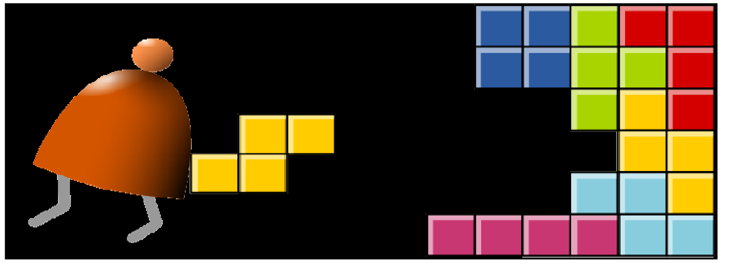
Virtual Machine

Part II: Program Control



Building a Modern Computer From First Principles

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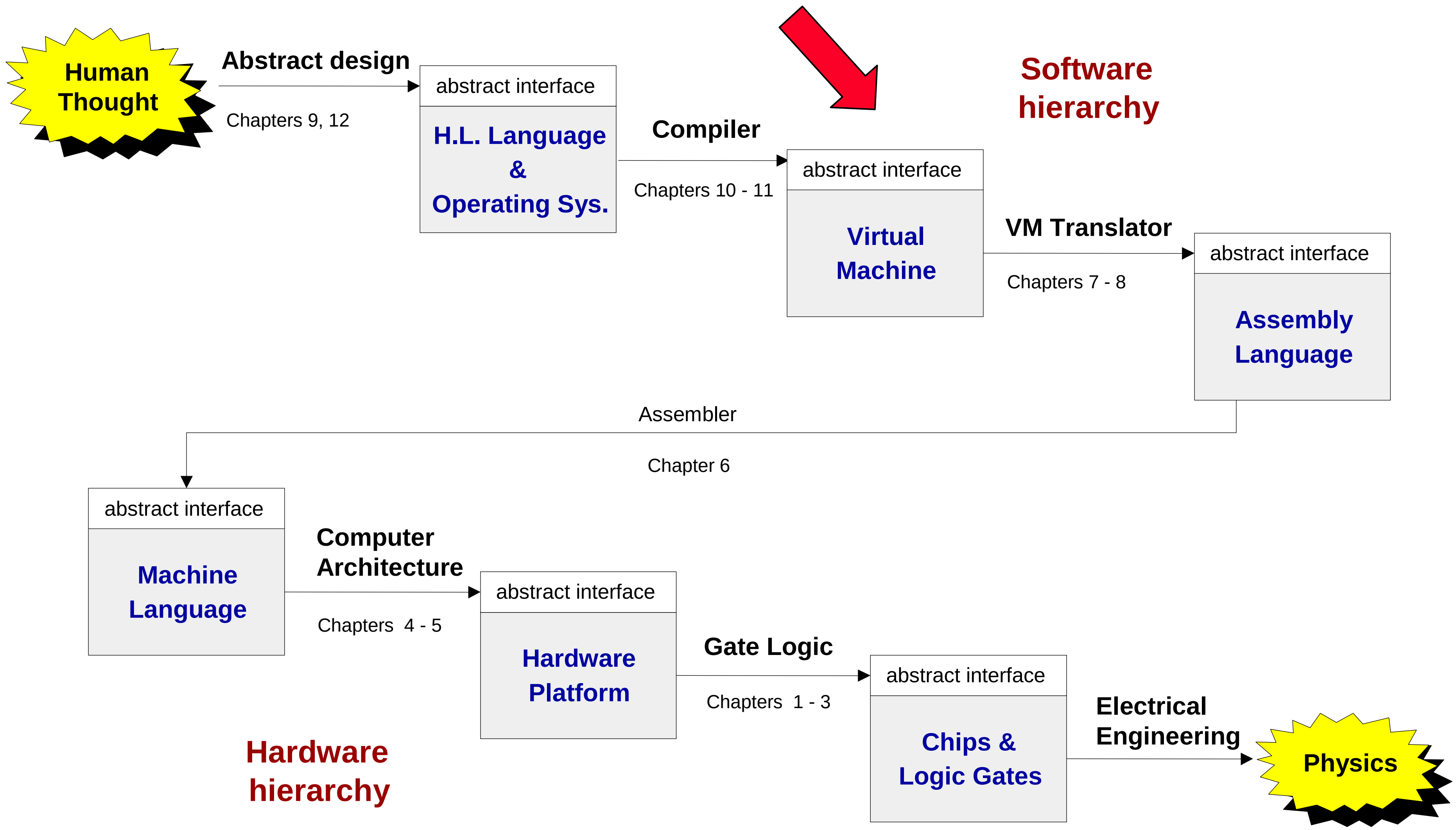
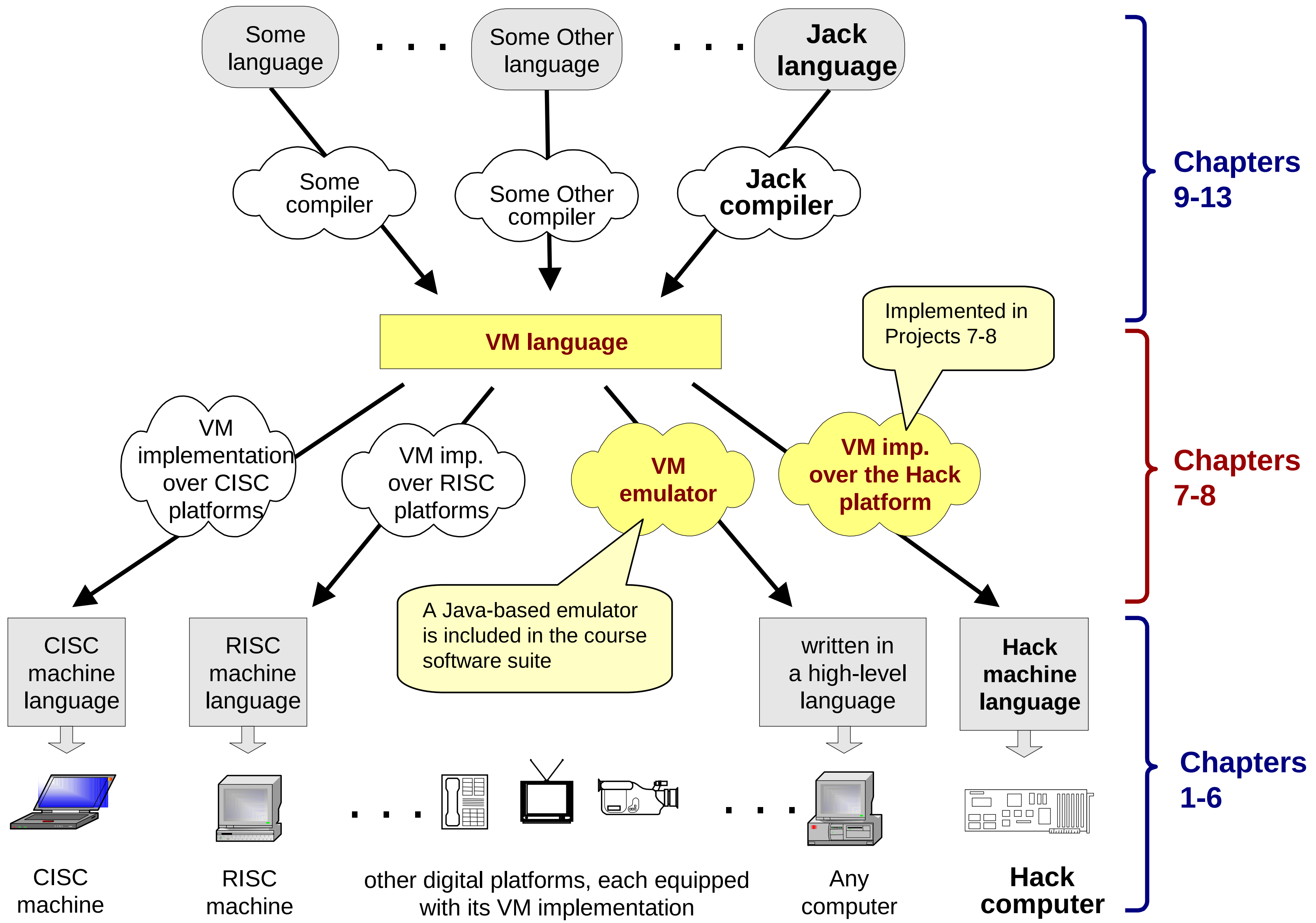
Where we are at:



The big picture



The VM langauge

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

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)

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.

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 quadearic 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

```
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
0000000000010010
1110001100000001
0000000000010000
1111110000010000
0000000000010001
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
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 contLable
elseLabel:
   push c
   neg
   push b
   call div
   pop x
contLable:
```

VM translator

Machine code

```
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
0000000000010010
1110001100000001
0000000000010000
1111110000010000
0000000000010001
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
0000000000010010
1110001100000001
0000000000010000
1111110000010000
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

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)

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 three 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 platfrom
- How to do it? see project 8.

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

"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 in the VM language

Calling code (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
```

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 called command / function is responsible for removing the argument(s) from the stack, and for popping onto the stack the result of its execution.

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 ommitted
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.

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)

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 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`.

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

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

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*.

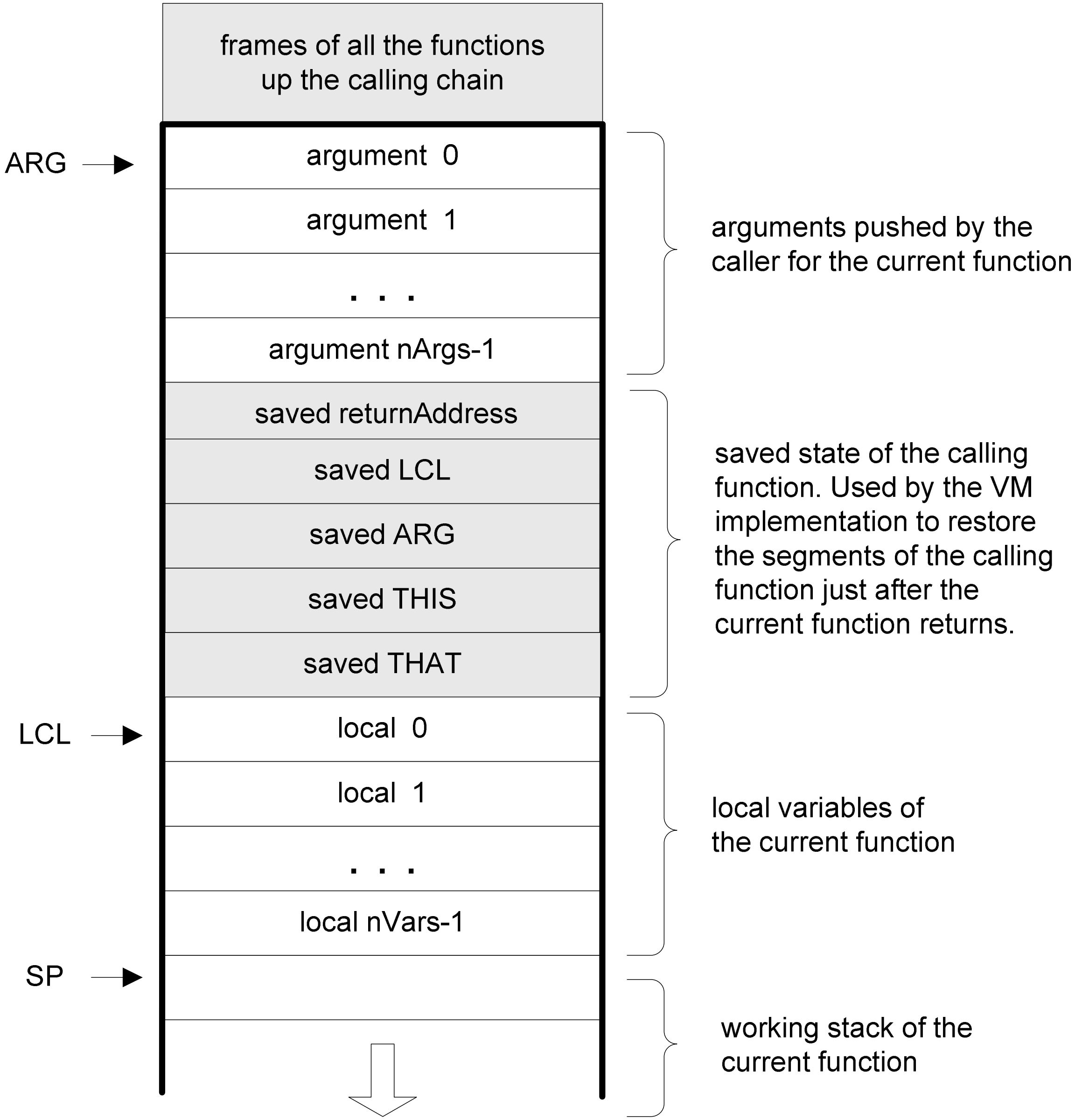
When *g* terminates and control should return to *f*, the VM implementation must:

- 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



<u>Global stack:</u>
the entire RAM area dedicated to hold the stack

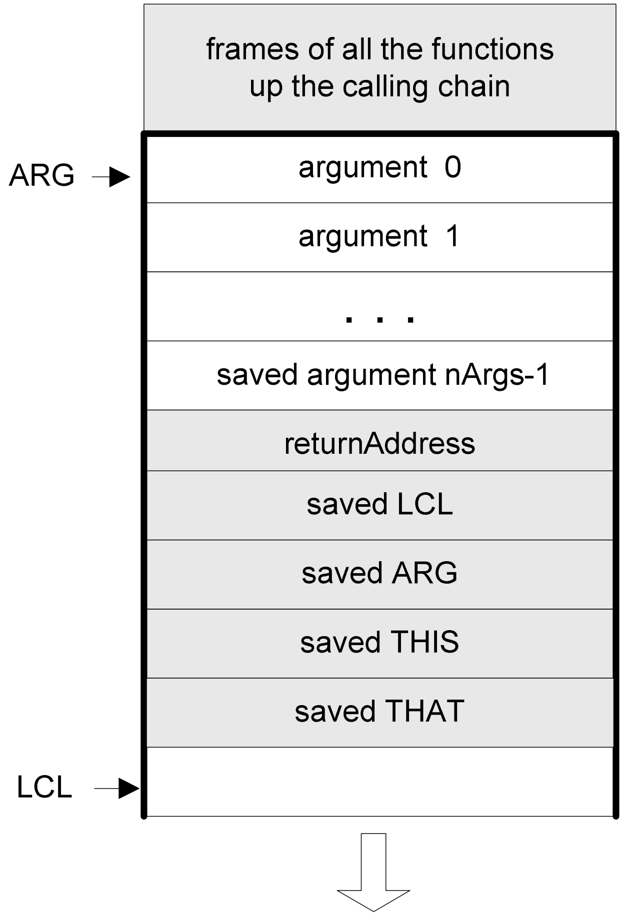
<u>Working stack:</u>
from SP onwards: the stack that the current function sees

- 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, as well as its virtual 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)

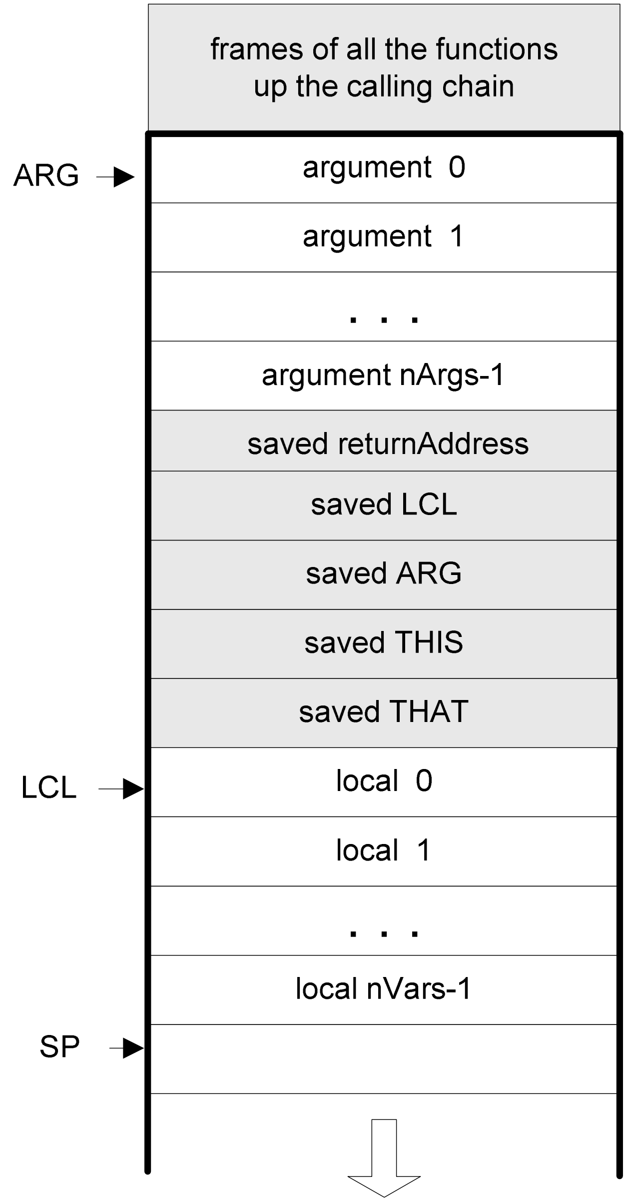
<u>Implementation:</u> If the VM is implemented as a program that translates VM code into assembly code, the translator must emit the above logic in assembly.

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
```

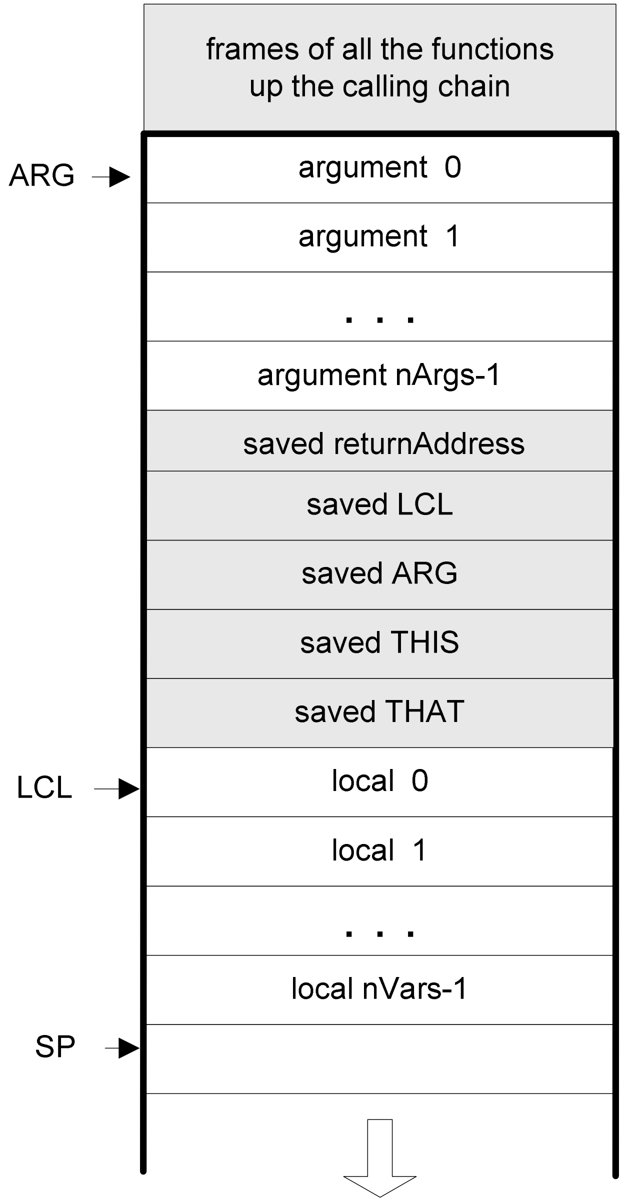


<u>Implementation:</u> If the VM is implemented as a program that translates VM code into assembly code, the translator must emit the above logic in assembly.

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
```



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

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
```

VM implementation over the Hack platform

- Extends the VM implementation described in the last lecture (chapter 7)
- The result: a single assembly program file 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

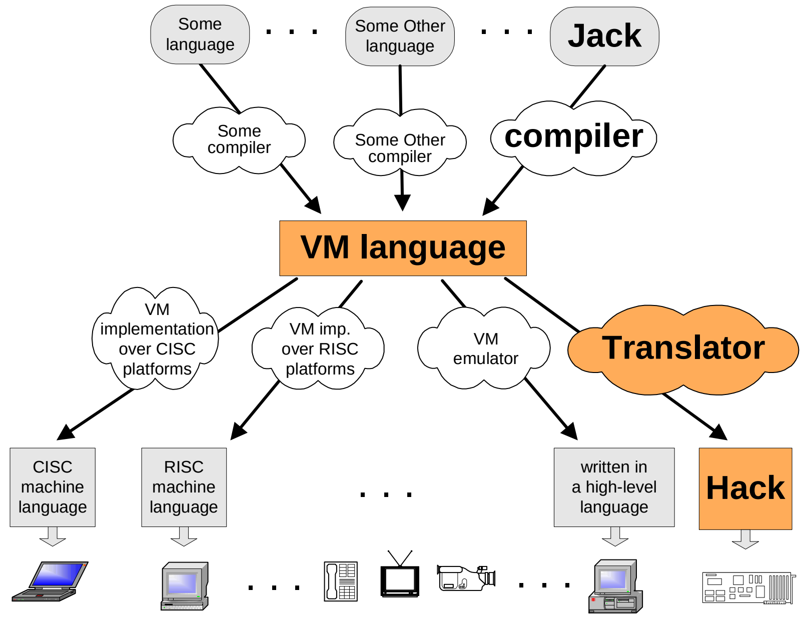
CodeWriter: Translates VM commands into Hack assembly code. The routines listed here should be added to the `CodeWriter` module API given in chapter 7.

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.