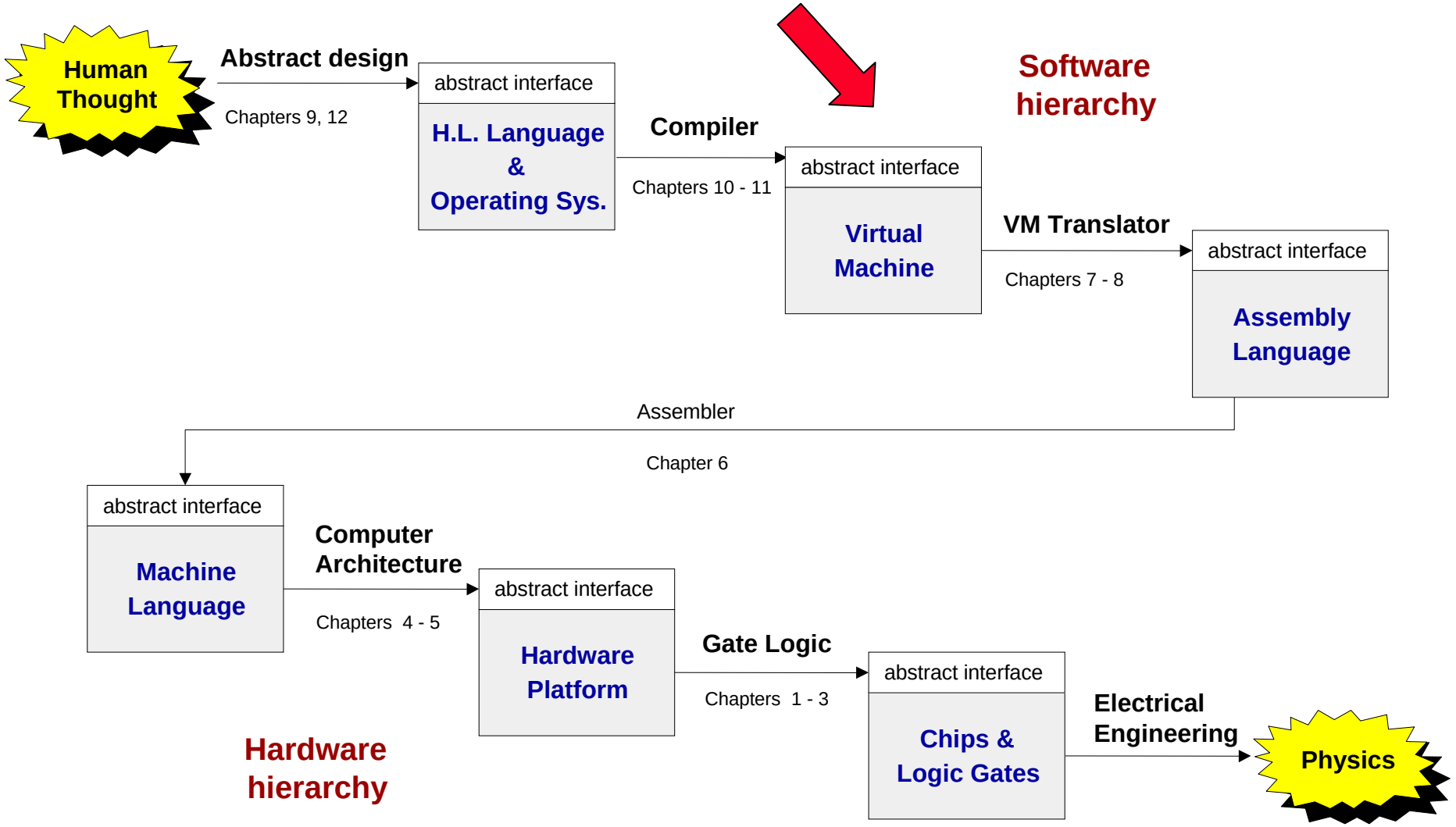
Chapter 7: Virtual Machine I: Stack Arithmetic

Where we are at:



Motivation

```
class Main {
  static int x;

  function void main() {
    // Input and multiply 2 numbers
    var int a, b;
    let a = Keyboard.readInt("Enter a number");
    let b = Keyboard.readInt("Enter a number");
    x = mult(a,b);
    return;
  }
}

  // Multiplies two numbers.
  function int mult(int x, int y) {
    var int result, j;
    let result = 0; let j = y;
    while not(j = 0) {
      let result = result + x;
      let j = j - 1;
    }
    return result;
  }
}
```

Ultimate goal:

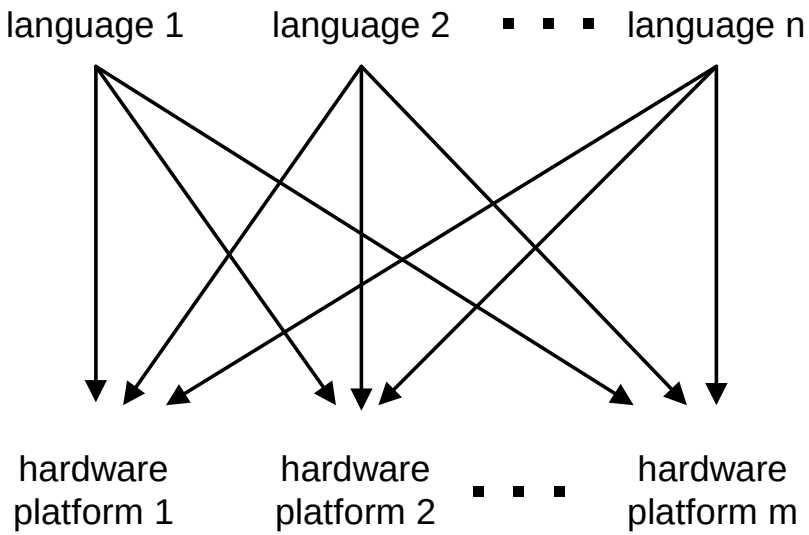
Translate high-level programs into executable code.

Compiler

```
   ...
   @a
   M=D
   @b
   M=0
(LOOP)
   @a
   D=M
   @b
   D=D-A
   @END
   D;JGT
   @j
   D=M
   @temp
   M=D+M
   @j
   M=M+1
   @LOOP
   0;JMP
(END)
   @END
   0;JMP
   ...
```

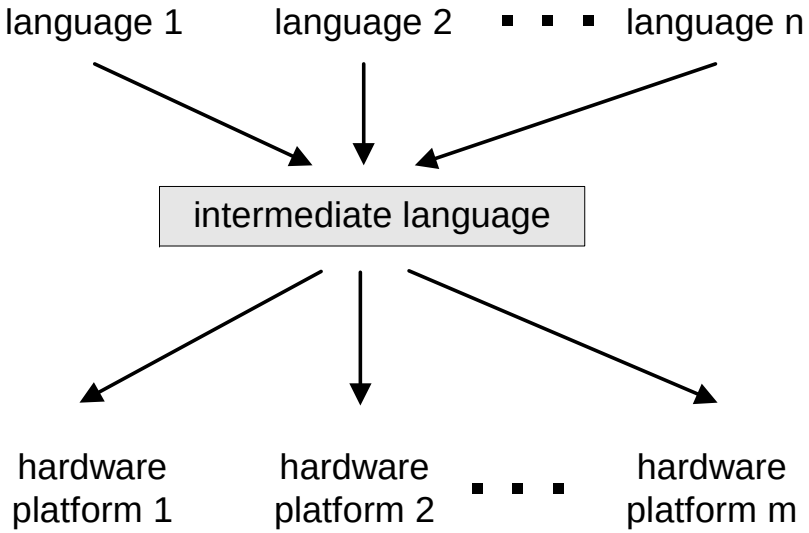
Compilation models

direct compilation:



requires $n \cdot m$ translators

2-tier compilation:

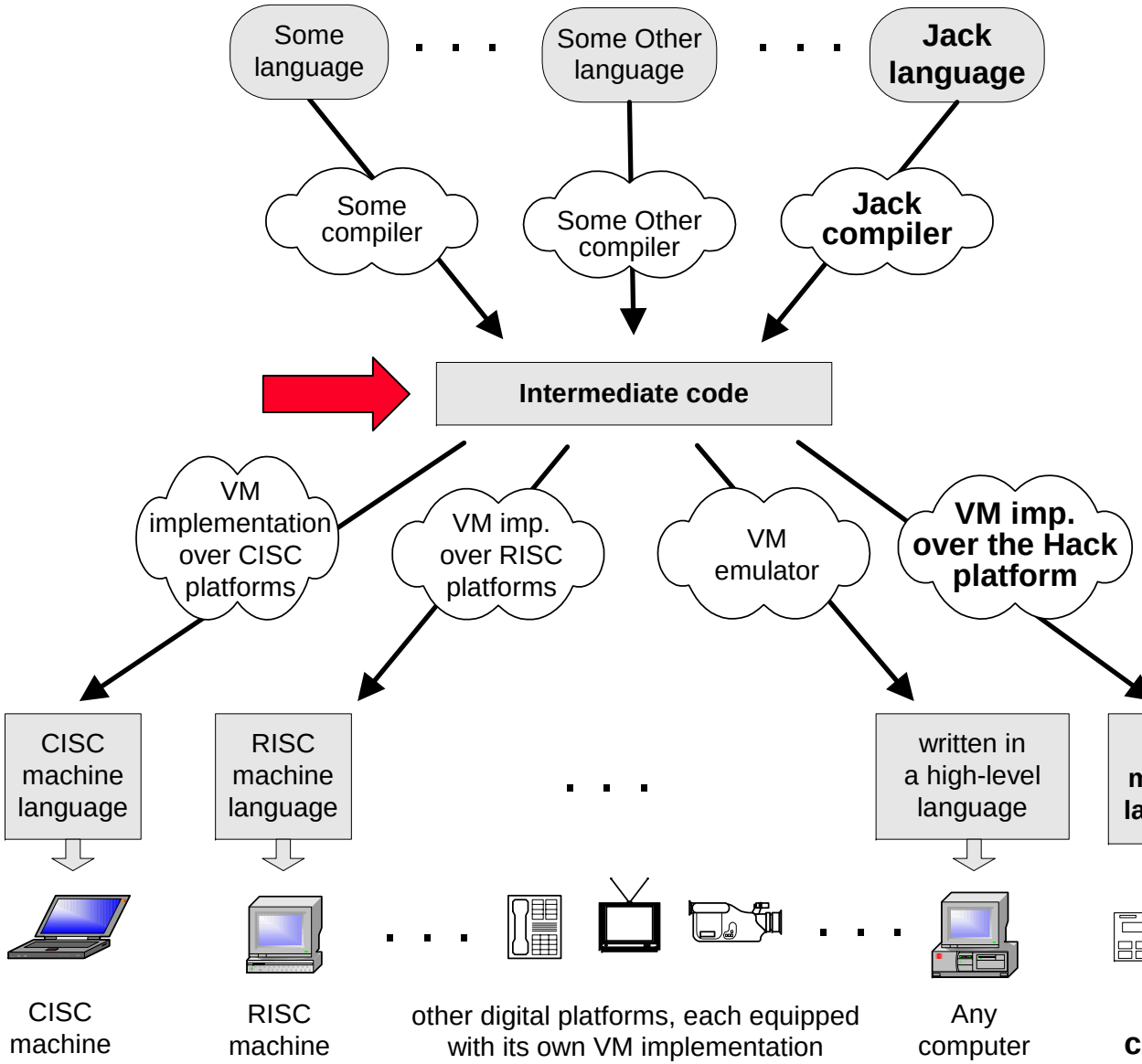


requires $n + m$ translators

Two-tier compilation:

- First compilation stage depends only on the details of the source language
- Second compilation stage depends only on the details of the target platform.

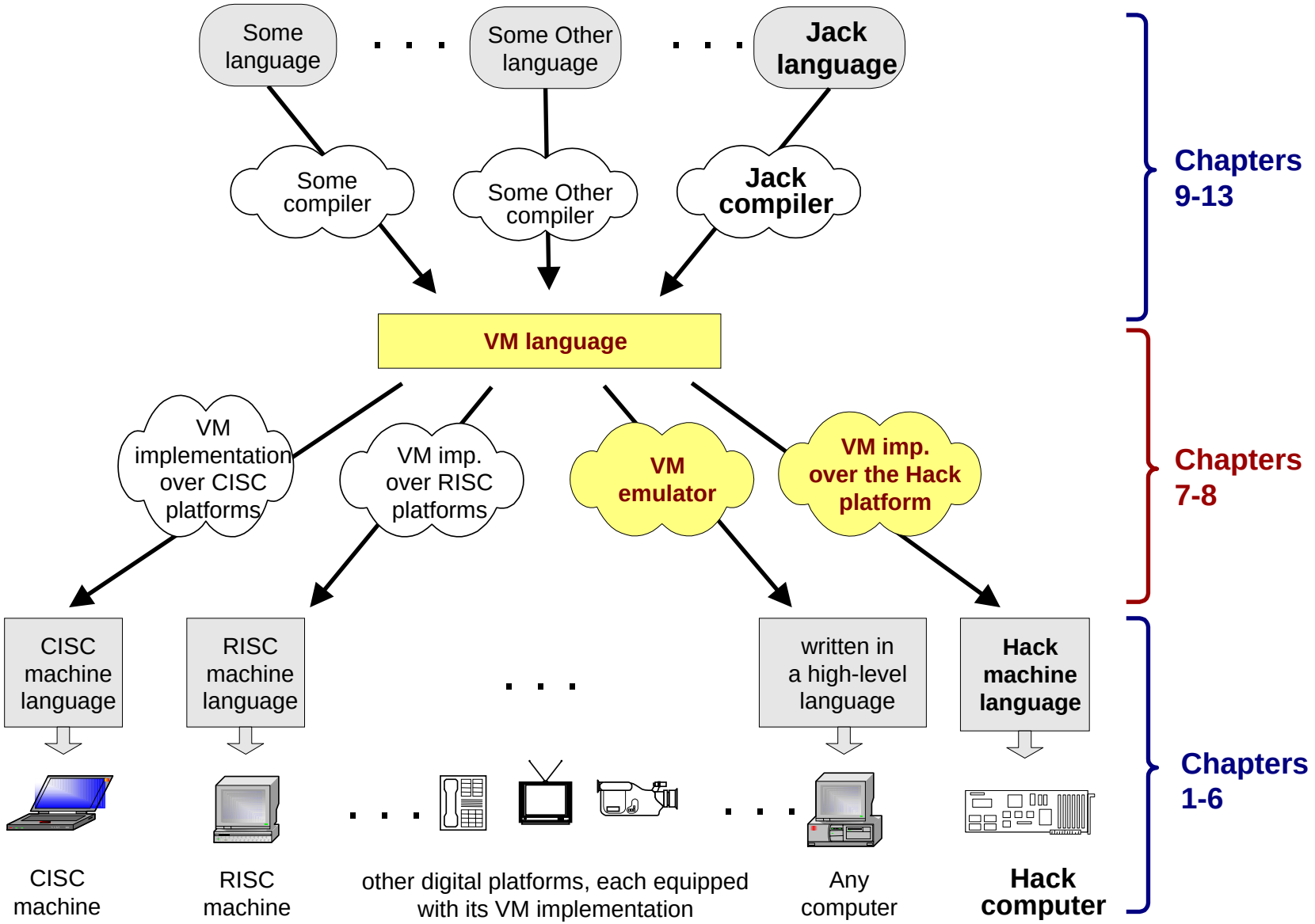
The big picture



The intermediate code:

- The interface between the 2 compilation stages
- Must be sufficiently general to support many <high-level language, machine language> pairs
- Can be modeled as the language of an abstract virtual machine (VM)
- Can be implemented in many different ways.

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
```

This lecture

Memory access commands

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

Program flow commands

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

Next 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 VM language

Important:

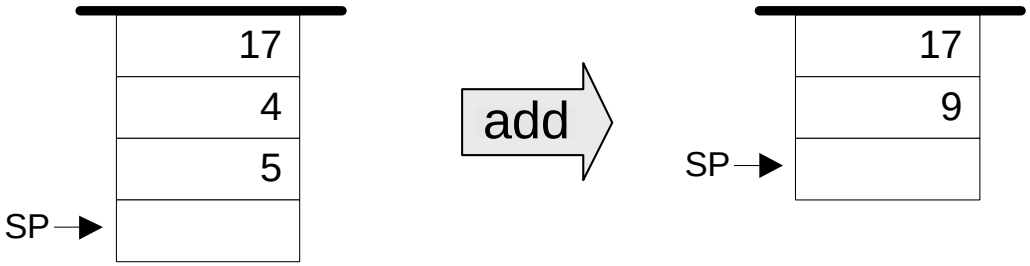
From here till the end of this and the next lecture we describe the VM model used in the Hack-Jack platform

Other VM models (like JVM/JRE and IL/CLR) are similar in spirit and different in scope and details.

Our VM features a single 16-bit data type that can be used as:

- Integer
- Boolean
- Pointer.

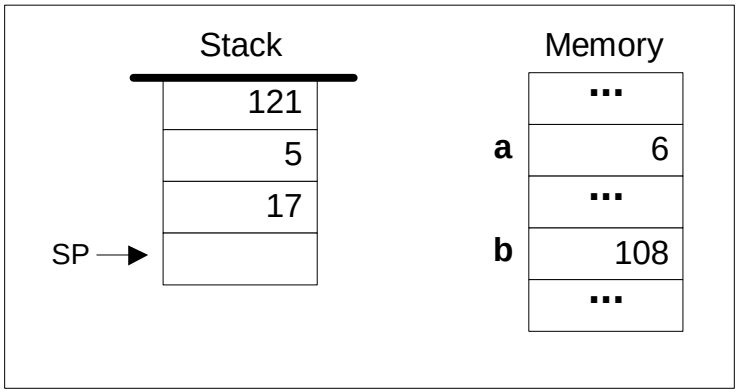
Stack arithmetic



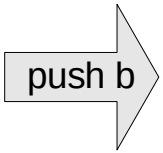
- Typical operation:
  - Pops topmost values x,y from the stack
  - Computes f(x,y)
  - Pushes the result onto the stack

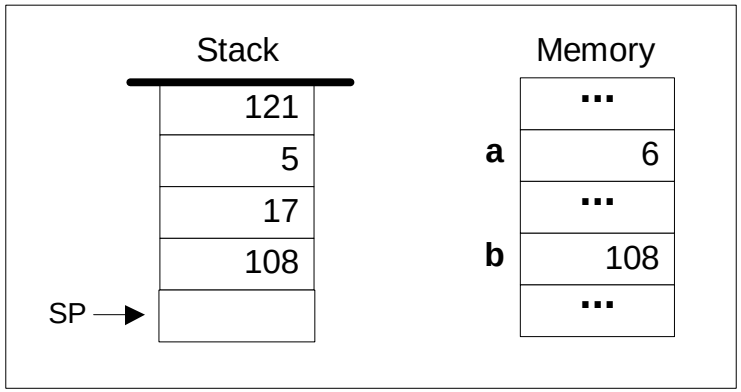
  (Unary operations are similar, using x and f(x) instead)
- Impact: the operands are replaced with the operation's result
- In general: all arithmetic and Boolean operations are implemented similarly.

Memory access (first approximation)



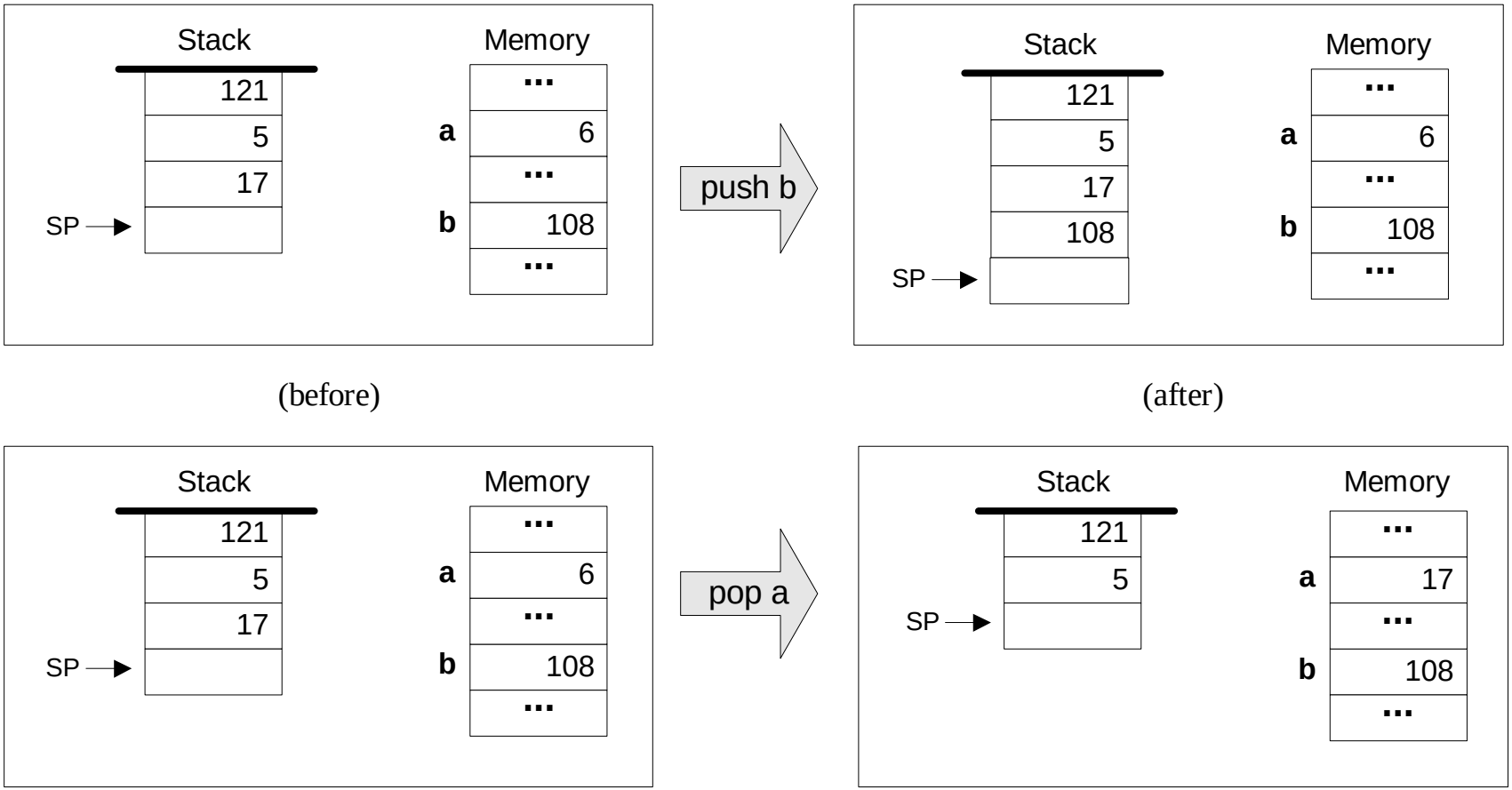
(before)





(after)

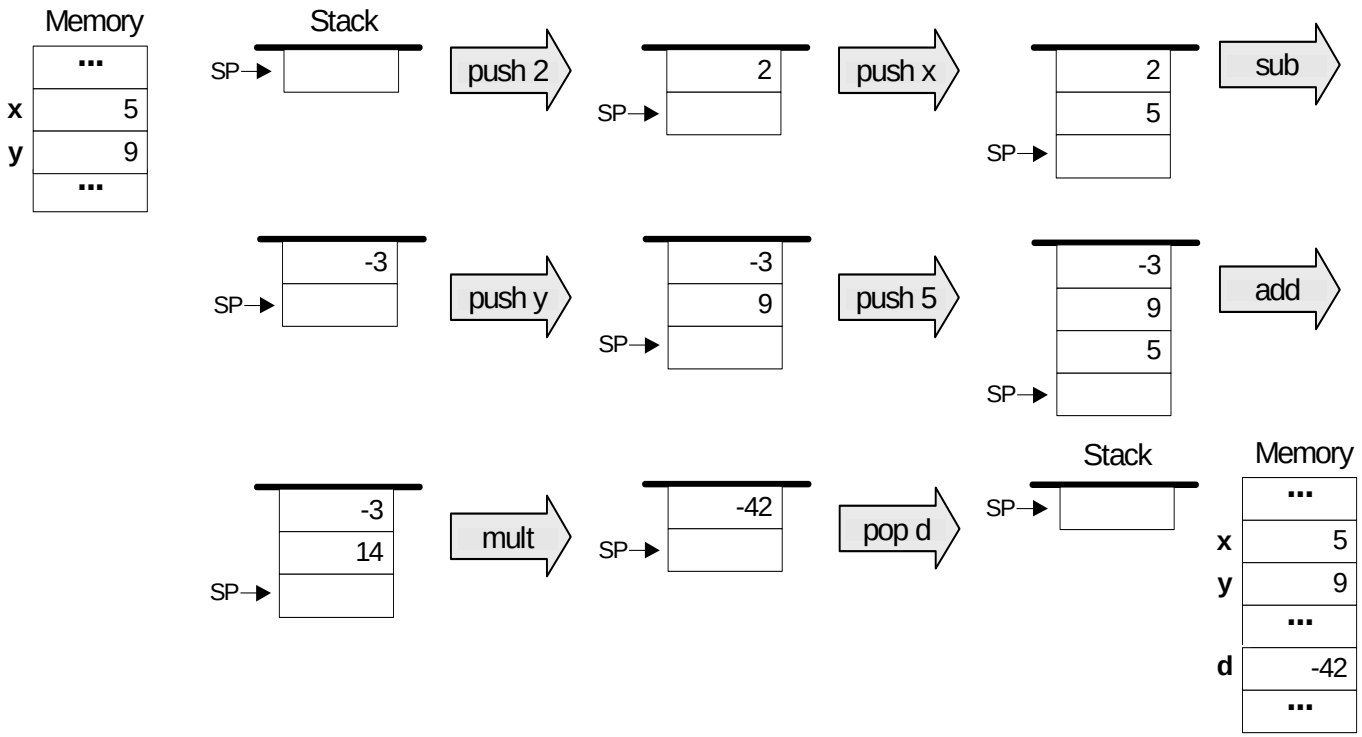
Memory access (first approximation)



- Classical data structure
- Elegant and powerful
- Implementation options.

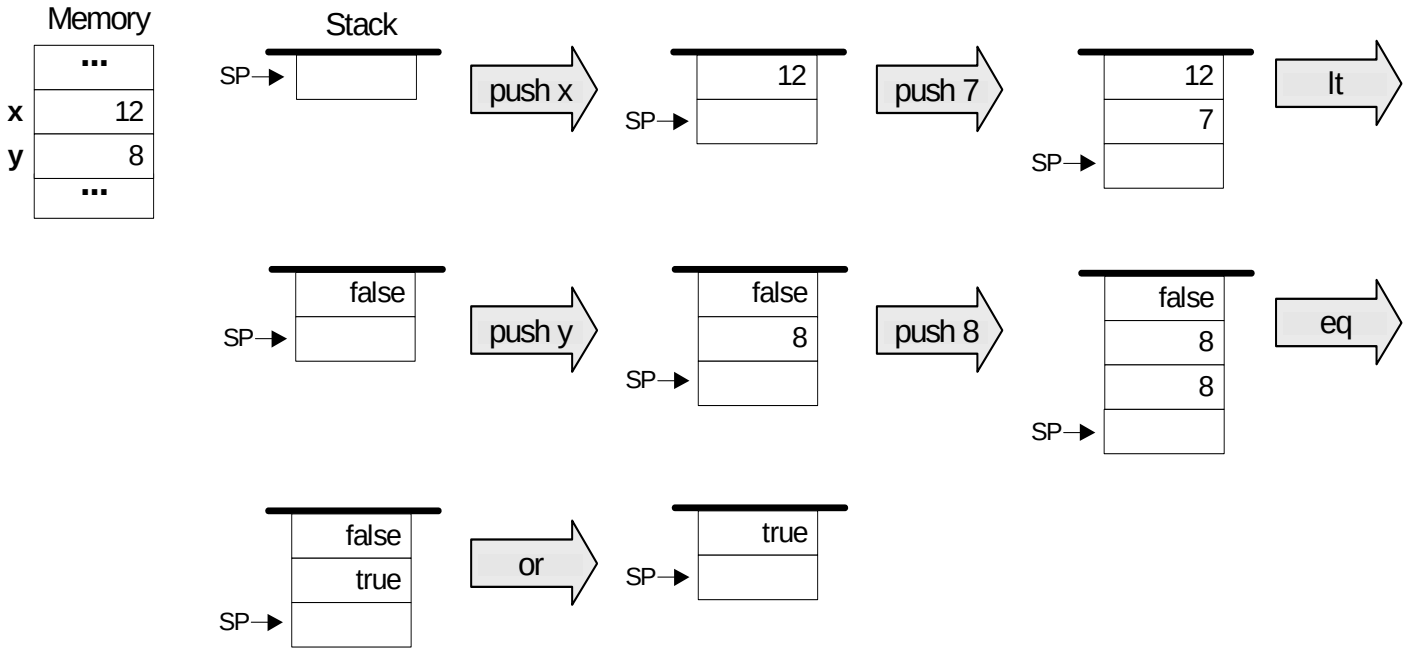
Evaluation of arithmetic expressions

```
// d=(2-x)*(y+5)
push 2
push x
sub
push y
push 5
add
mult
pop d
```



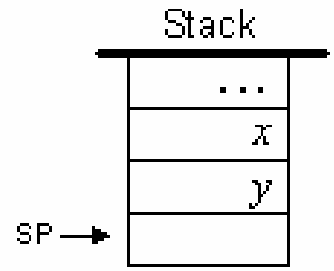
Evaluation of Boolean expressions

```
// if (x<7) or (y=8)
push x
push 7
lt
push y
push 8
eq
or
```



Arithmetic and Boolean commands (wrap-up)

Command	**Return value** (after popping the operand/s)	**Comment**
`add`	$x+y$	Integer addition (2's complement)
`sub`	$x-y$	Integer subtraction (2's complement)
`neg`	$-y$	Arithmetic negation (2's complement)
`eq`	true if $x=y$ and false otherwise	Equality
`gt`	true if $x>y$ and false otherwise	Greater than
`lt`	true if $x<y$ and false otherwise	Less than
`and`	x And y	Bit-wise
`or`	x Or y	Bit-wise
`not`	Not y	Bit-wise



Memory access (motivation)

A typical modern programming language features (at least) the following variable kinds:

- Class level
  - Static variables
  - Field variables (object properties)
- Method level:
  - Local variables
  - Argument variables
- And:
  - Array variables
  - Constants

The language translator, of which the VM is a key component, must support all these variable kinds.

Memory access commands

Command format:

pop *segment i*

push *segment i*

(Rather than **pop** *x* and **push** *y*,
as was shown in previous slides,
which was a conceptual simplification)

Where *i* is a non-negative integer and *segment* is one of the following vectors:

- **`static`**: holds global variables, shared by all functions in the same class
- **`argument`**: holds argument variables of the current function
- **`local`**: holds local variables of the current function
- **`constant`**: pseudo segment holding all the constants in the range 0…32767
- **`this`**, **`that`**: general-purpose segments;
  can be made to represent different areas in the heap
- **`pointer`**: used to map **`this`** and **`that`** on different areas in the heap
- **`temp`**: fixed 8-entry segment that holds temporary variables for general use; Shared by all VM functions in the program.

VM programming

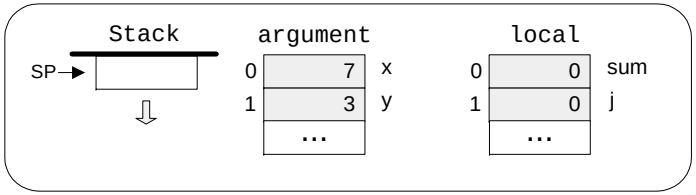
- VM programs are normally written by *compilers*, not by humans
- In order to write compilers, you have to understand the spirit of VM programming. So we will now see some examples:
  - Arithmetic task
  - Object handling task
  - Array handling task
- These example don't belong to this lecture, and are given here for motivation only.

Arithmetic example

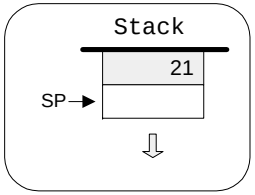
High-level code

```
function mult(x,y) {
  int result, j;
  result=0;
  j=y;
  while ~(j=0) {
    result=result+x;
      j=j-1;
  }
  return result;
}
```

Just after mult(7,3) is entered:



Just after mult(7,3) returns:



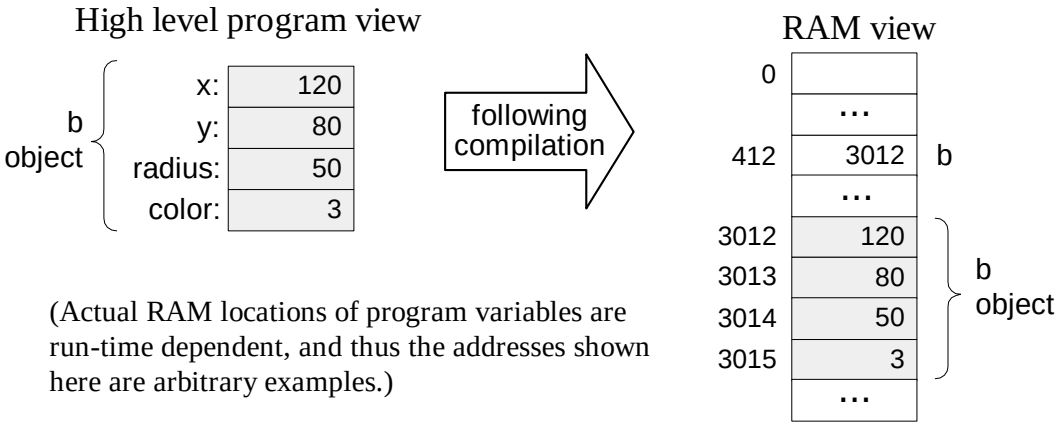
VM code (first approx.)

```
function mult(x,y)
   push 0
   pop result
   push y
   pop j
label loop
   push j
   push 0
   eq
   if-goto end
   push result
   push x
   add
   pop result
   push j
   push 1
   sub
   pop j
   goto loop
label end
   push result
   return
```

VM code

```
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
```

Object handling example

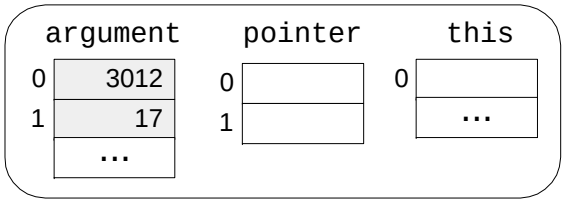


(Actual RAM locations of program variables are run-time dependent, and thus the addresses shown here are arbitrary examples.)

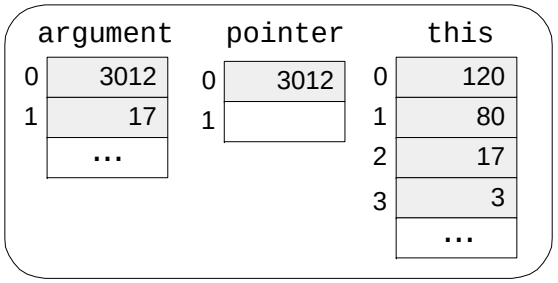
```
/* Assume that b and r were
   passed to the function as
   its first two arguments.
   The following code
   implements the operation
   b.radius=r. */

// Get b's base address:
push argument 0
// Point the this seg. to b:
pop pointer 0
// Get r's value
push argument 1
// Set b's third field to r:
pop this 2
```

Virtual memory segments just before the operation `b.radius=17`:

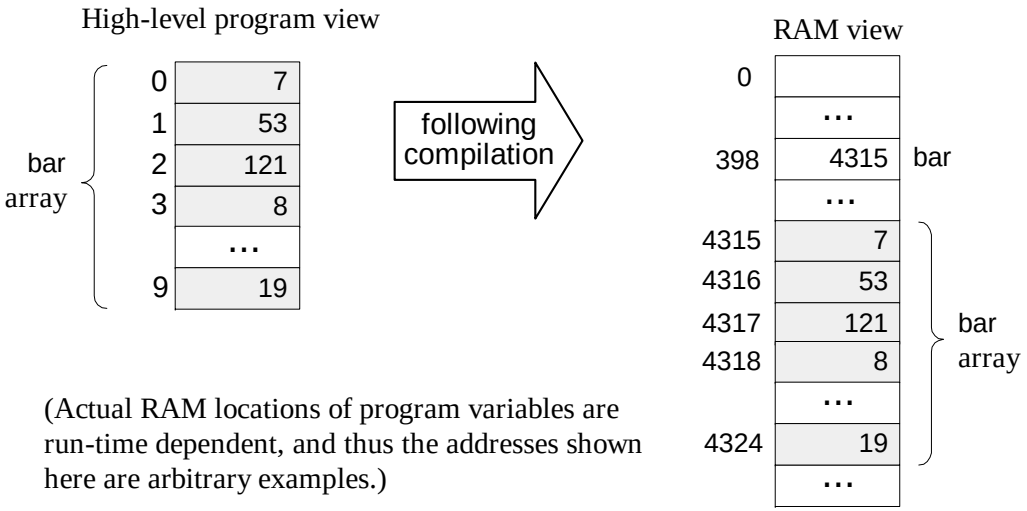


Virtual memory segments just after the operation `b.radius=17`:



(`this 0` is now alligned with `RAM[3012]`)

Array handling example

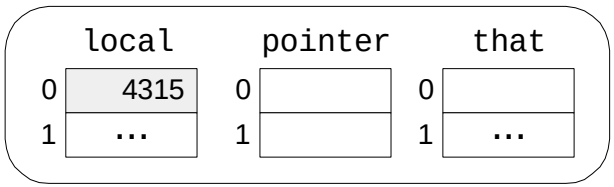


(Actual RAM locations of program variables are run-time dependent, and thus the addresses shown here are arbitrary examples.)

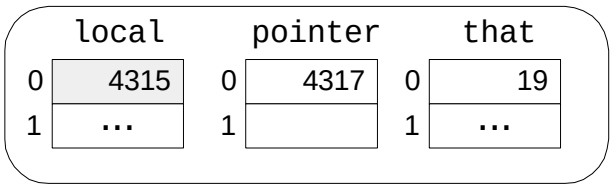
```
/* Assume that bar is the
first local variable declared
in the high-level program. The
code below implements
bar[2]=19, or *(bar+2)=19. */

// Get bar's base address:
push local 0
push constant 2
add
// Set that's base to (bar+2):
pop  pointer 1
push constant 19
// *(bar+2)=19:
pop  that 0
```

Virtual memory segments
Just before the bar[2]=19 operation:



Virtual memory segments
Just after the bar[2]=19 operation:



(`that 0` is now alligned with `RAM[4317]`)

Lecture plan

Goal: Specify and implement a VM model and language

Arithmetic / Boolean commands

```
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and
or
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```

This lecture

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Program flow commands

```
label     (declaration)
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Next lecture

Function calling commands

```
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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.

Implementation

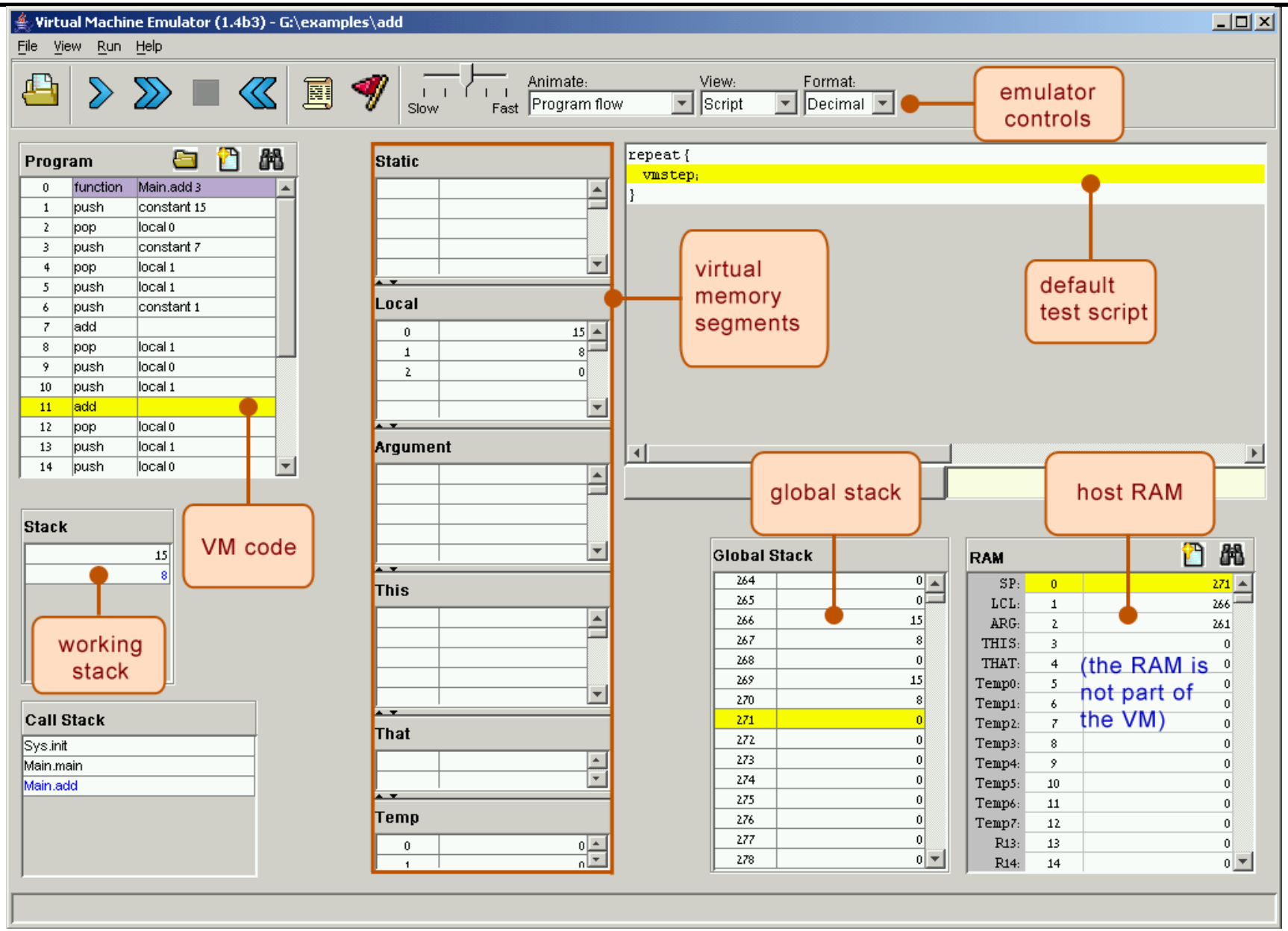
VM implementation options:

- Software-based (emulation)
- Translator-based (e.g., to the Hack language)
- Hardware-based (CPU-level)

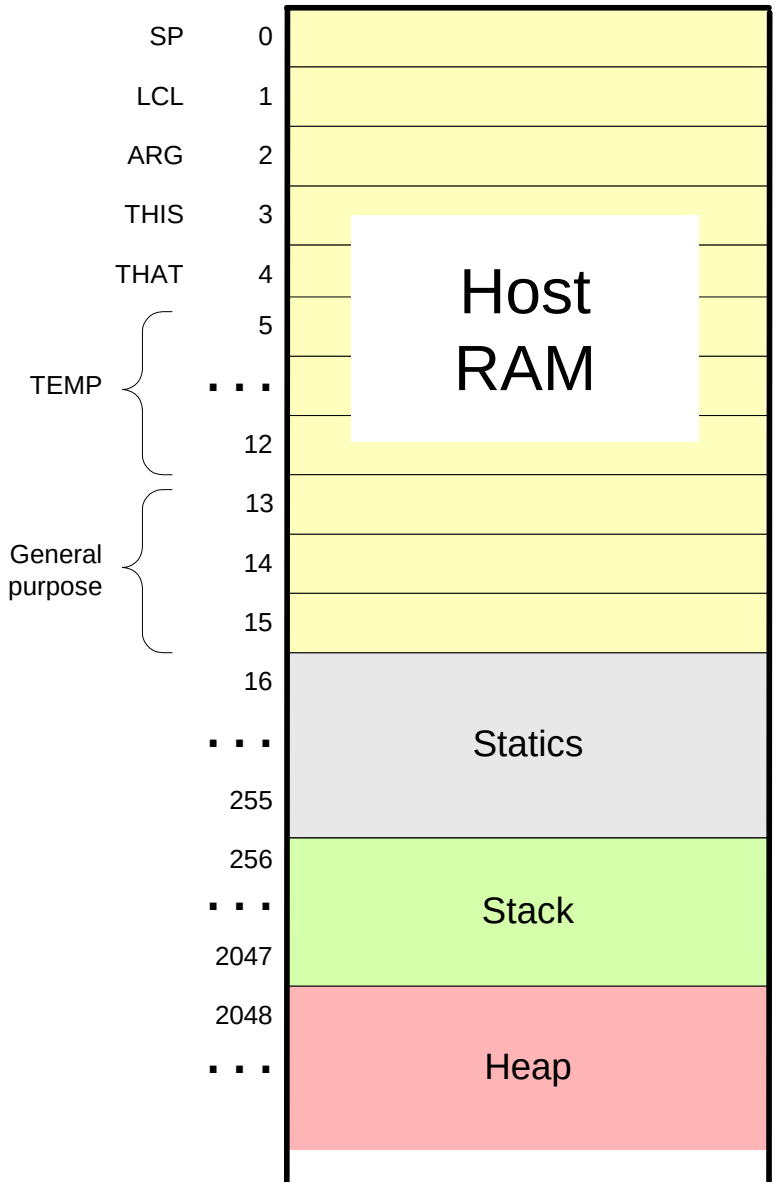
Famous translator-based implementations:

- JVM (runs bytecode in the Java platform)
- CLR (runs IL programs in the .NET platform).

Our VM emulator (part of the course software suite)



VM implementation on the Hack platform



- **The challenge:** (a) map the VM constructs on the host RAM, and (b) given this mapping, figure out how to implement each VM command using assembly commands that operate on the RAM
- **`local, argument, this, that`:** mapped on the RAM. The base addresses of these segments are kept in **`LCL, ARG, THIS, THAT`**. Access to the i-th entry of a segment is implemented by accessing the (base + i) word in the RAM
- **`static`:** static variable number j in a VM file f is implemented by the assembly language symbol **`f.j`** (and recall that the assembler implementation maps such symbols to the RAM starting from address 16)
- **`constant`:** truly a virtual segment. Access to **`constant i`** is implemented by supplying the constant i
- **`pointer, temp:`** see the book
- Exercise: given the above game rules, write the Hack commands that implement, say, **`push constant 5`** and **`pop local 2`**.

Parser module (proposed design)

Parser: Handles the parsing of a single `.vm` file, and encapsulates access to the input code. It reads VM commands, parses them, and provides convenient access to their components. In addition, it removes all white space and comments.			
Routine	**Arguments**	**Returns**	**Function**
Constructor	Input file / stream	--	Opens the input file/stream and gets ready to parse it.
`hasMoreCommands`	--	boolean	Are there more commands in the input?
`advance`	--	--	Reads the next command from the input and makes it the current command. Should be called only if `hasMoreCommands()` is true. Initially there is no current command.
`commandType`	--	`C_ARITHMETIC, C_PUSH, C_POP, C_LABEL, C_GOTO, C_IF, C_FUNCTION, C_RETURN, C_CALL`	Returns the type of the current VM command. `C_ARITHMETIC` is returned for all the arithmetic commands.
`arg1`	--	string	Returns the first argument of the current command. In the case of `C_ARITHMETIC`, the command itself (`add`, `sub`, etc.) is returned. Should not be called if the current command is `C_RETURN`.
`arg2`	--	int	Returns the second argument of the current command. Should be called only if the current command is `C_PUSH, C_POP, C_FUNCTION, or C_CALL.`

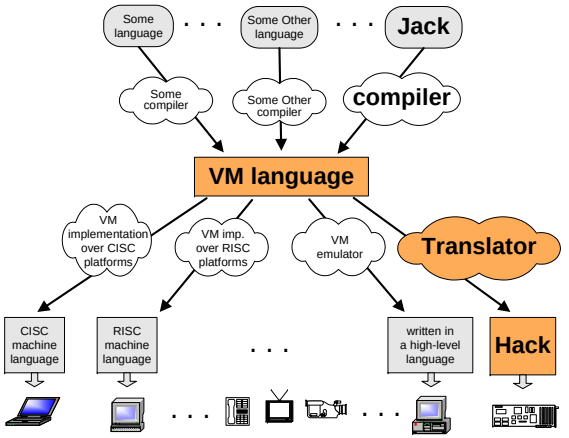
CodeWriter module (proposed design)

CodeWriter: Translates VM commands into Hack assembly code.			
Routine	**Arguments**	**Returns**	**Function**
Constructor	Output file / stream	--	Opens the output file/stream and gets ready to write into it.
`setFileName`	`fileName (string)`	--	Informs the code writer that the translation of a new VM file is started.
`writeArithmetic`	`command (string)`	--	Writes the assembly code that is the translation of the given arithmetic command.

`WritePushPop`	`Command (C_PUSH or C_POP),`
	
	`segment (string),`
	
	`index (int)`
		--	Writes the assembly code that is the translation of the given `command`, where `command` is either `C_PUSH or C_POP`.

`Close`	--	--	Closes the output file.
Comment: More routines will be added to this module in chapter 8.			

Perspective



- We began the process of building a compiler
- Modern compiler architecture:
  - Front end (translates from high level language to a VM language)
  - Back end (implements the VM language on a target platform)
- History of virtual machines (some milestones)
  - 1970's: p-Code
  - 1990's: Java's JVM
  - 2000's: Microsoft .NET
- A full blown VM implementation typically includes a common software library (can be viewed as a mini, portable OS)
- Road ahead: complete the VM spec. and implementation (chs. 7,8), build a compiler (Ch. 9,10,11), then build a run-time library (ch. 12).