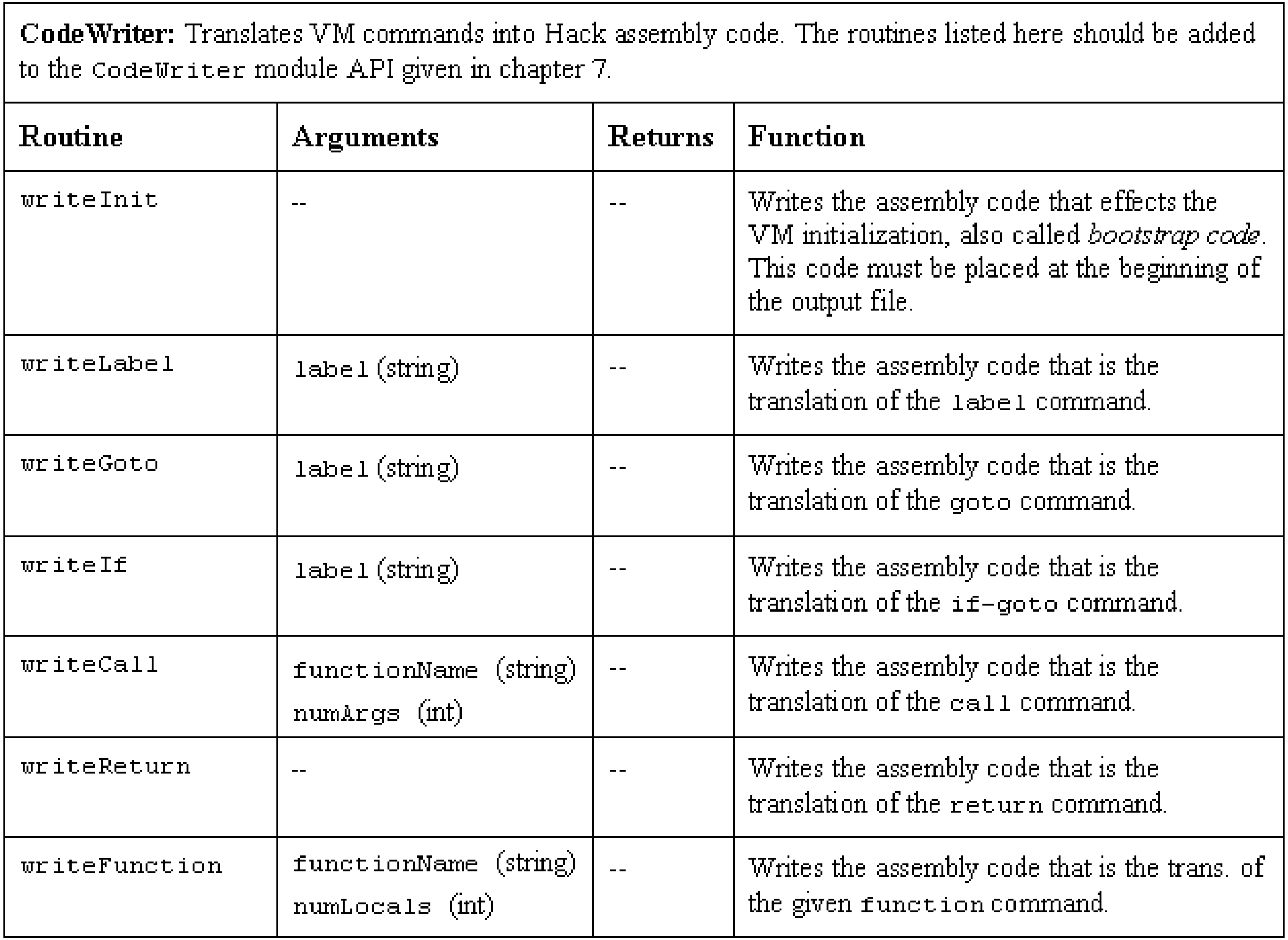
VM implementation over the Hack platform

- Extends the VM implementation described in the last lecture (chapter 7)
- The result: a big assembly program with lots of agreed-upon symbols:



Symbol	*Usage*
`SP`, `LCL`, `ARG`, `THIS`, `THAT`	These predefined symbols point, respectively, to the stack top and to the base addresses of the virtual segments `local`, `argument`, `this`, and `that`.
`R13 - R15`	These predefined symbols can be used for any purpose.
`Xxx.j`	Each static variable `j` in a VM file `Xxx.vm` is translated into the assembly symbol `Xxx.j`. In the subsequent assembly process, these symbolic variables will be allocated RAM space by the Hack assembler.
`functionName$label`	Each `label b` command in a VM function `f` should generate a globally unique symbol "`f$b`" where "`f`" is the function name and "`b`" is the label symbol within the VM function's code. When translating `goto b` and `if-goto b` VM commands into the target language, the full label specification "`f$b`" must be used instead of "`b`".
`(FunctionName)`	Each VM function f should generates a symbol "`f`" that refers to its entry point in the instruction memory of the target computer.
return-address	Each VM function call should generate and insert into the translated code a unique symbol that serves as a return address, namely the memory location (in the target platform's memory) of the command following the function call.

Proposed API



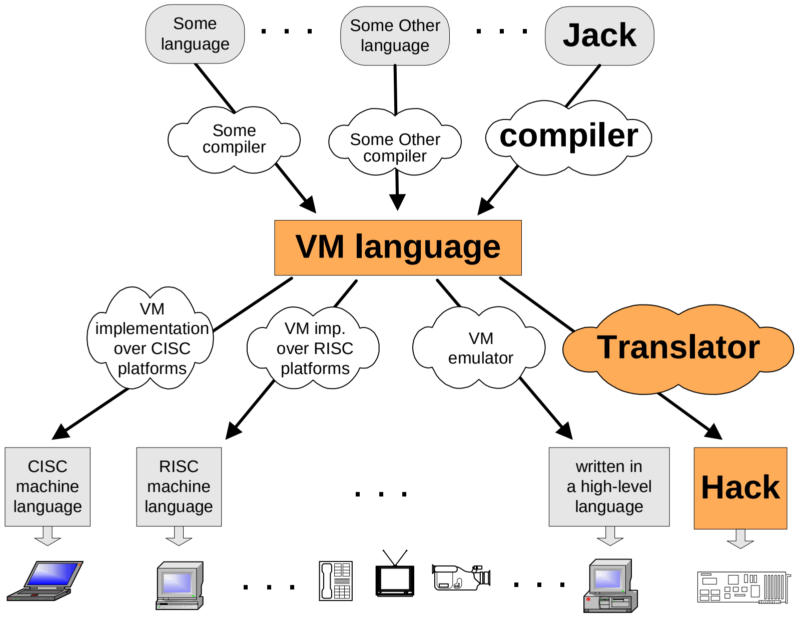
CodeWriter: Translates VM commands into Hack assembly code. The routines listed here should be added to the `CodeWriter` module API given in chapter 7.

Routine	**Arguments**	**Returns**	**Function**
`writeInit`	--	--	Writes the assembly code that effects the VM initialization, also called *bootstrap code*. This code must be placed at the beginning of the output file.
`writeLabel`	`label` (string)	--	Writes the assembly code that is the translation of the `label` command.
`writeGoto`	`label` (string)	--	Writes the assembly code that is the translation of the `goto` command.
`writeIf`	`label` (string)	--	Writes the assembly code that is the translation of the `if-goto` command.
`writeCall`	`functionName` (string) `numArgs` (int)	--	Writes the assembly code that is the translation of the `call` command.
`writeReturn`	--	--	Writes the assembly code that is the translation of the `return` command.
`writeFunction`	`functionName` (string) `numLocals` (int)	--	Writes the assembly code that is the trans. of the given `function` command.

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
- 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.