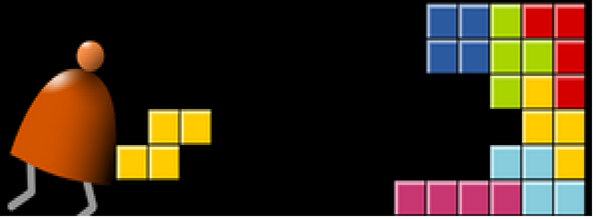
From Nand to Tetris

Building a Modern Computer from First Principles



Lecture 8

Virtual Machine II: Control

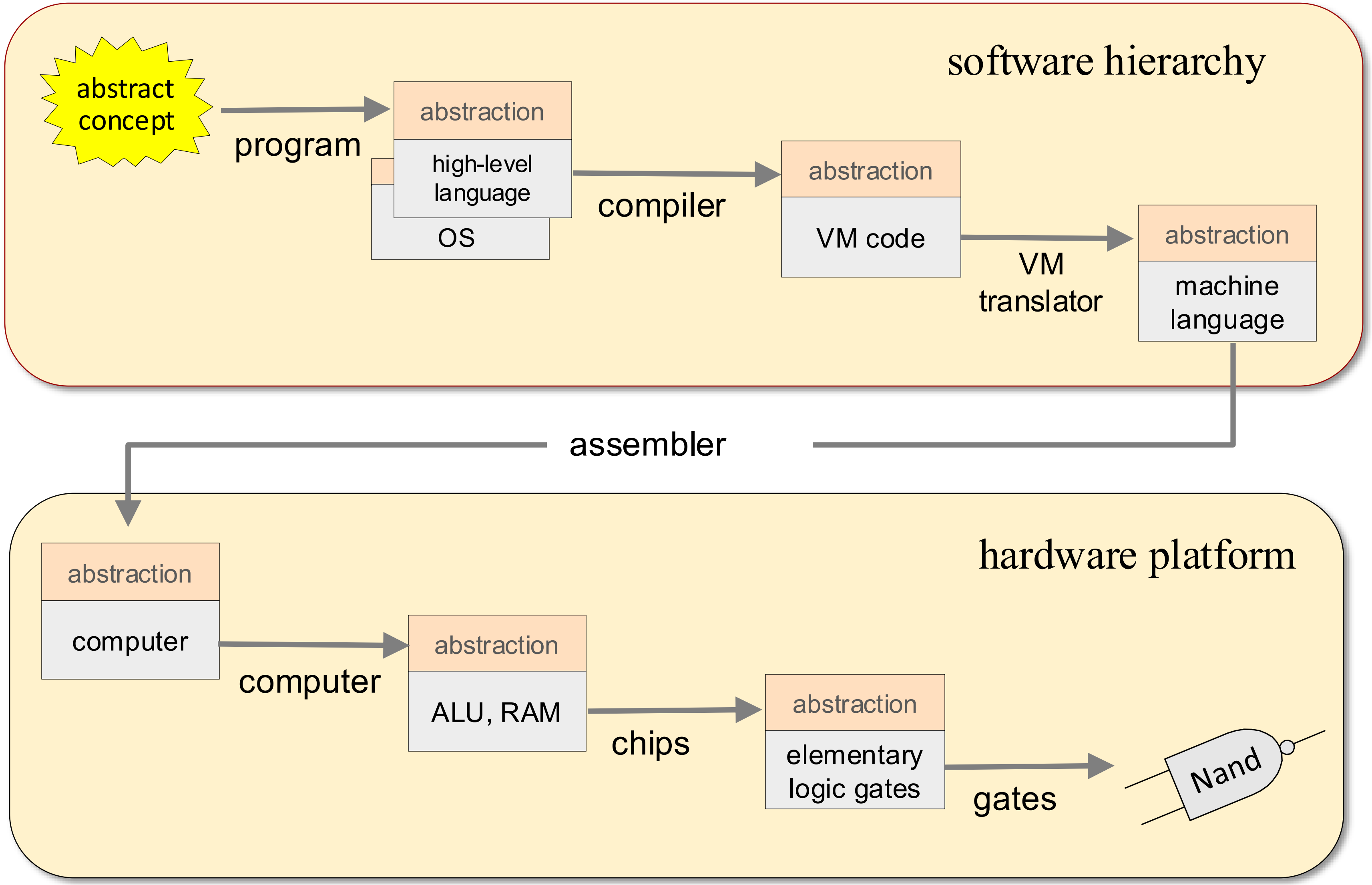
Slide deck for Chapter 8 of the book

The Elements of Computing Systems (2nd edition)

By Noam Nisan and Shimon Schocken

MIT Press

Nand to Tetris Roadmap



software hierarchy

abstract concept

program

abstraction

high-level language

OS

compiler

abstraction

VM code

VM translator

abstraction

machine language

assembler

hardware platform

abstraction

computer

computer

abstraction

ALU, RAM

chips

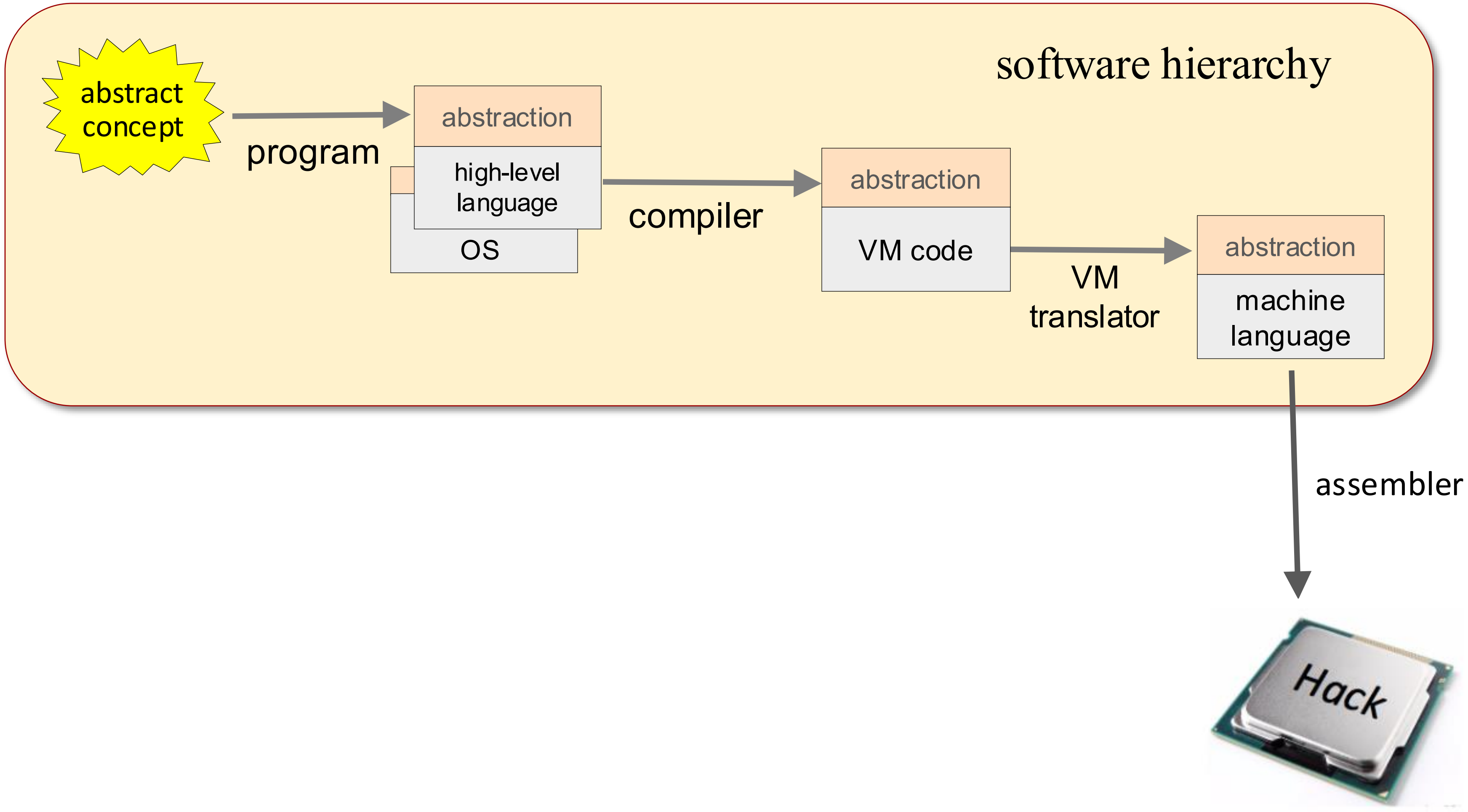
abstraction

elementary logic gates

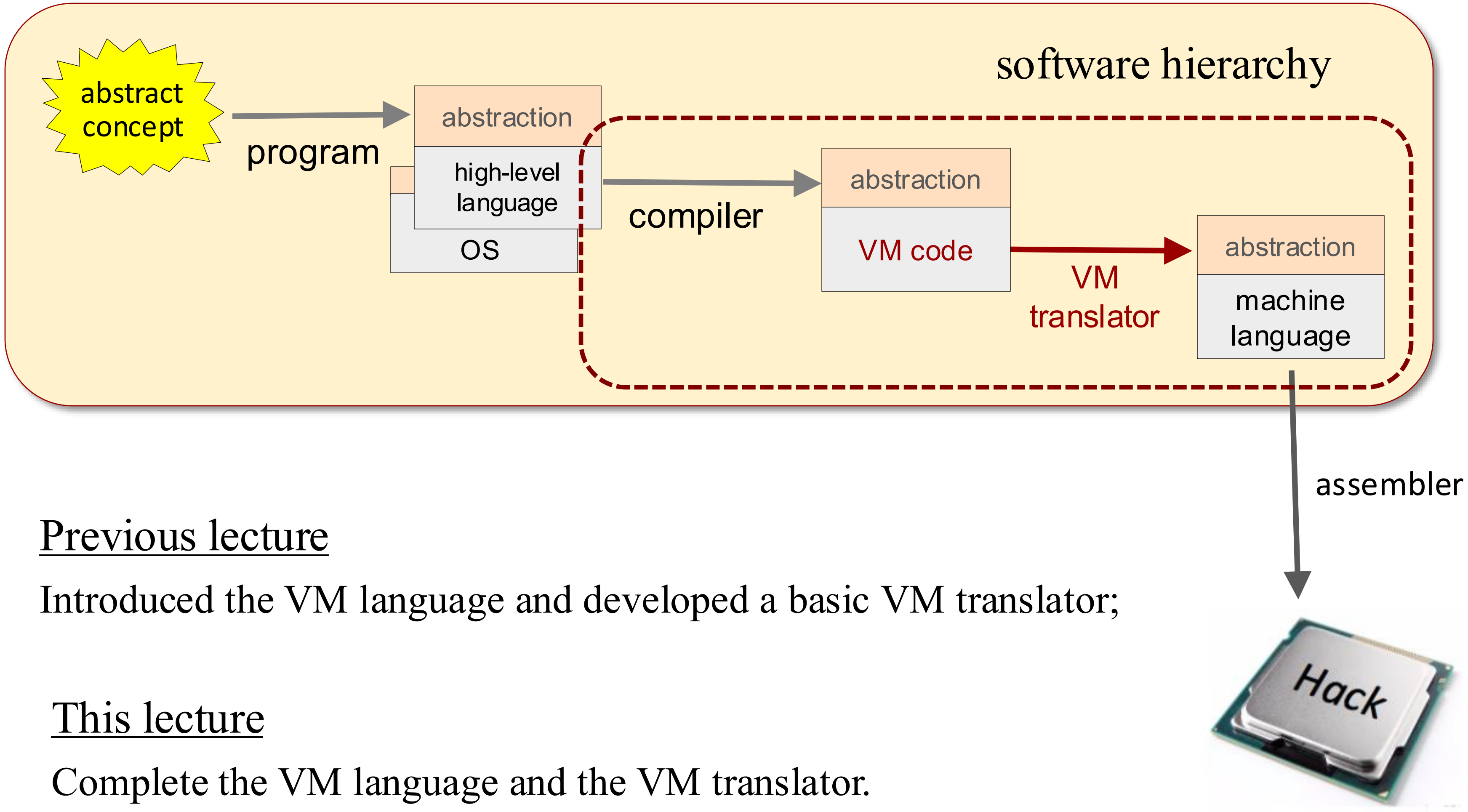
gates

Nand

Nand to Tetris Roadmap: Part II



Nand to Tetris Roadmap: Part II



Previous lecture

Introduced the VM language and developed a basic VM translator;

This lecture

Complete the VM language and the VM translator.

The VM language

✓ Push / pop commands

`push` *segment i*

`pop` *segment i*

✓ Arithmetic / Logical commands

`add`, `sub` , `neg`

`eq` , `gt` , `lt`

`and`, `or` , `not`

Previous lecture

Branching commands

`label` *label*

`goto` *label*

`if-goto` *label*

Function commands

`Function` *functionName nVars*

`Call` *functionName nArgs*

`return`

This lecture

Branching: Abstraction

```
// Returns arg0 * arg1
function mult 2
   push constant 0
   pop local 0
   push constant 1
   pop local 1
label WHILE_LOOP
   push local 1
   push argument 1
   gt
   if-goto END_LOOP
   push local 0
   push argument 0
   add
   pop local 0
   push local 1
   push constant 1
   add
   pop local 1
   goto WHILE_LOOP
label END_LOOP
   push local 0
   return
```

VM branching commands (syntax)

`label` *label*

`goto` *label*

`if-goto` *label*

Branching: Abstraction

```
// Returns arg0 * arg1
function mult 2
   push constant 0
   pop local 0
   push constant 1
   pop local 1
label WHILE_LOOP
   push local 1
   push argument 1
   gt
   if-goto END_LOOP
   push local 0
   push argument 0
   add
   pop local 0
   push local 1
   push constant 1
   add
   pop local 1
   goto WHILE_LOOP
label END_LOOP
   push local 0
   return
```

VM branching commands (syntax)

`label` *label*

`goto` *label*

`if-goto` *label*

Semantics

Marks the destination of `goto` commands.

Branching: Abstraction

```
// Returns arg0 * arg1
function mult 2
   push constant 0
   pop local 0
   push constant 1
   pop local 1
label WHILE_LOOP
   push local 1
   push argument 1
   gt
   if-goto END_LOOP
   push local 0
   push argument 0
   add
   pop local 0
   push local 1
   push constant 1
   add
   pop local 1
   goto WHILE_LOOP
label END_LOOP
   push local 0
   return
```

VM branching commands (syntax)

`label` *label*

`goto` *label*

`if-goto` *label*

Semantics

Jump to execute the command just after the *label*.

Branching: Abstraction

```
// Returns arg0 * arg1
function mult 2
   push constant 0
   pop local 0
   push constant 1
   pop local 1
label WHILE_LOOP
   push local 1
   push argument 1
   gt
   if-goto END_LOOP
   push local 0
   push argument 0
   add
   pop local 0
   push local 1
   push constant 1
   add
   pop local 1
   goto WHILE_LOOP
label END_LOOP
   push local 0
   return
```

VM branching commands (syntax)

`label` *label*

`goto` *label*

`if-goto` *label*

Semantics

let *cond* = `pop`

if *cond*, jump to execute the command just after the *label*;
else, execute the next command.

Branching: Abstraction

```
// Returns arg0 * arg1
function mult 2
   push constant 0
   pop local 0
   push constant 1
   pop local 1
label WHILE_LOOP
   push local 1
   push argument 1
   gt
   if-goto END_LOOP
   push local 0
   push argument 0
   add
   pop local 0
   push local 1
   push constant 1
   add
   pop local 1
   goto WHILE_LOOP
label END_LOOP
   push local 0
   return
```

VM branching commands (syntax)

`label` *label*

`goto` *label*

`if-goto` *label*

Semantics

let *cond* = `pop`

if *cond*, jump to execute the command just after the *label*;
else, execute the next command.

Convention: The code writer (typically, a *compiler*) must write code that pushes a boolean expression onto the stack before the `if-goto` command;
In this example, the highlighted code implements the semantics:

`if (local 1 > argument 1) goto END_LOOP`

Branching: Implementation

Abstraction (recap)

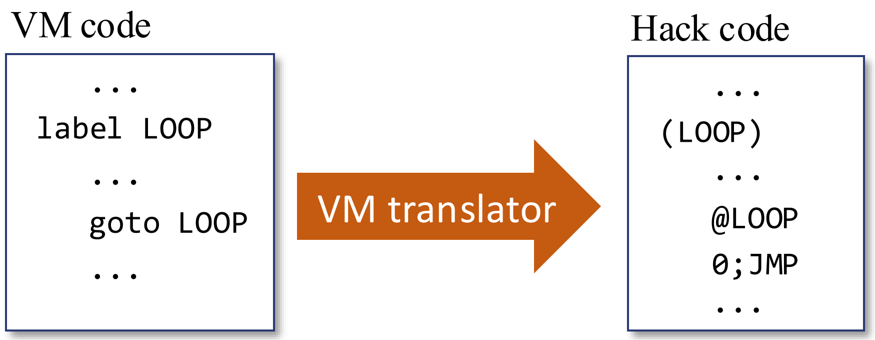
`label` *label* // label declaration

`goto` *label* // jump to execute the command just after the label

`if-goto` *label* // let *cond* = `pop`
 // if *cond* jump to execute the command just after the *label*

Implementation (VM translator)

For each VM branching command, we generate machine language instructions that realize the command on the target platform. Example:



VM code

```
    ...
label LOOP
    ...
    goto LOOP
    ...
```

Hack code

```
    ...
(LOOP)
    ...
    @LOOP
    0;JMP
    ...
```

The instruction set of every computer features low-level “labeling” and “goto” primitives;

Therefore, the translation of the VM branching commands to the machine language of the target platform is not difficult.

The VM language

✓ Push / pop commands

`push` *segment i*

`pop` *segment i*

✓ Arithmetic / Logical commands

`add`, `sub` , `neg`

`eq` , `gt` , `lt`

`and`, `or` , `not`

✓ Branching commands

`label` *label*

`goto` *label*

`if-goto` *label*

→ Function commands

`Function` *functionName nVars*

`Call` *functionName nArgs*

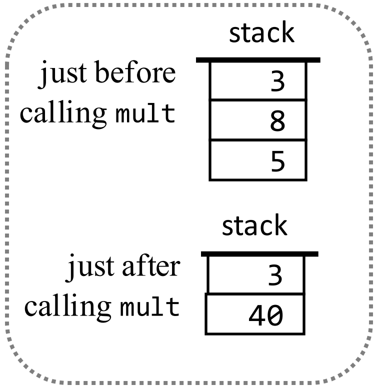
`return`

Functions: Abstraction

caller

```
function bar 4
  ...
  // Computes 3 + 8 * 5
  push constant 3
  push constant 8
  push constant 5
  call mult 2
  add
  ...
  return
```

bar's view:



callee

```
// Returns arg0 * arg1
function mult 2
   push constant 0
   pop local 0
   push constant 1
   pop local 1
label LOOP
   push local 1
   push argument 1
   gt
   if-goto END
   push local 0
   push argument 0
   add
   pop local 0
   push local 1
   push constant 1
   add
   pop local 1
   goto LOOP
label END
   push local 0
   return
```

Typical scenario

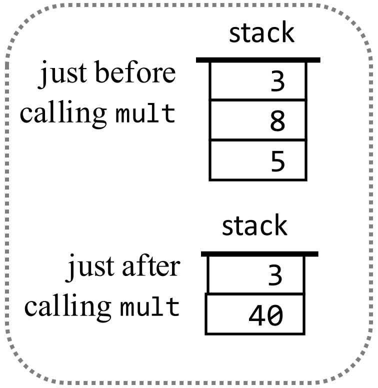
A function (the *caller*) calls
a function (the *callee*)
for its effect

Functions: Abstraction

caller

```
function bar 4
   ...
   // Computes 3 + 8 * 5
   push constant 3
   push constant 8
   push constant 5
   call mult 2
   add
   ...
   return
```

bar’s view:



callee

```
// Returns arg0 * arg1
function mult 2
    push constant 0
    pop local 0
    push constant 1
    pop local 1
label LOOP
    push local 1
    push argument 1
    gt
    if-goto END
    push local 0
    push argument 0
    add
    pop local 0
    push local 1
    push constant 1
    add
    pop local 1
    goto LOOP
label END
    push local 0
    return
```

VM function commands

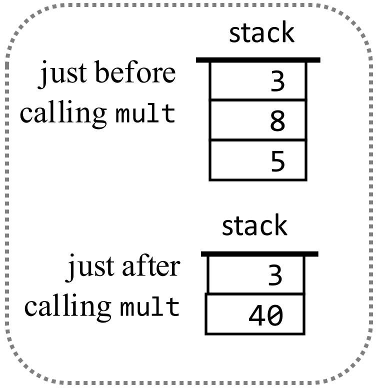
```
call
function
return
```

Functions: Abstraction

caller

```
function bar 4
   ...
   // Computes 3 + 8 * 5
   push constant 3
   push constant 8
   push constant 5
   call mult 2
   add
   ...
   return
```

bar's view:



stack

just before calling mult

3
8
5

stack

just after calling mult

3
40

callee

```
// Returns arg0 * arg1
function mult 2
    push constant 0
    pop local 0
    push constant 1
    pop local 1
label LOOP
    push local 1
    push argument 1
    gt
    if-goto END
    push local 0
    push argument 0
    add
    pop local 0
    push local 1
    push constant 1
    add
    pop local 1
    goto LOOP
label END
    push local 0
    return
```

VM function commands

`call`

`function`

`return`

Syntax: `call` *functionName nArgs*

Semantics: Calls function *functionName* for its effect, informing that *nArgs* argument values were pushed onto the stack

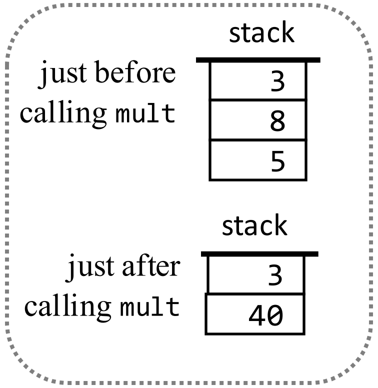
Convention: The caller must push *nArgs* arguments onto the stack before the `call` command.

Functions: Abstraction

caller

```
function bar 4
   ...
   // Computes 3 + 8 * 5
   push constant 3
   push constant 8
   push constant 5
   call mult 2
   add
   ...
   return
```

bar's view:



stack

just before calling mult

3
8
5

stack

just after calling mult

3
40

callee

```
// Returns arg0 * arg1
function mult 2
   push constant 0
   pop local 0
   push constant 1
   pop local 1
label LOOP
   push local 1
   push argument 1
   gt
   if-goto END
   push local 0
   push argument 0
   add
   pop local 0
   push local 1
   push constant 1
   add
   pop local 1
   goto LOOP
label END
   push local 0
   return
```

VM function commands

`call`

➡ `function`

`return`

Syntax: `function` *functionName nVars*

Semantics

Here starts the declaration of a function that has name *functionName* and *nVars* local variables

Note: In this example the caller passes 2 arguments, and the function has 2 local variables;

This is just a coincidence;

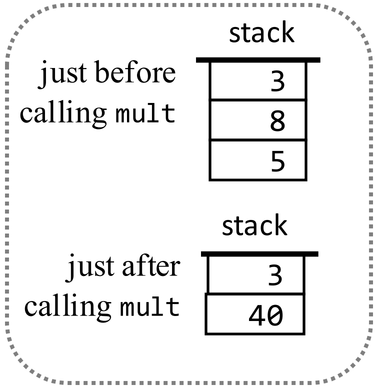
nArgs had nothing to do with *nVars*.

Functions: Abstraction

caller

```
function bar 4
   ...
   // Computes 3 + 8 * 5
   push constant 3
   push constant 8
   push constant 5
   call mult 2
   add
   ...
   return
```

bar's view:



stack

just before calling mult

3
8
5

stack

just after calling mult

3
40

callee

```
// Returns arg0 * arg1
function mult 2
   push constant 0
   pop local 0
   push constant 1
   pop local 1
label LOOP
   push local 1
   push argument 1
   gt
   if-goto END
   push local 0
   push argument 0
   add
   pop local 0
   push local 1
   push constant 1
   add
   pop local 1
   goto LOOP
label END
   push local 0
   return
```

VM function commands

- call
- function
- return

Syntax: return

Convention: The callee must
(1) push a return value onto the stack, and
(2) execute a return command

Semantics

The *return value* will replace (in the stack) the argument values that were pushed by the caller before the call;

Control will be transferred back to the caller;

Execution will resume with the command just after the call.

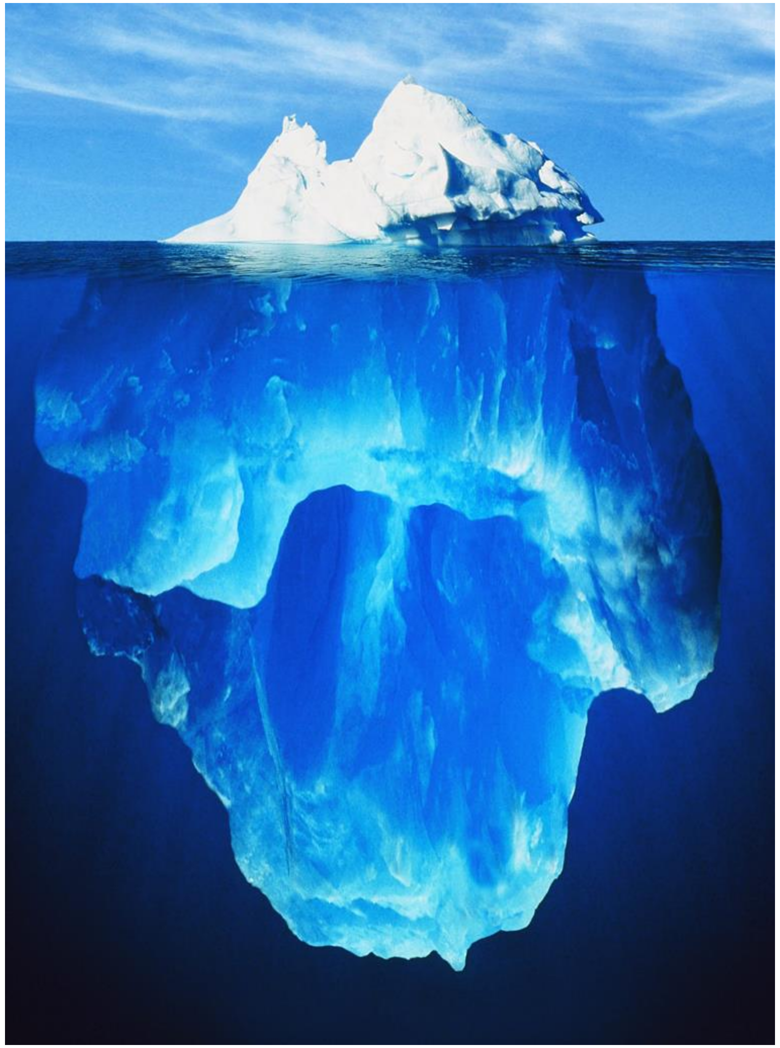
Functions: Implementation

Abstraction:

Functions: Implementation

Abstraction:

Implementation:



Function call and return

caller

```
function Foo.bar 4
   ...
   // Computes 3 + 8 * 5
   push constant 3
   push constant 8
   push constant 5
   call Foo.mult 2
   add
   ...
   return
```

callee

```
// Returns arg0 * arg1
function Foo.mult 2
    push constant 0
    pop local 0
    push constant 1
    pop local 1
    ...
    push local 0
    return
```

Function naming conventions

The full name of a VM function is *fileName*.*functionName*

In this example, the caller and the callee happen to be in the same VM file, `Foo.vm`

In general, they can be in different VM files.

Function call and return

caller

```
function Foo.bar 4
   ...
   // Computes 3 + 8 * 5
   push constant 3
   push constant 8
   push constant 5
   call Foo.mult 2
   add
   ...
   return
```

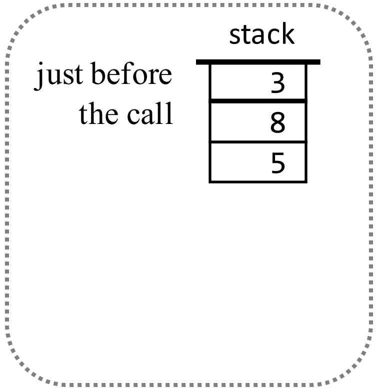
callee

```
// Returns arg0 * arg1
function Foo.mult 2
   push constant 0
   pop local 0
   push constant 1
   pop local 1
   ...
   push local 0
   return
```

Typical function-call-and-return scenario

Function `Foo.bar` (the *caller*) calls function `Foo.mult` (the *callee*) for its effect

`Foo.bar`'s view



Function call and return

caller

```
function Foo.bar 4
  ...
  // Computes 3 + 8 * 5
  push constant 3
  push constant 8
  push constant 5
  call Foo.mult 2
  add
  ...
  return
```

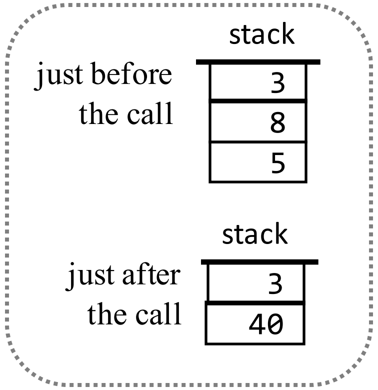
callee

```
// Returns arg0 * arg1
function Foo.mult 2
   push constant 0
   pop local 0
   push constant 1
   pop local 1
   ...
   push local 0
   return
```

<u>Typical function-call-and-return scenario</u>

Function `Foo.bar` (the *caller*) calls function `Foo.mult` (the *callee*) for its effect

Foo.bar's view



Magic!

Let's open
the black box

Function call and return

caller

```
function Foo.bar 4
   ...
   // Computes 3 + 8 * 5
   push constant 3
   push constant 8
   push constant 5
   call Foo.mult 2
   add
   ...
   return
```

callee

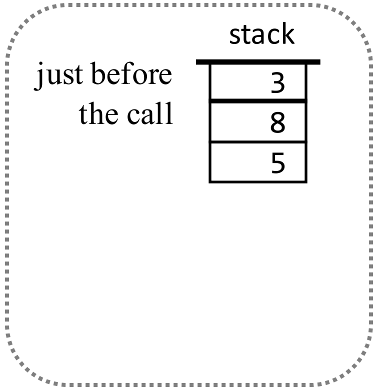
```
    // Returns arg0 * arg1
0   function Foo.mult 2
1      push constant 0
2      pop local 0
3      push constant 1
4      pop local 1
...    ...
20     push local 0
21     return
```

line numbers added, just for reference

Typical function-call-and-return scenario

Function `Foo.bar` (the *caller*) calls function `Foo.mult` (the *callee*) for its effect

`Foo.bar`'s view



Function call and return

caller

```
function Foo.bar 4
   ...
   // Computes 3 + 8 * 5
   push constant 3
   push constant 8
   push constant 5
   call Foo.mult 2
   add
   ...
   return
```

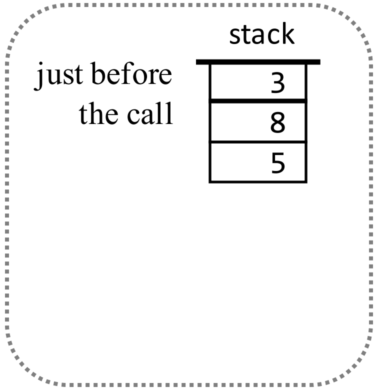
callee

```
// Returns arg0 * arg1
function Foo.mult 2
   push constant 0
   pop local 0
   push constant 1
   pop local 1
   ...
   push local 0
   return
```

Typical function-call-and-return scenario

Function `Foo.bar` (the *caller*) calls function `Foo.mult` (the *callee*) for its effect

`Foo.bar`'s view



The caller's execution is put on hold

Function call and return

caller

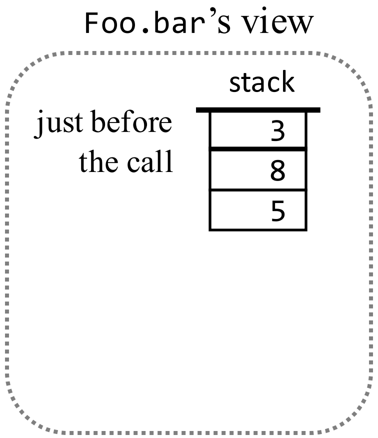
```
function Foo.bar 4
   ...
   // Computes 3 + 8 * 5
   push constant 3
   push constant 8
   push constant 5
   call Foo.mult 2
   add
   ...
   return
```

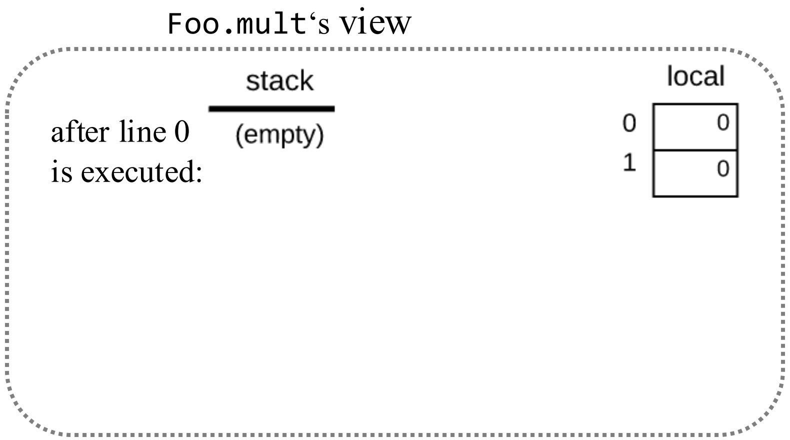
callee

```
     // Returns arg0 * arg1
0    function Foo.mult 2
1       push constant 0
2       pop local 0
3       push constant 1
4       pop local 1
...     ...
20      push local 0
21      return
```

Typical function-call-and-return scenario

Function `Foo.bar` (the *caller*) calls function `Foo.mult` (the *callee*) for its effect





The caller's execution is put on hold

Function call and return

caller

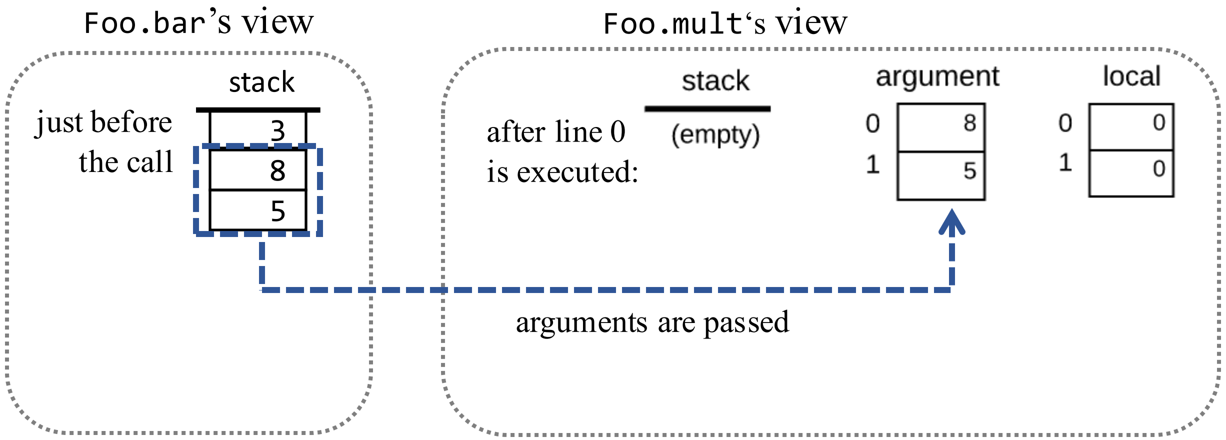
```
function Foo.bar 4
   ...
   // Computes 3 + 8 * 5
   push constant 3
   push constant 8
   push constant 5
   call Foo.mult 2
   add
   ...
   return
```

callee

```
      // Returns arg0 * arg1
 0    function Foo.mult 2
 1       push constant 0
 2       pop local 0
 3       push constant 1
 4       pop local 1
...      ...
20       push local 0
21       return
```

Typical function-call-and-return scenario

Function `Foo.bar` (the *caller*) calls function `Foo.mult` (the *callee*) for its effect



The caller's execution is put on hold

Function call and return

caller

```
function Foo.bar 4
   ...
   // Computes 3 + 8 * 5
   push constant 3
   push constant 8
   push constant 5
   call Foo.mult 2
   add
   ...
   return
```

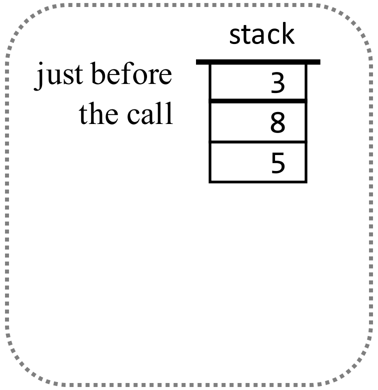
callee

```
    // Returns arg0 * arg1
 0  function Foo.mult 2
 1     push constant 0
 2     pop local 0
 3     push constant 1
 4     pop local 1
...    ...
20     push local 0
21     return
```

Typical function-call-and-return scenario

Function `Foo.bar` (the *caller*) calls function `Foo.mult` (the *callee*) for its effect

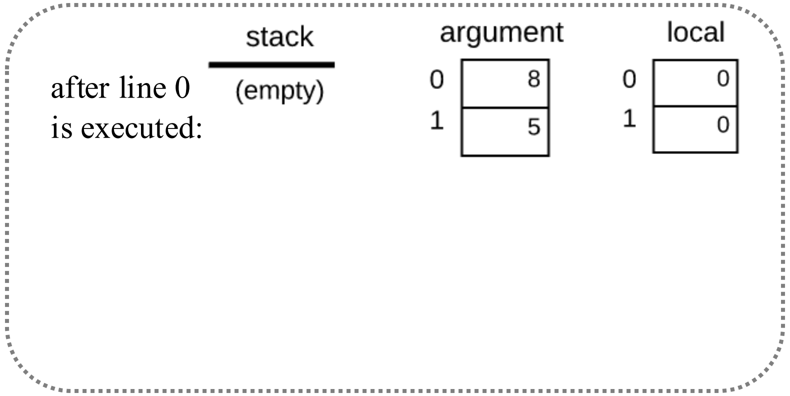
`Foo.bar`'s view



just before the call

stack
3
8
5

`Foo.mult`'s view



after line 0 is executed:

stack: (empty)

argument	
0	8
1	5

local	
0	0
1	0

The callee's code is executed

Function call and return

caller

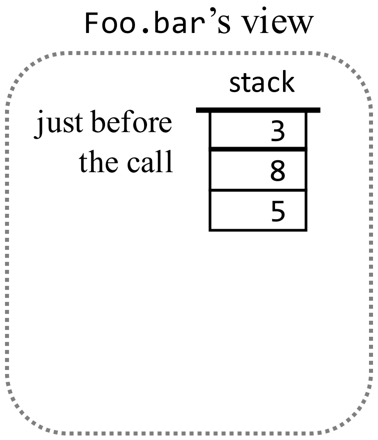
```
function Foo.bar 4
   ...
   // Computes 3 + 8 * 5
   push constant 3
   push constant 8
   push constant 5
   call Foo.mult 2
   add
   ...
   return
```

callee

```
    // Returns arg0 * arg1
0   function Foo.mult 2
1      push constant 0
2      pop local 0
3      push constant 1
4      pop local 1
...    ...
20     push local 0
21     return
```

Typical function-call-and-return scenario

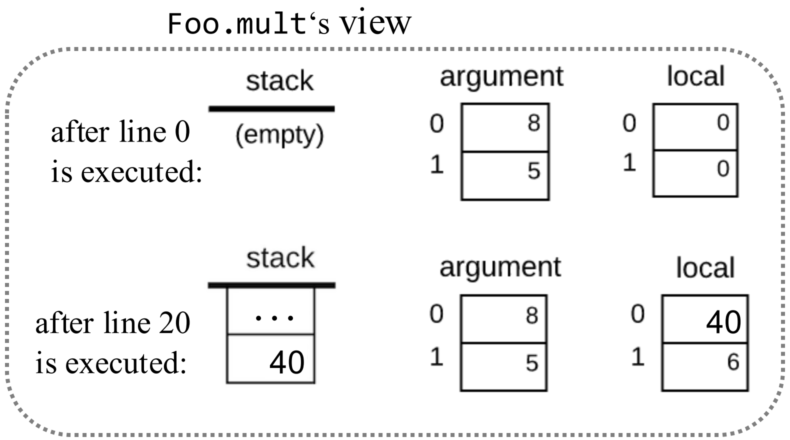
Function `Foo.bar` (the *caller*) calls function `Foo.mult` (the *callee*) for its effect



`Foo.bar`'s view

just before the call

stack
3
8
5



`Foo.mult`'s view

after line 0 is executed:

stack: (empty)

argument	
0	8
1	5

local	
0	0
1	0

after line 20 is executed:

stack
...
40

argument	
0	8
1	5

local	
0	40
1	6

The callee's code is executed

Function call and return

caller

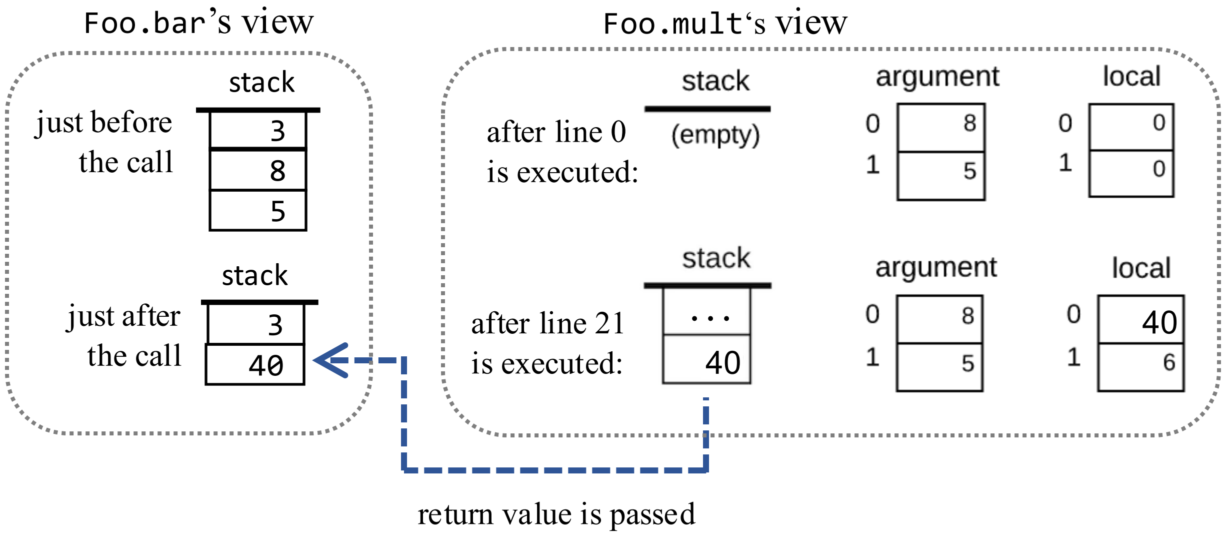
```
function Foo.bar 4
   ...
   // Computes 3 + 8 * 5
   push constant 3
   push constant 8
   push constant 5
   call Foo.mult 2
   add
   ...
   return
```

callee

```
       // Returns arg0 * arg1
0      function Foo.mult 2
1         push constant 0
2         pop local 0
3         push constant 1
4         pop local 1
...       ...
20        push local 0
21        return
```

Typical function-call-and-return scenario

Function `Foo.bar` (the *caller*) calls function `Foo.mult` (the *callee*) for its effect



`Foo.bar`'s view

just before the call

stack: 3, 8, 5

just after the call

stack: 3, 40

`Foo.mult`'s view

after line 0 is executed:

stack: (empty)

argument	
0	8
1	5

local	
0	0
1	0

after line 21 is executed:

stack: ..., 40

argument	
0	8
1	5

local	
0	40
1	6

return value is passed

The callee's execution is terminating

Function call and return

caller

```
function Foo.bar 4
   ...
   // Computes 3 + 8 * 5
   push constant 3
   push constant 8
   push constant 5
   call Foo.mult 2
   add
   ...
   return
```

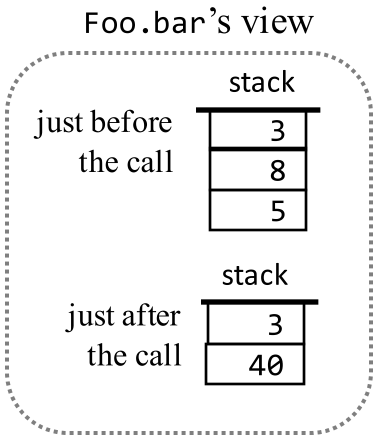
callee

```
    // Returns arg0 * arg1
0   function Foo.mult 2
1      push constant 0
2      pop local 0
3      push constant 1
4      pop local 1
...    ...
20     push local 0
21     return
```

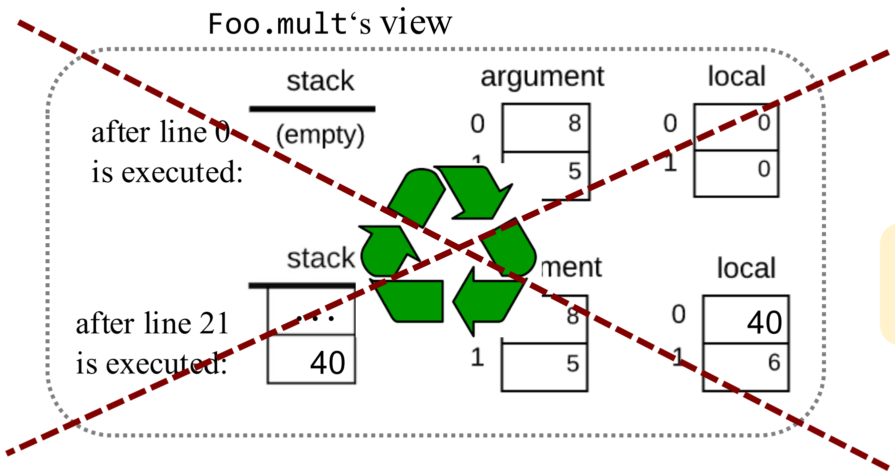
Typical function-call-and-return scenario

Function `Foo.bar` (the *caller*) calls function `Foo.mult` (the *callee*) for its effect

`Foo.bar`’s view



`Foo.mult`‘s view



The callee’s execution is terminating

Function call and return

caller

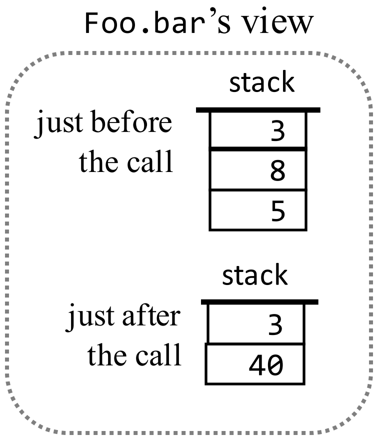
```
function Foo.bar 4
   ...
   // Computes 3 + 8 * 5
   push constant 3
   push constant 8
   push constant 5
   call Foo.mult 2
   add
   ...
   return
```

callee

```
// Returns arg0 * arg1
function Foo.mult 2
   push constant 0
   pop local 0
   push constant 1
   pop local 1
   ...
   push local 0
   return
```

Typical function-call-and-return scenario

Function `Foo.bar` (the *caller*) calls function `Foo.mult` (the *callee*) for its effect



`Foo.bar`'s view

just before the call

stack

3
8
5

just after the call

stack

3
40

The caller's execution is resumed

(the next command to be executed: `add`)

Function call and return

caller

```
function Foo.bar 4
   ...
   // Computes 3 + 8 * 5
   push constant 3
   push constant 8
   push constant 5
   call Foo.mult 2
   add
   ...
   return
```

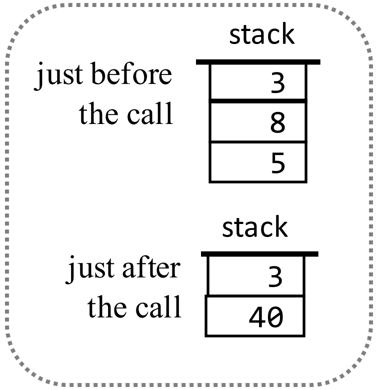
callee

```
// Returns arg0 * arg1
function Foo.mult 2
   push constant 0
   pop local 0
   push constant 1
   pop local 1
   ...
   push local 0
   return
```

Typical function-call-and-return scenario

Function `Foo.bar` (the *caller*) calls function `Foo.mult` (the *callee*) for its effect

Foo.bar's view



just before the call

stack

3
8
5

just after the call

stack

3
40

Magic!

Function call and return

Abstraction (recap)

A VM program typically consists of many VM functions;

The functions call each other, for their effect (including recursively);

Each function execution sees its own working stack, and its own memory segments;

Arguments and return values are passed, somehow.

Implementation (VM translator)

We'll describe the translation process in two stages:

- Pseudocode
- Detailed

Translation (pseudocode)

VM code

caller:

```
function Foo.bar 4
   ...
   // Computes 3 + 8 * 5
   push constant 3
   push constant 8
   push constant 5
   call Foo.mult 2
   add
   ...
   return
```

callee:

```
// Computes arg 0 * arg 1
function Foo.mult 2
   push constant 0
   pop local 0
   push constant 1
   pop local 1
   ...
   // Returns the result
   push local 0
   return
```

Conventions (reminder)

Each VM function must:

start with a `function` command,

end with a `return` command;

return a value.

Responsibility:

The VM code writer (typically, a compiler).

Translation (pseudocode)

VM code

caller:

```
function Foo.bar 4
   ...
   // Computes 3 + 8 * 5
   push constant 3
   push constant 8
   push constant 5
   call Foo.mult 2
   add
   ...
```

callee:

```
 // Computes arg 0 * arg 1
function Foo.mult 2
   push constant 0
   pop local 0
   push constant 1
   pop local 1
   ...
   // Returns the result
   push local 0
   return
```

VM translator

Generated code (pseudo assembly)

Translation (pseudocode)

VM code

caller:

```
function Foo.bar 4
    ...
    // Computes 3 + 8 * 5
    push constant 3
    push constant 8
    push constant 5
    call Foo.mult 2
    add
    ...
```

callee:

```
  // Computes arg 0 * arg 1
function Foo.mult 2
    push constant 0
    pop local 0
    push constant 1
    pop local 1
    ...
    // Returns the result
    push local 0
    return
```

VM translator

Generated code (pseudo assembly)

```
// function Foo.bar 4
(Foo.bar)  // injected function's entry point label
    // assembly code that initializes the function's 4 local variables
```

Translation (pseudocode)

VM code

caller:

```
function Foo.bar 4
    ...
    // Computes 3 + 8 * 5
    push constant 3
    push constant 8
    push constant 5
    call Foo.mult 2
    add
    ...
```

callee:

```
  // Computes arg 0 * arg 1
function Foo.mult 2
    push constant 0
    pop local 0
    push constant 1
    pop local 1
    ...
    // Returns the result
    push local 0
    return
```

VM translator

Generated code (pseudo assembly)

```
// function Foo.bar 4
(Foo.bar)  // injected function's entry point label
   // assembly code that initializes the function's 4 local variables
   // assembly code that handles ..., push constant 3, ..., push constant 5
```

Blue pseudocode:
Generated by the basic VM translator (project 7);

Black pseudocode:
Generated by the final VM translator (project 8).

Translation (pseudocode)

VM code

caller:

```
function Foo.bar 4
   ...
   // Computes 3 + 8 * 5
   push constant 3
   push constant 8
   push constant 5
   call Foo.mult 2
   add
   ...
```

callee:

```
   // Computes arg 0 * arg 1
function Foo.mult 2
   push constant 0
   pop local 0
   push constant 1
   pop local 1
   ...
   // Returns the result
   push local 0
   return
```

VM translator

Generated code (pseudo assembly)

```
// function Foo.bar 4
(Foo.bar)   // injected function's entry point label
   // assembly code that initializes the function's 4 local variables
   // assembly code that handles  ..., push constant 3, ..., push constant 5
// call Foo.mult 2
   // Creates a return address label (Foo.bar$ret.1); Saves the return
   // address and the caller's segment pointers, and then generates:
    goto Foo.mult      // injected branching to the called function
(Foo.bar$ret.1)        // injected return address label
```

Blue pseudocode:
Generated by the basic VM translator (project 7);

Black pseudocode:
Generated by the final VM translator (project 8).

Translation (pseudocode)

VM code

caller:

```
function Foo.bar 4
    ...
    // Computes 3 + 8 * 5
    push constant 3
    push constant 8
    push constant 5
    call Foo.mult 2
    add
    ...
```

callee:

```
  // Computes arg 0 * arg 1
function Foo.mult 2
    push constant 0
    pop local 0
    push constant 1
    pop local 1
    ...
    // Returns the result
    push local 0
    return
```

VM translator

Generated code (pseudo assembly)

```
// function Foo.bar 4
(Foo.bar)  // injected function's entry point label
   // assembly code that initializes the function's 4 local variables
   // assembly code that handles  ..., push constant 3, ..., push constant 5
// call Foo.mult 2
   // Creates a return address label (Foo.bar$ret.1); Saves the return
   // address and the caller's segment pointers, and then generates:
    goto Foo.mult       // injected branching to the called function
(Foo.bar$ret.1)        // injected return address label
    // assembly code that handles  add, ...
```

Blue pseudocode:
Generated by the basic VM translator (project 7);

Black pseudocode:
Generated by the final VM translator (project 8).

Translation (pseudocode)

VM code

caller:

```
function Foo.bar 4
    ...
    // Computes 3 + 8 * 5
    push constant 3
    push constant 8
    push constant 5
    call Foo.mult 2
    add
    ...
```

callee:

```
   // Computes arg 0 * arg 1
function Foo.mult 2
    push constant 0
    pop local 0
    push constant 1
    pop local 1
    ...
    // Returns the result
    push local 0
    return
```

VM translator

Generated code (pseudo assembly)

```
// function Foo.bar 4
(Foo.bar)   // injected function's entry point label
     // assembly code that initializes the function's 4 local variables
     // assembly code that handles  ..., push constant 3, ..., push constant 5
// call Foo.mult 2
     // Creates a return address label (Foo.bar$ret.1); Saves the return
     // address and the caller's segment pointers, and then generates:
      goto Foo.mult      // injected branching to the called function
(Foo.bar$ret.1)          // injected return address label
      // assembly code that handles  add, ...

// function Foo.mult 2
(Foo.mult)   // injected function's entry point label
     // assembly code that initializes the function's 2 local variables
```

Blue pseudocode:
  Generated by the basic VM translator (project 7);

Black pseudocode:
  Generated by the final VM translator (project 8).

Translation (pseudocode)

VM code

caller:

```
function Foo.bar 4
    ...
    // Computes 3 + 8 * 5
    push constant 3
    push constant 8
    push constant 5
    call Foo.mult 2
    add
    ...
```

callee:

```
  // Computes arg 0 * arg 1
function Foo.mult 2
    push constant 0
    pop local 0
    push constant 1
    pop local 1
    ...
    // Returns the result
    push local 0
    return
```

VM translator

Generated code (pseudo assembly)

```
// function Foo.bar 4
(Foo.bar)   // injected function's entry point label
    // assembly code that initializes the function's 4 local variables
    // assembly code that handles ..., push constant 3, ..., push constant 5
// call Foo.mult 2
    // Creates a return address label (Foo.bar$ret.1); Saves the return
    // address and the caller's segment pointers, and then generates:
    goto Foo.mult      // injected branching to the called function
(Foo.bar$ret.1)        // injected return address label
    // assembly code that handles add, ...

// function Foo.mult 2
(Foo.mult)   // injected function's entry point label
    // assembly code that initializes the function's 2 local variables
    // assembly code that handles push constant 0 , ..., push local 0
```

Blue pseudocode:
Generated by the basic VM translator (project 7);

Black pseudocode:
Generated by the final VM translator (project 8).

Translation (pseudocode)

VM code

caller:

```
function Foo.bar 4
    ...
    // Computes 3 + 8 * 5
    push constant 3
    push constant 8
    push constant 5
    call Foo.mult 2
    add
    ...
```

callee:

```
  // Computes arg 0 * arg 1
function Foo.mult 2
    push constant 0
    pop local 0
    push constant 1
    pop local 1
    ...
    // Returns the result
    push local 0
    return
```

VM translator

Generated code (pseudo assembly)

```
// function Foo.bar 4
(Foo.bar)   // injected function's entry point label
    // assembly code that initializes the function's 4 local variables
    // assembly code that handles  ..., push constant 3, ..., push constant 5
// call Foo.mult 2
    // Creates a return address label (Foo.bar$ret.1); Saves the return
    // address and the caller's segment pointers, and then generates:
    goto Foo.mult       // injected branching to the called function
(Foo.bar$ret.1)        // injected return address label
     // assembly code that handles  add, ...

// function Foo.mult 2
(Foo.mult)   // injected function's entry point label
    // assembly code that initializes the function's 2 local variables
    // assembly code that handles push constant 0 , ..., push local 0

// return
    // Gets the saved return address (which, in this example, happens to be
    // Foo.bar$ret.1), replaces the arguments pushed by the caller with
    // the return value (stack's top element), reinstates the segment pointers
    // of the caller, and then generates:
    goto Foo.bar$ret.1  // injected branching back to the calling site.
```

Blue pseudocode:
Generated by the basic VM translator (project 7);

Black pseudocode:
Generated by the final VM translator (project 8).

Translation (pseudocode)

VM code

caller:

```
function Foo.bar 4
   ...
   // Computes 3 + 8 * 5
   push constant 3
   push constant 8
   push constant 5
   call Foo.mult 2
   add
   ...
```

callee:

```
   // Computes arg 0 * arg 1
function Foo.mult 2
   push constant 0
   pop local 0
   push constant 1
   pop local 1
   ...
   // Returns the result
   push local 0
   return
```

VM translator

Generated code (pseudo assembly)

```
// function Foo.bar 4
(Foo.bar)   // injected function's entry point label
   // assembly code that initializes the function's 4 local variables
   // assembly code that handles  ..., push constant 3, ..., push constant 5
// call Foo.mult 2
   // Creates a return address label (Foo.bar$ret.1); Saves the return
   // address and the caller's segment pointers, and then generates:
   goto Foo.mult       // injected branching to the called function
(Foo.bar$ret.1)        // injected return address label
    // assembly code that handles  add, ...

// function Foo.mult 2
(Foo.mult)   // injected function's entry point label
   // assembly code that initializes the function's 2 local variables
   // assembly code that handles push constant 0 , ..., push local 0

// return
   // Gets the saved return address (which, in this example, happens to be
   // Foo.bar$ret.1), replaces the arguments pushed by the caller with
   // the return value (stack's top element), reinstates the segment pointers
   // of the caller, and then generates:
   goto Foo.bar$ret.1  // injected branching back to the calling site.
```

Blue pseudocode:
Generated by the basic VM translator (project 7);

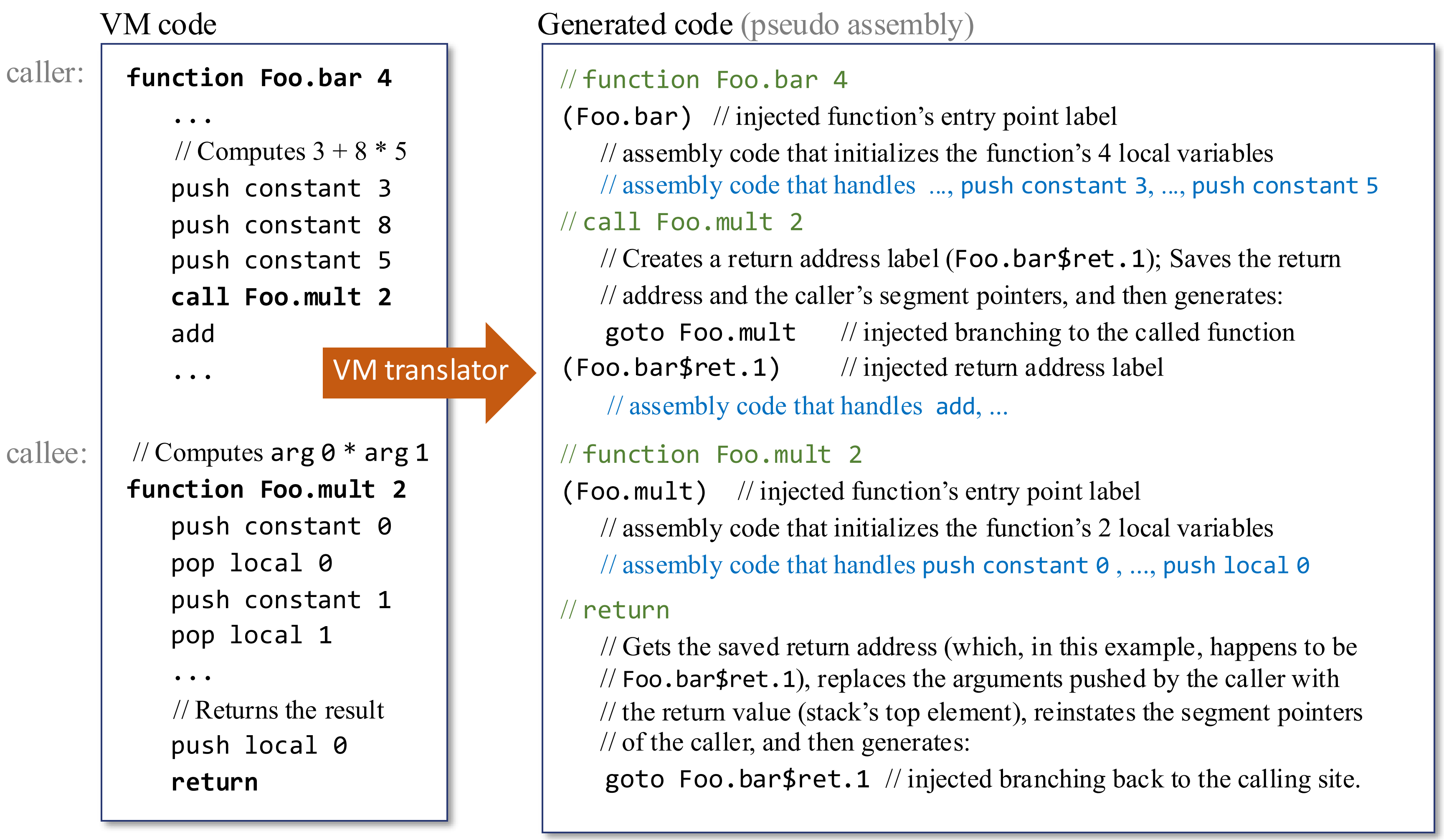
Black pseudocode:
Generated by the final VM translator (project 8).

Implementation

This pseudocode must be generated in the target platform's assembly language;

When the resulting assembly code will execute, it will cause the host machine to execute the semantics implied by the VM code.

Translation (pseudocode)



VM code

caller:

```
function Foo.bar 4
   ...
   // Computes 3 + 8 * 5
   push constant 3
   push constant 8
   push constant 5
   call Foo.mult 2
   add
   ...
```

callee:

```
  // Computes arg 0 * arg 1
function Foo.mult 2
   push constant 0
   pop local 0
   push constant 1
   pop local 1
   ...
   // Returns the result
   push local 0
   return
```

VM translator

Generated code (pseudo assembly)

```
// function Foo.bar 4
(Foo.bar)  // injected function's entry point label
   // assembly code that initializes the function's 4 local variables
   // assembly code that handles ..., push constant 3, ..., push constant 5
// call Foo.mult 2
   // Creates a return address label (Foo.bar$ret.1); Saves the return
   // address and the caller's segment pointers, and then generates:
   goto Foo.mult      // injected branching to the called function
(Foo.bar$ret.1)       // injected return address label
    // assembly code that handles add, ...

// function Foo.mult 2
(Foo.mult)  // injected function's entry point label
   // assembly code that initializes the function's 2 local variables
   // assembly code that handles push constant 0 , ..., push local 0

// return
   // Gets the saved return address (which, in this example, happens to be
   // Foo.bar$ret.1), replaces the arguments pushed by the caller with
   // the return value (stack's top element), reinstates the segment pointers
   // of the caller, and then generates:
   goto Foo.bar$ret.1 // injected branching back to the calling site.
```

Implementation open issues

How to pass the argument values to the caller?

How to represent local variables?

Where to "save the return address?

How to "get the return address"?

How to pass the return value to the caller?

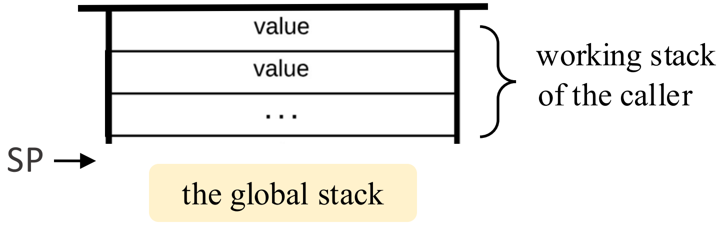
How to save the virtual memory segments of the caller before the call?

How to reinstate them when the callee terminates?

Implementation: `call / function / return`

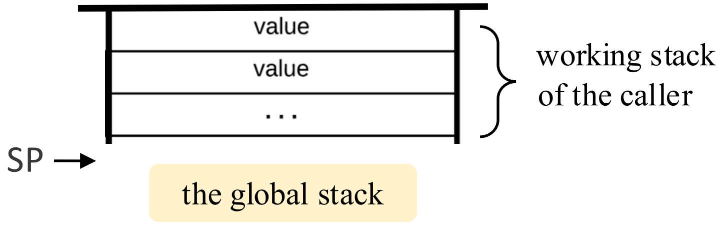
Implementation: `call` / `function` / `return`

The caller is running,
doing various things



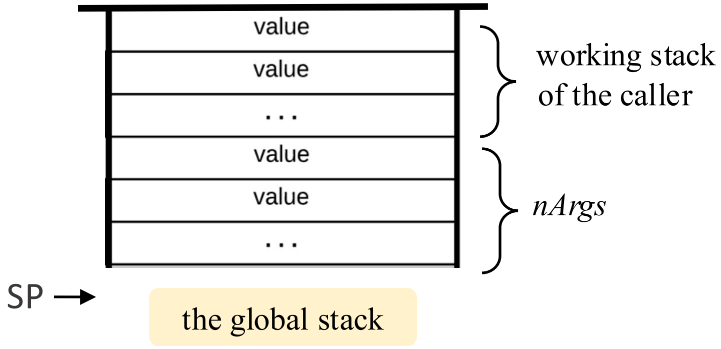
Implementation: `call` / `function` / `return`

The caller prepares to call another function;
It pushes 0 or more arguments onto the stack



Implementation: `call` / `function` / `return`

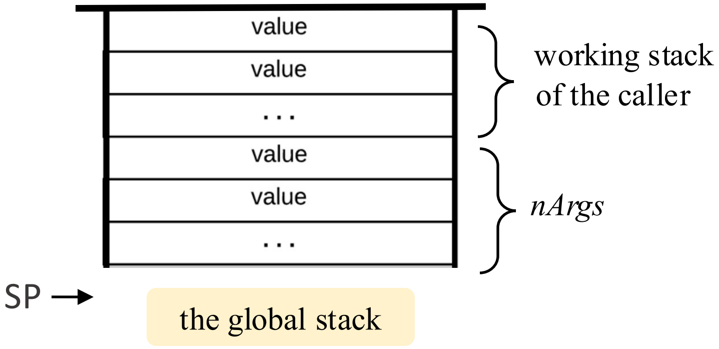
The caller prepares to call another function;
It pushes 0 or more arguments onto the stack



Implementation: `call` / `function` / `return`

The caller says:

`call` *functionName nArgs*



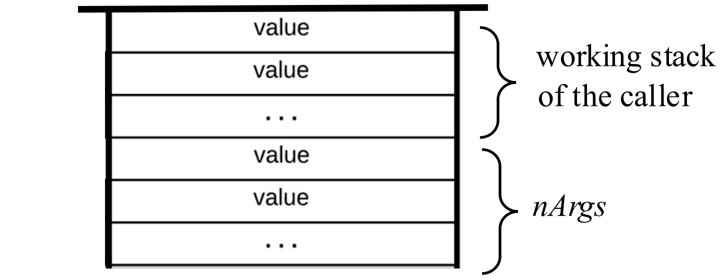
Handling `call` *functionName nArgs*

We have to:

Implementation: `call` / `function` / `return`

The caller says:

`call` *functionName nArgs*



the global stack

<u>Handling</u> `call` *functionName nArgs*

We have to:

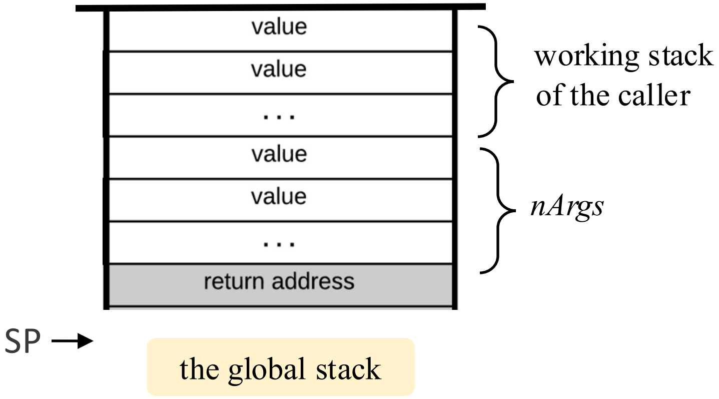
- Save the return address

The address to which control should return when the callee's execution is terminated

Implementation: `call` / `function` / `return`

The caller says:

`call` *functionName nArgs*



Handling `call` *functionName nArgs*

We have to:

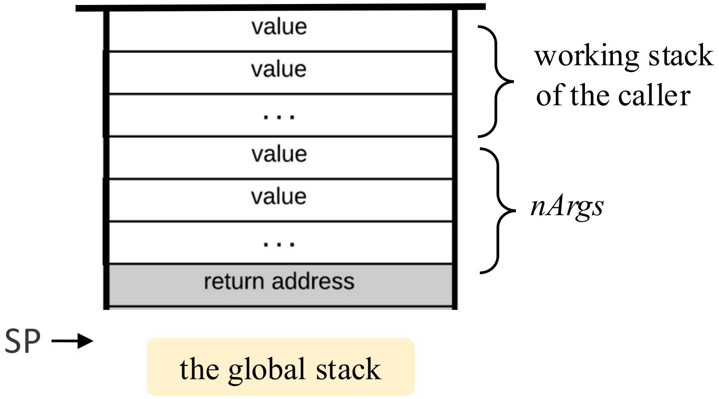
- Save the return address

The address to which control should return when the callee's execution is terminated

Implementation: `call` / `function` / `return`

The caller says:

`call` *functionName nArgs*



Handling `call` *functionName nArgs*

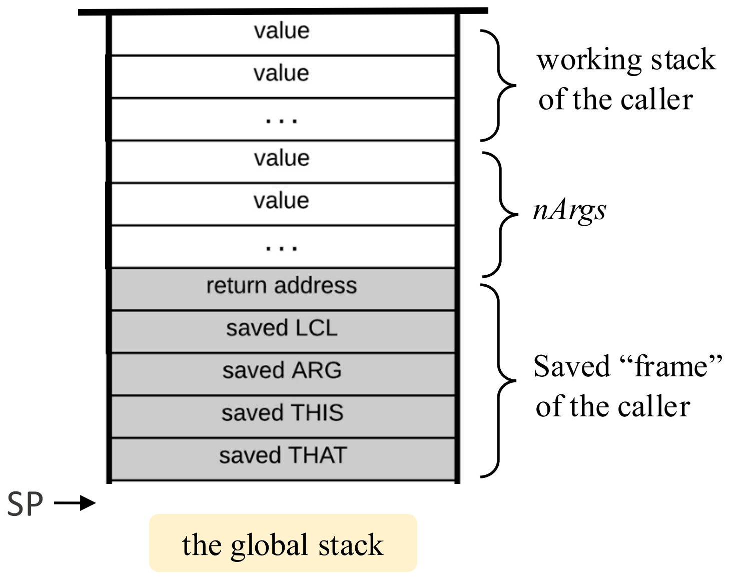
We have to:

- Save the return address
- Save the caller's segment pointers

Implementation: **`call`** / `function` / `return`

The caller says:

`call` *functionName nArgs*



<u>Handling</u> `call` *functionName nArgs*

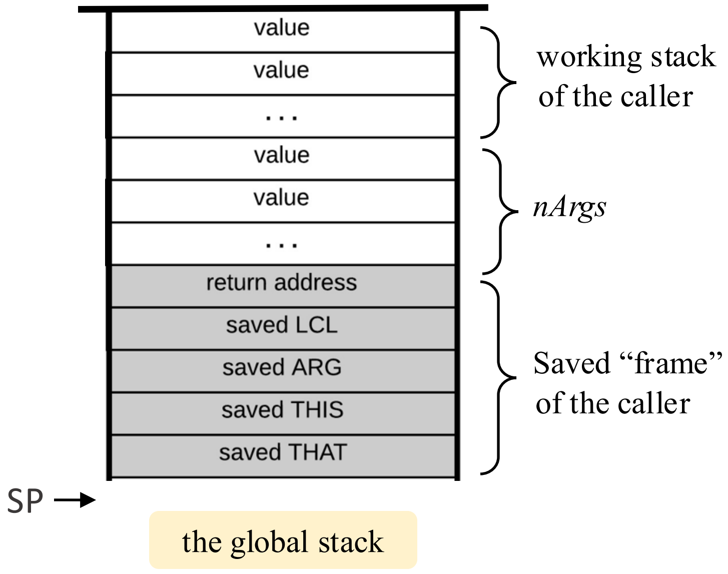
We have to:

- Save the return address
- Save the caller's segment pointers

Implementation: `call` / `function` / `return`

The caller says:

`call` *functionName nArgs*



Handling `call` *functionName nArgs*

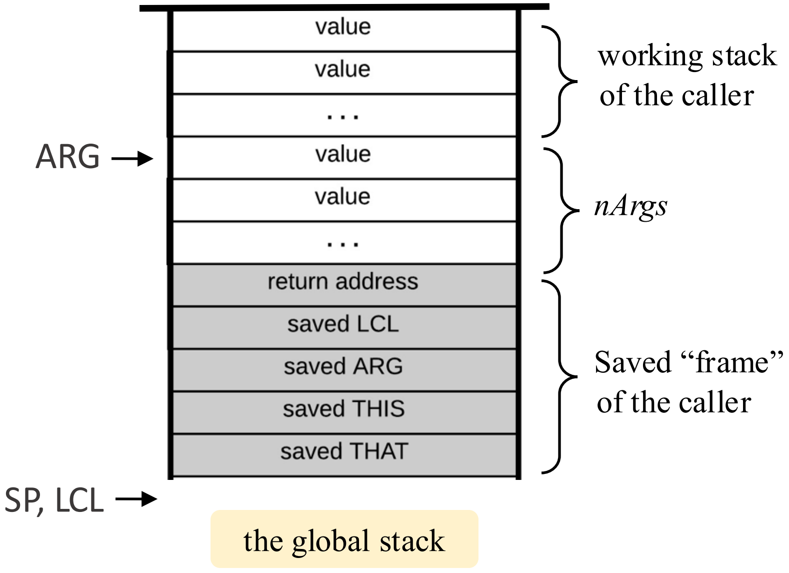
We have to:

- Save the return address
- Save the caller's segment pointers
- Reposition `ARG` (for the callee)
- Reposition `LCL` (for the callee)

Implementation: `call` / `function` / `return`

The caller says:

`call` *functionName nArgs*



Handling `call` *functionName nArgs*

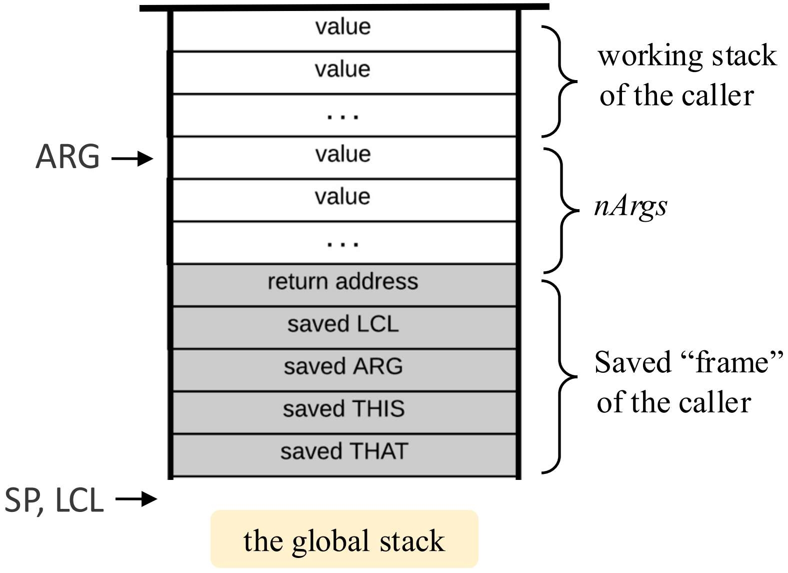
We have to:

- Save the return address
- Save the caller's segment pointers
- Reposition `ARG` (for the callee)
- Reposition `LCL` (for the callee)

Implementation: **`call`** / `function` / `return`

The caller says:

`call` *functionName nArgs*



Handling `call` *functionName nArgs*

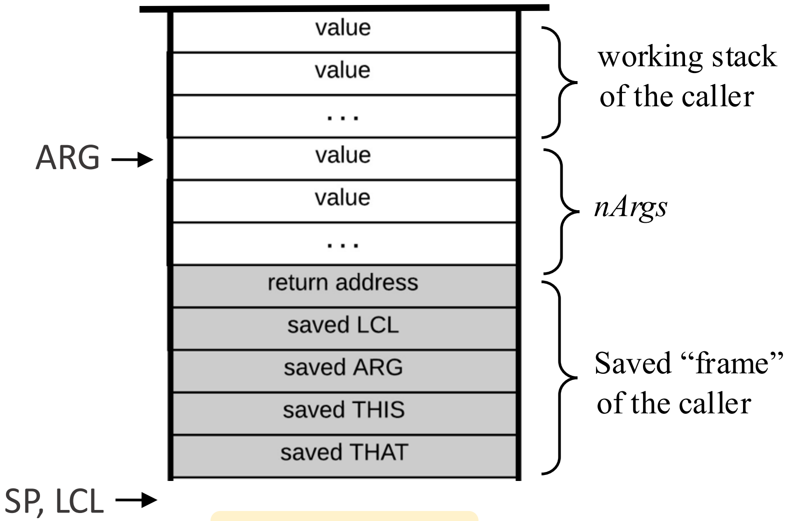
We have to:

- Save the return address
- Save the caller’s segment pointers
- Reposition `ARG` (for the callee)
- Reposition `LCL` (for the callee)
- Go to execute the callee’s code

Implementation: `call` / `function` / `return`

The caller says:

`call` *functionName nArgs*



value
value
...
value
value
...
return address
saved LCL
saved ARG
saved THIS
saved THAT

working stack of the caller

nArgs

Saved "frame" of the caller

ARG →

SP, LCL →

the global stack

<u>Handling</u> `call` *functionName nArgs*

We have to:

- Save the return address
- Save the caller's segment pointers
- Reposition `ARG` (for the callee)
- Reposition `LCL` (for the callee)
- Go to execute the callee's code

Generated code

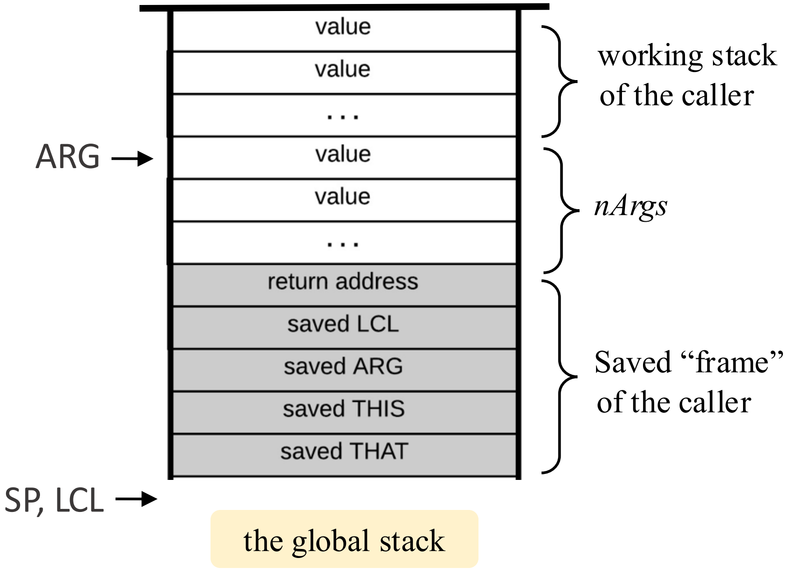
```
   // call functionName nArgs
    push retAddrLabel      // Generates and pushes this label
    push LCL               // Saves the caller's LCL
    push ARG               // Saves the caller's ARG
    push THIS              // Saves the caller's THIS
    push THAT              // Saves the caller's THAT
    ARG = SP – 5 – nArgs   // Repositions ARG
    LCL = SP               // Repositions LCL
    goto functionName      // Transfers control to the callee
(retAddrLabel)             // Injects this label into the code
```

(The VM translator must generate all this pseudocode in assembly)

Implementation: `call / function / return`

The callee is entered:

`function` *functionName nVars*



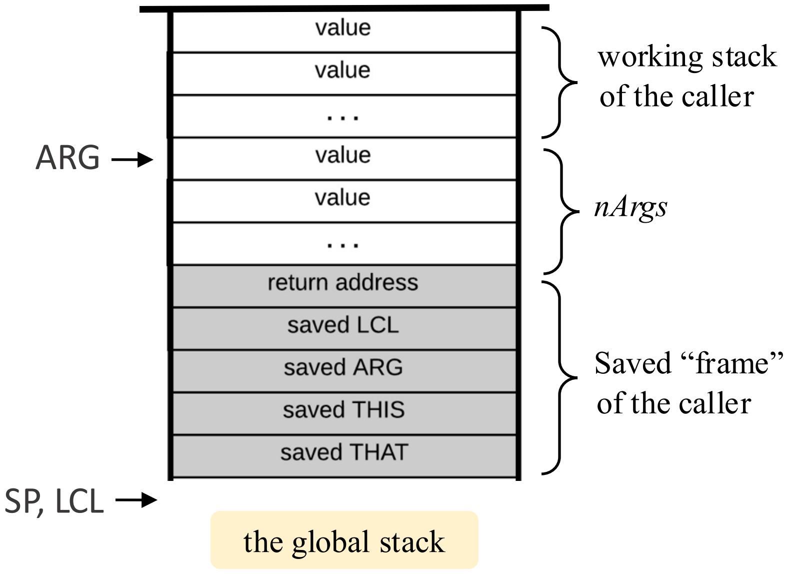
Handling `function` *functionName nVars*

We have to:

Implementation: `call` / **`function`** / `return`

The callee is entered:

`function` *functionName nVars*



Handling `function` *functionName nVars*

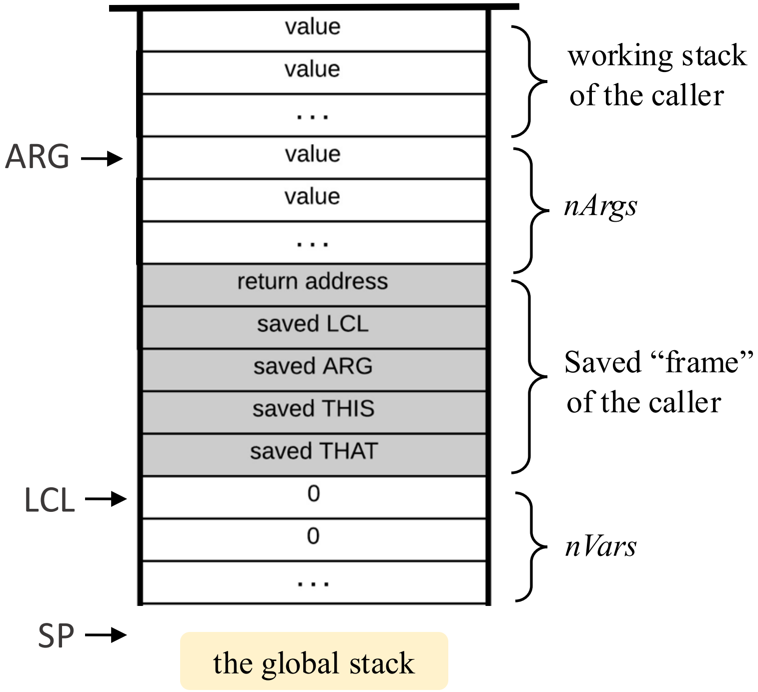
We have to:

- Inject an entry point label into the code
- Initialize the `local` segment of the callee

Implementation: `call` / **`function`** / `return`

The callee is entered:

`function` *functionName nVars*



Handling `function` *functionName nVars*

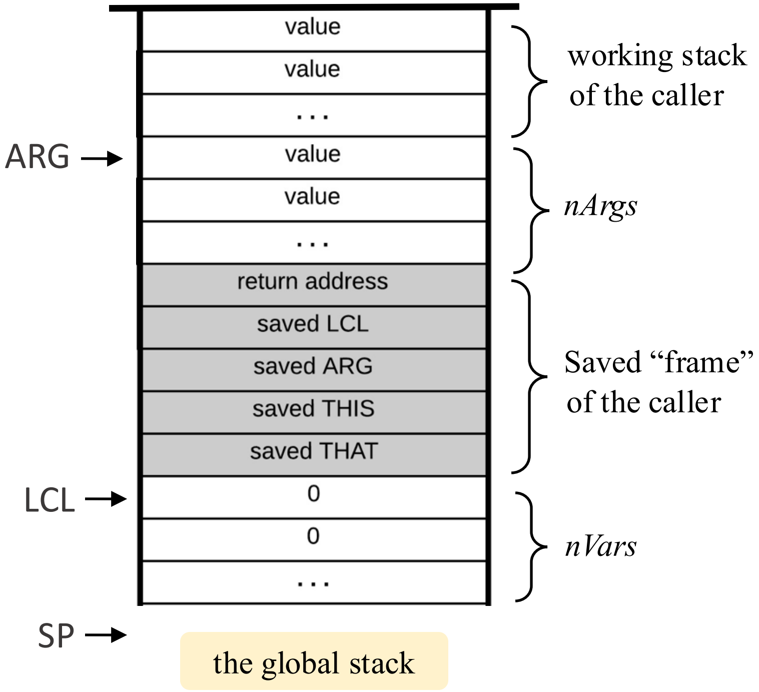
We have to:

- Inject an entry point label into the code
- Initialize the `local` segment of the callee

Implementation: `call` / `function` / `return`

The callee is entered:

`function` *functionName nVars*

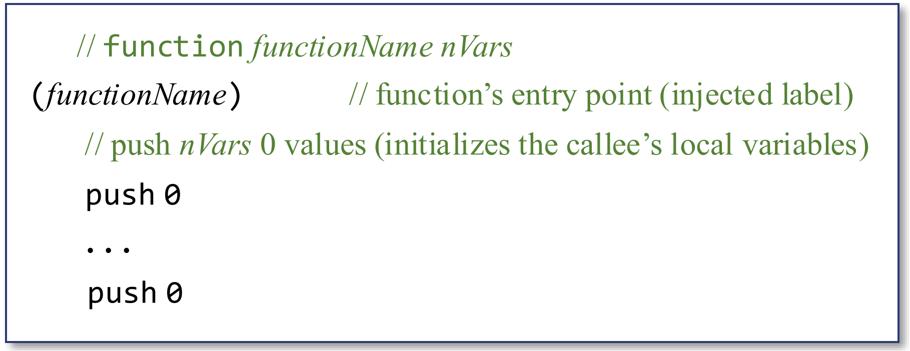


<u>Handling</u> `function` *functionName nVars*

We have to:

- Inject an entry point label into the code
- Initialize the `local` segment of the callee

Generated code



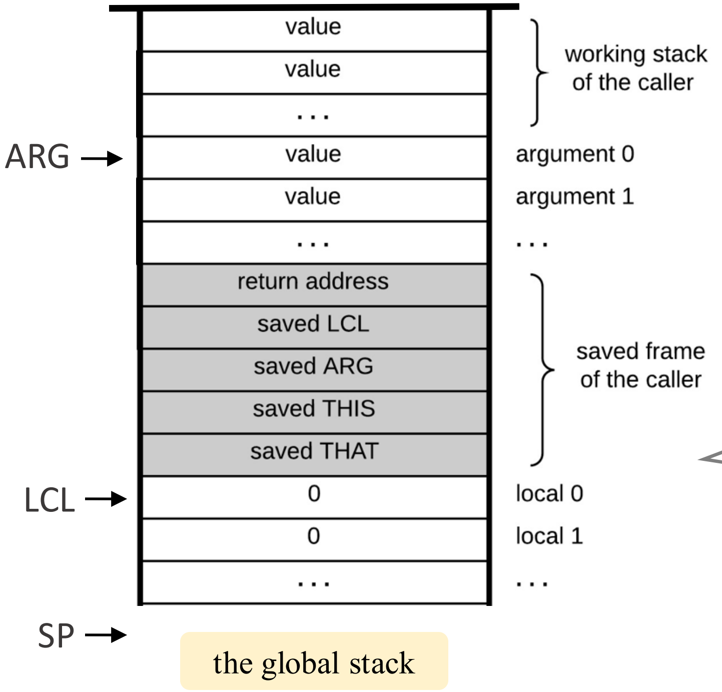
```
    // function functionName nVars
(functionName)          // function's entry point (injected label)
    // push nVars 0 values (initializes the callee's local variables)
    push 0
    ...
    push 0
```

(The VM translator must generate all this pseudocode in assembly)

Implementation: `call / function / return`

The callee is entered:

`function` *functionName nVars*

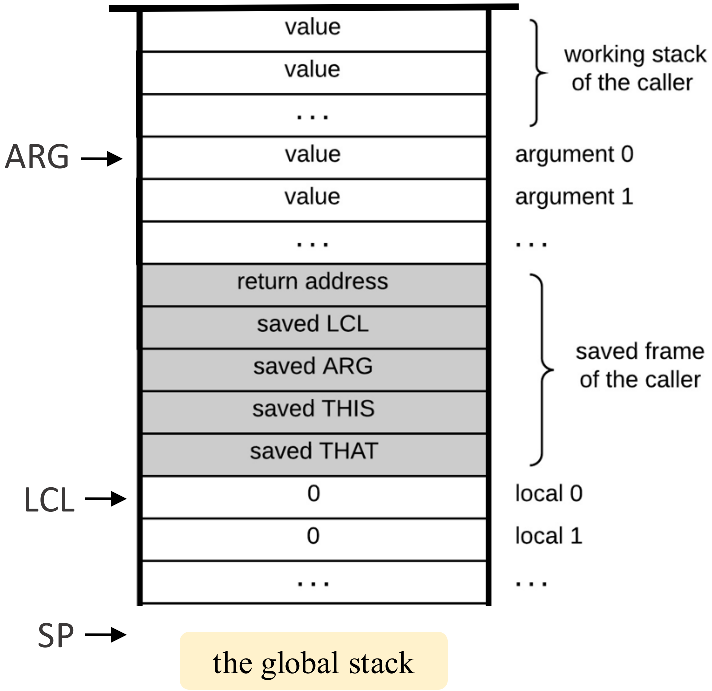


The callee is all set. It has:

- Arguments (passed by the caller)
- Local variables (all set to 0)
- Working stack (empty)

Implementation: `call / function / return`

The callee executes,
doing various things



value

value

. . .

ARG → value — argument 0

value — argument 1

. . . — . . .

return address

saved LCL

saved ARG

saved THIS

saved THAT

LCL → 0 — local 0

0 — local 1

. . . — . . .

SP →

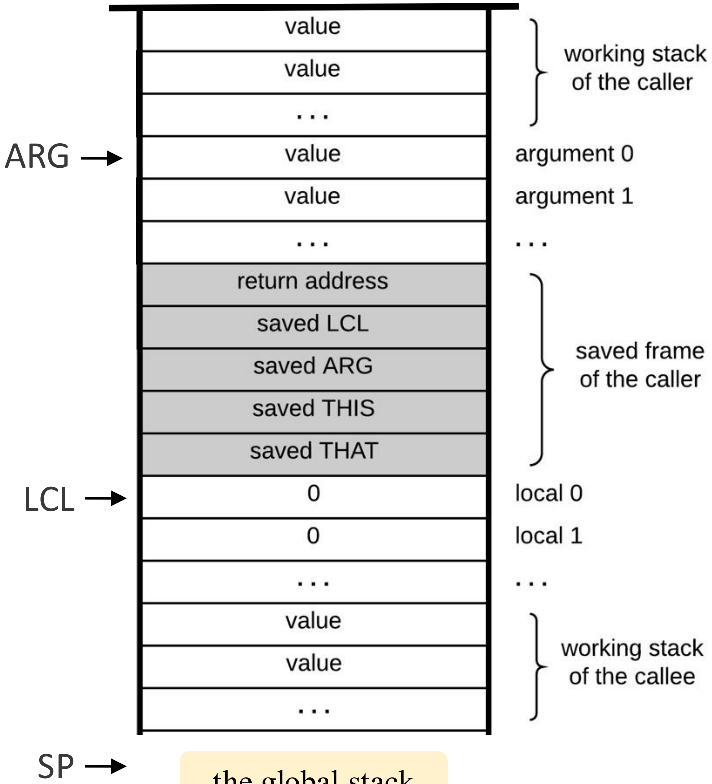
working stack
of the caller

saved frame
of the caller

the global stack

Implementation: `call / function / return`

The callee executes, doing various things



value
value
. . .
working stack of the caller

ARG → value — argument 0
value — argument 1
. . . — . . .

return address
saved LCL
saved ARG
saved THIS
saved THAT
saved frame of the caller

LCL → 0 — local 0
0 — local 1
. . . — . . .

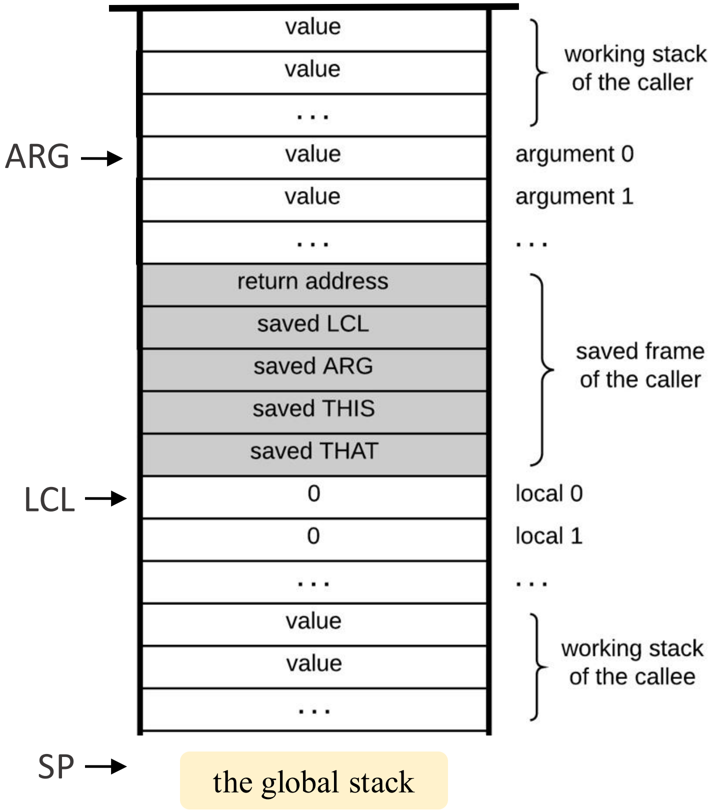
value
value
. . .
working stack of the callee

SP →

the global stack

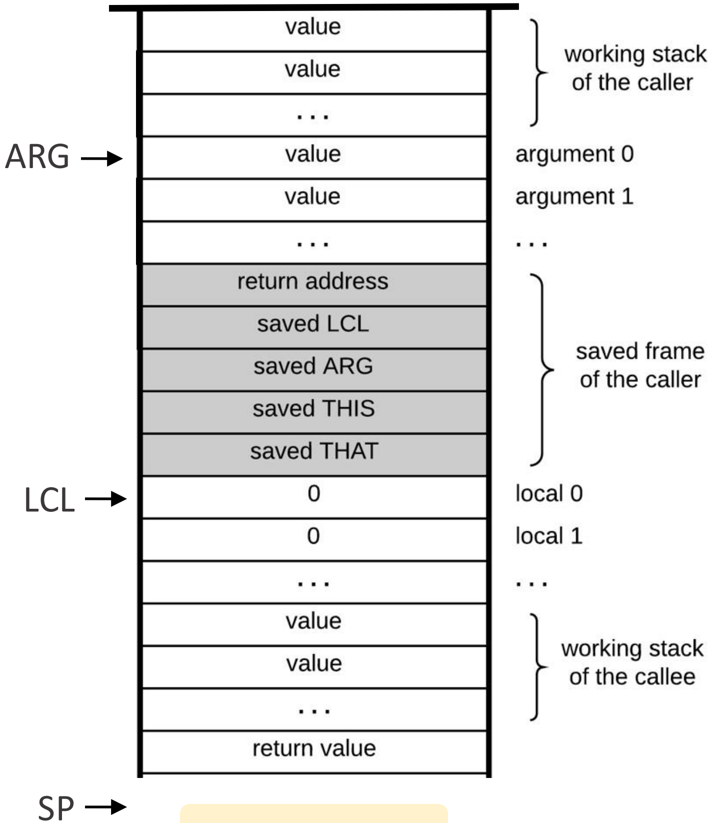
Implementation: `call / function / return`

The callee prepares to return:
It pushes a *return value*



Implementation: `call / function / return`

The callee prepares to return:
It pushes a *return value*



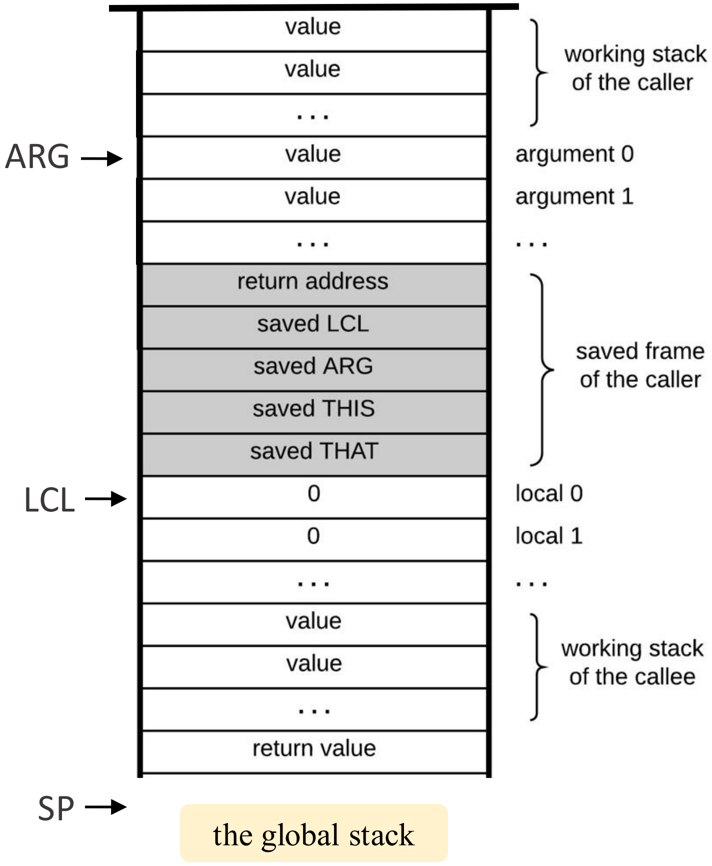
	value	working stack of the caller
	value	
	. . .	
ARG →	value	argument 0
	value	argument 1
	. . .	. . .
	return address	saved frame of the caller
	saved LCL	
	saved ARG	
	saved THIS	
	saved THAT	
LCL →	0	local 0
	0	local 1
	. . .	. . .
	value	working stack of the callee
	value	
	. . .	
	return value	
SP →		

the global stack

Implementation: call / function / **return**

The callee says:

`return`



the global stack

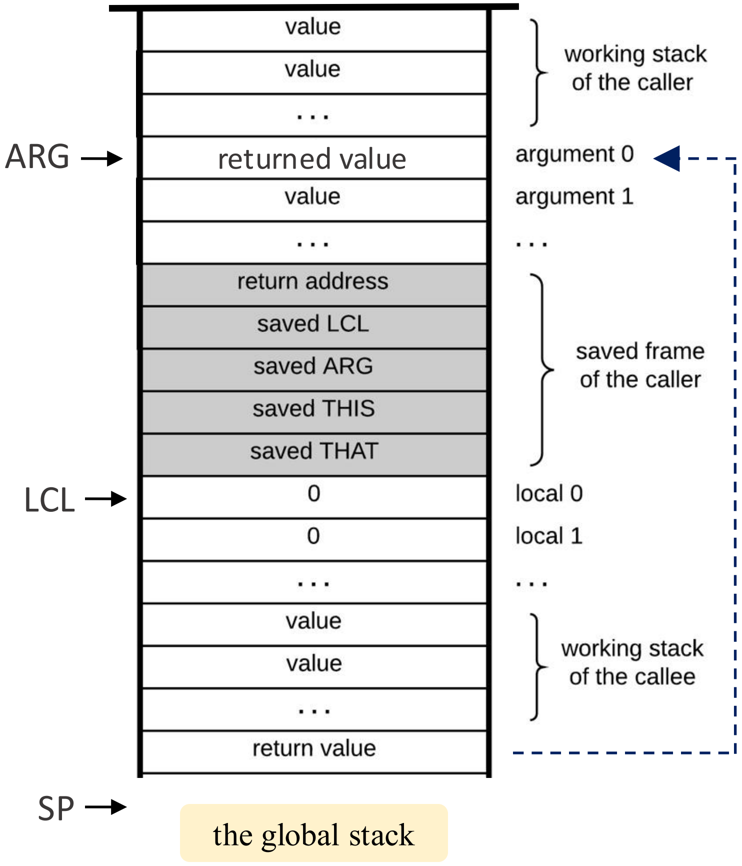
Handling `return`:

We have to:

Implementation: `call` / `function` / **`return`**

The callee says:

`return`



<u>Handling `return`:</u>

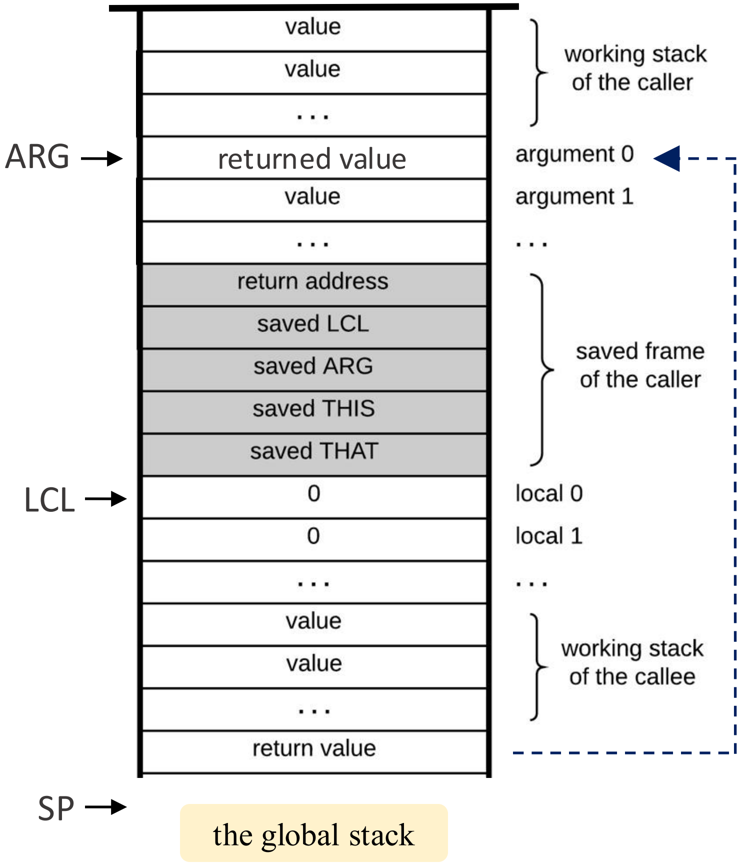
We have to:

1. Replace the arguments that the caller pushed with the value returned by the callee

Implementation: call / function / **return**

The callee says:

`return`



<u>Handling `return`:</u>

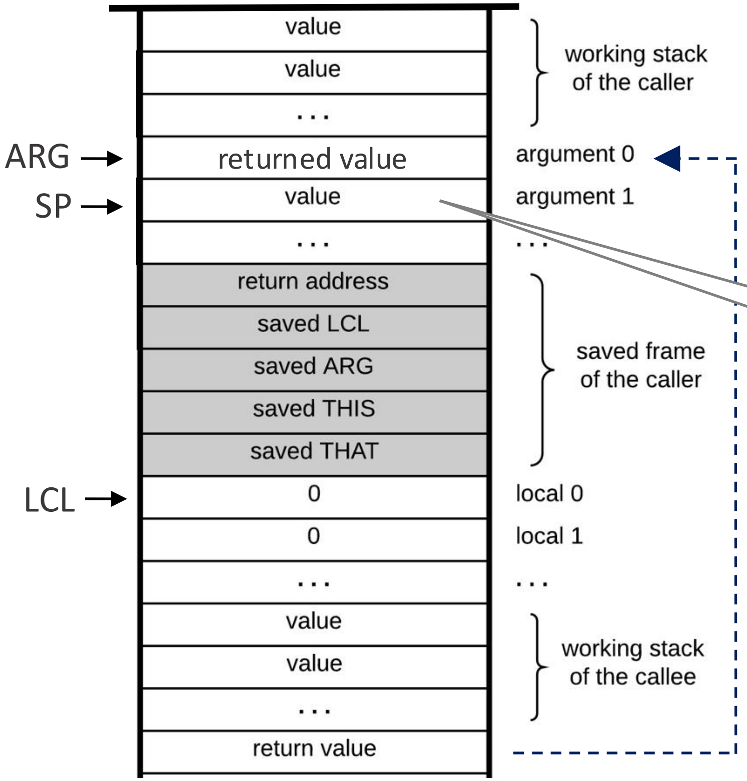
We have to:

1. Replace the arguments that the caller pushed with the value returned by the callee
2. Recycle the memory used by the callee

Implementation: `call / function / return`

The callee says:

`return`



the global stack

Handling `return`:

We have to:

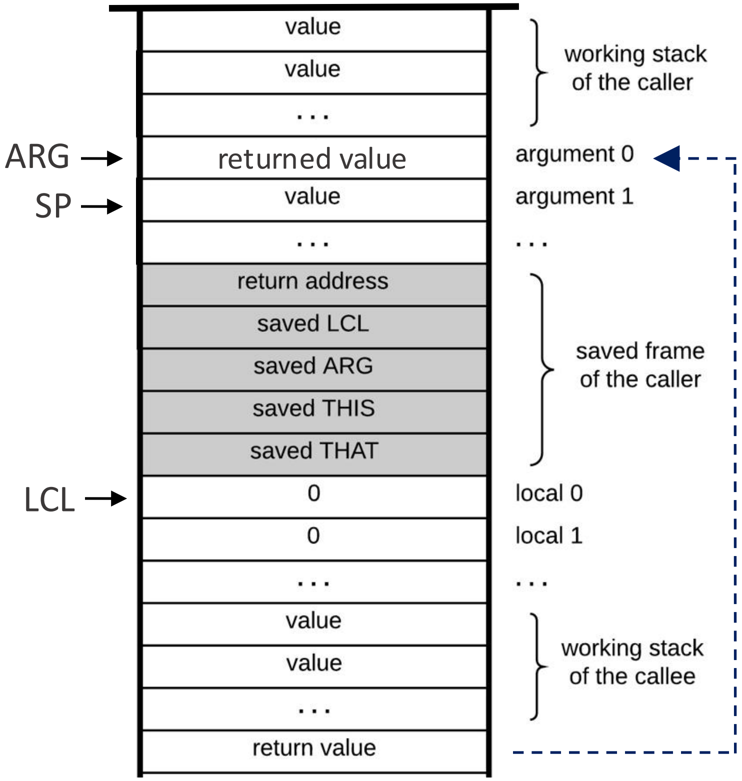
1. Replace the arguments that the caller pushed with the value returned by the callee
2. Recycle the memory used by the callee

The stack space below the return value is effectively wiped out

Implementation: `call / function / return`

The callee says:

`return`



the global stack

Handling `return`:

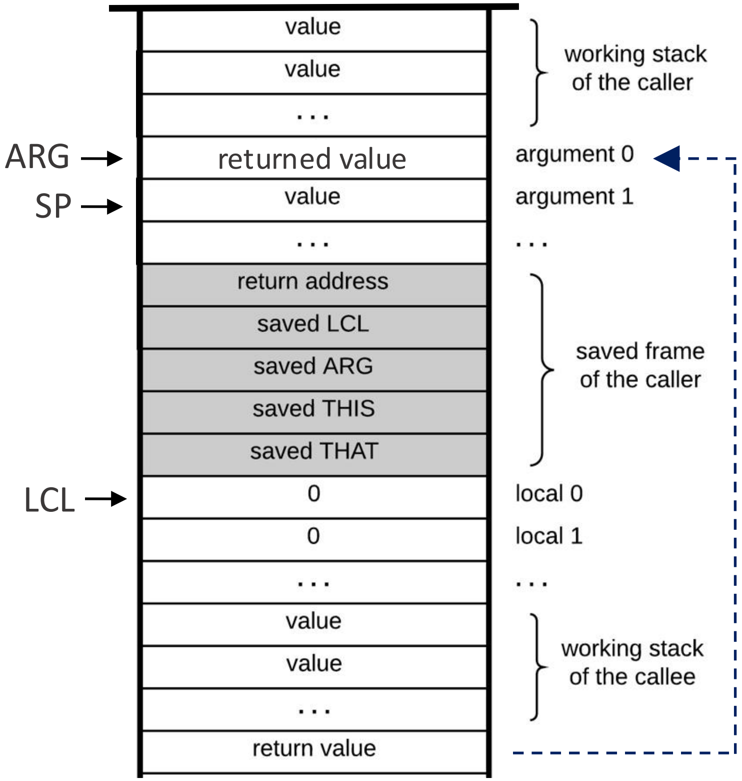
We have to:

1. Replace the arguments that the caller pushed with the value returned by the callee
2. Recycle the memory used by the callee
3. Restore the caller's segment pointers
4. Jump to the return address

Implementation: call / function / **return**

The callee says:

`return`



the global stack

Handling return:

We have to:

1. Replace the arguments that the caller pushed with the value returned by the callee
2. Recycle the memory used by the callee
3. Restore the caller’s segment pointers
4. Jump to the return address

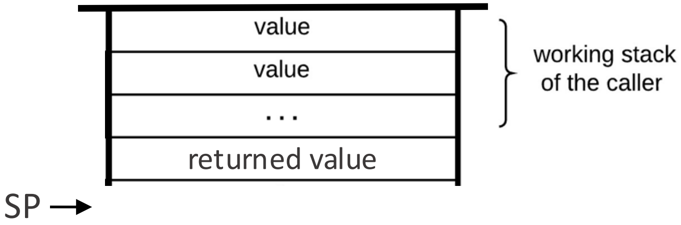
Generated code

```
// The code below creates and uses two temporary variables:
// endFrame and retAddr;
// The pointer notation *addr is used to denote: RAM[addr]
endFrame = LCL              // gets the address at the frame’s end
retAddr = *(endFrame – 5)   // gets the return address
*ARG = pop()                // puts the return value for the caller
SP = ARG + 1                // repositions SP
THAT = *(endFrame – 1)      // restores THAT
THIS = *(endFrame – 2)      // restores THIS
ARG = *(endFrame – 3)       // restores ARG
LCL = *(endFrame – 4)       // restores LCL
goto retAddr                // jumps to the return address
```

(The VM translator must generate all this pseudocode in assembly)

Implementation: `call / function / return`

The caller resumes its execution



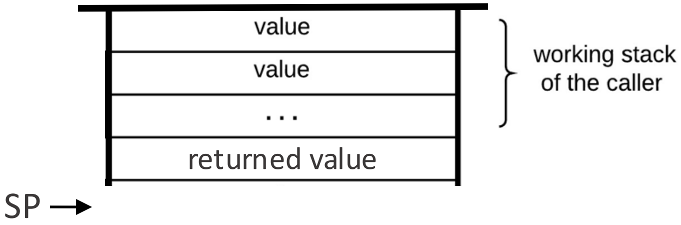
Result: The caller's world is exactly the same as before the call, except that the arguments that it pushed before the call were replaced by the value returned by the callee.

Any sufficiently advanced technology is indistinguishable from magic.

– Arthur C. Clarke, 1962

Implementation: `call / function / return`

The caller resumes its execution



What if the calling chain is nested?

`foo` calls `bar`

`bar` calls `baz`

`baz` calls `moo`,

...

etc.

And what about recursion?

Implementation

Follows exactly the same scheme, once for every call-and-return scenario;

The global stack will grow and shrink telescopically: *Last in, first out*

"Now that is wisdom: In every instance of your labor, hitch your wagon to a star, and see your chore done by the gods themselves" – Ralph Waldo Emerson, 1870

(Nand to Tetris twist: Change "star" to "stack")

Lecture plan

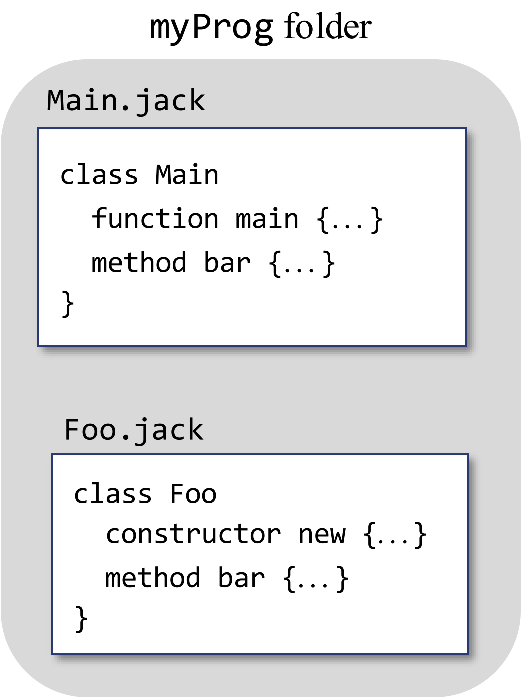
✓ VM language

- Branching commands (abstraction / implementation)
- Function commands (abstraction / implementation)

➡ VM translator

- Bootstrap
- Standard mapping
- Architecture
- Project 8

The big picture: Compilation



`myProg` folder

Main.jack

```
class Main
  function main {...}
  method bar {...}
}
```

Foo.jack

```
class Foo
  constructor new {...}
  method bar {...}
}
```

High level language conventions

(much more about it in lecture 9):

Jack program: a set of one or more class files, all in the same folder;

Jack class: a set of one or more *methods*, *functions* (static methods), and *constructors*;

There must be at least one class file named `Main.jack`, and this file must contain at least one method named `main`;

Program's entry point: `Main.main()`

OS conventions

(much more about it in lecture 12):

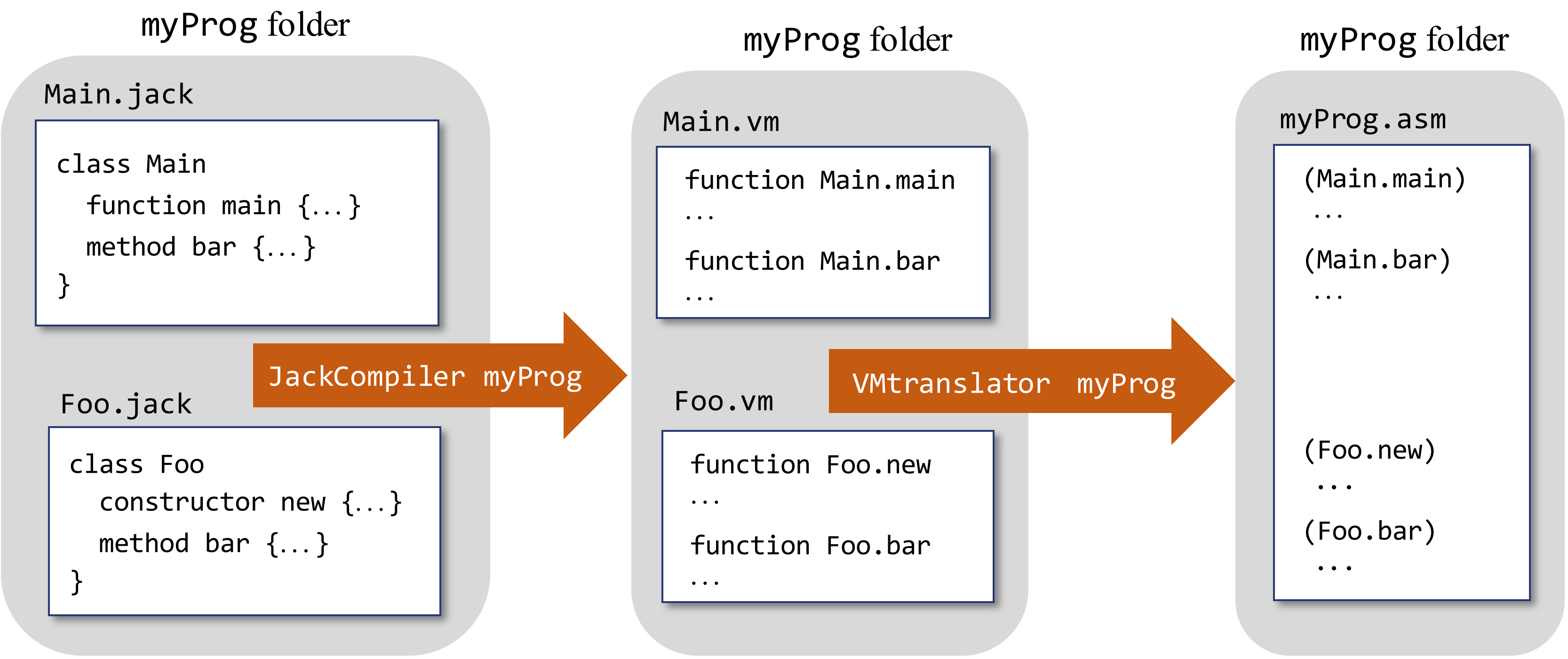
The OS is written in Jack (just like Unix is written in C);

One OS class, `Sys`, contains a method named `init`

When the computer boots, it executes `Sys.init`

`Sys.init` calls `Main.main`.

The big picture: Compilation



myProg folder

Main.jack

```
class Main
  function main {...}
  method bar {...}
}
```

Foo.jack

```
class Foo
  constructor new {...}
  method bar {...}
}
```

myProg folder

Main.vm

```
function Main.main
...
function Main.bar
...
```

Foo.vm

```
function Foo.new
...
function Foo.bar
...
```

myProg folder

myProg.asm

```
(Main.main)
 ...
(Main.bar)
 ...


(Foo.new)
 ...
(Foo.bar)
 ...
```

Each *Jack class* is a set of *methods*, *functions*, and *constructors*

Every *method*, *function*, and *constructor* is translated into a *VM function*

All the VM functions from all the compiled class files are translated into a single assembly file

(the notion of multiple VM files melts away)

Program’s entry point: `Main.main()`

Bootstrap code

Run-time conventions

The compiled code base includes the program:
A set of VM functions (in any order), one of which is `Main.main`

The compiled code base also includes the operating system:
Also a set of VM functions, one of which is `Sys.init`

`Sys.init` calls `Main.main`, and enters an infinite loop

The stack is stored in the RAM, starting at address 256

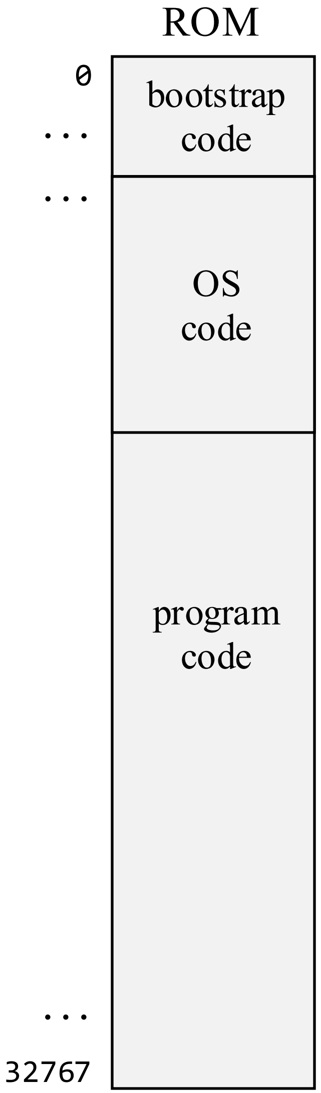
To make this happen

The assembly code generated by the VM translator should start with the following code:

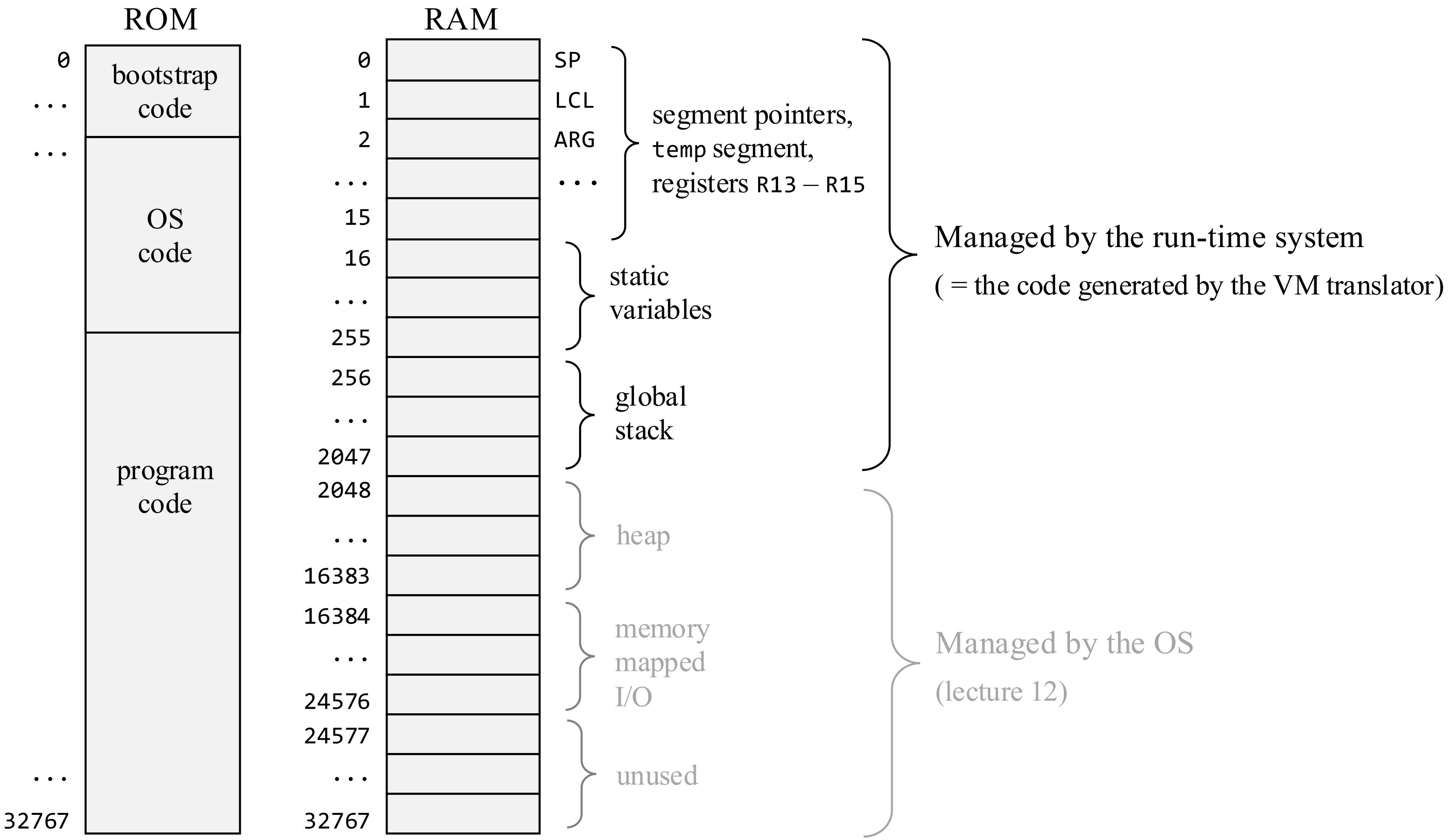
```
// Bootstrap code
SP = 256
call Sys.init   // (no arguments)
```

(The VM translator must generate this pseudocode in assembly).

Standard mapping (of the VM on the Hack platform)



Standard mapping (of the VM on the Hack platform)



Lecture plan

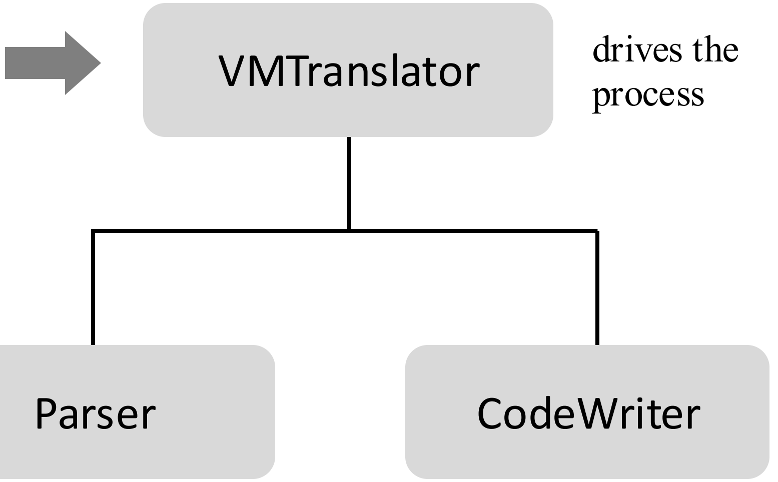
✓ VM language

- Branching commands (abstraction / implementation)
- Function commands (abstraction / implementation)

VM translator

- Bootstrap
- Standard mapping
- ➡ Architecture
- Project 8

VM translator



drives the process

Reads and parses a VM command

Generates the assembly code that realizes the parsed command

Each module extends the corresponding module developed in project 7,
Adding the implementation of the *branching* and *function* commands.

VM translator

Usage: (if the translator is implemented in Java; Other languages will have a similar command line)

```
$ java VMTranslator source
```

Where *source* is either a single *fileName*`.vm`, or a *folderName* containing one or more `.vm` files;

(The *source* may contain a file path; the first character of *filename* must be an uppercase letter)

Output: A single assembly file named *source*`.asm`

(stored in the same folder as the source files)

Action

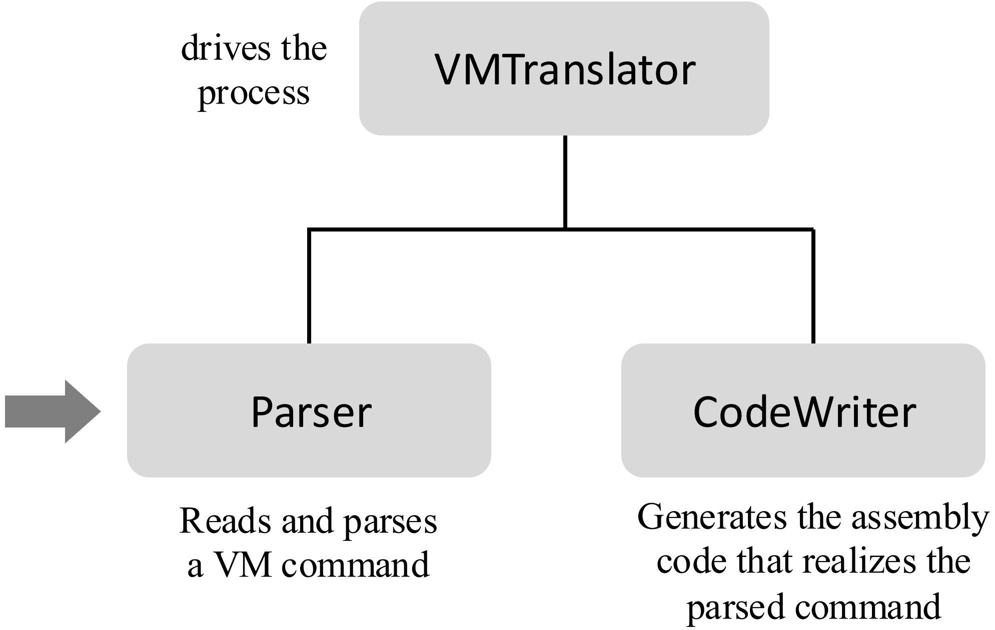
- Constructs a `CodeWriter`
- If *source* is a `.vm` file:

  Constructs a `Parser` to handle the input file;

  For each VM command in the input file:
  uses the `Parser` to parse the command,
  uses the `CodeWriter` to generate assembly code from it
- If *source* is a folder:

  Handles every `.vm` file in the folder in the manner described above.

VM translator

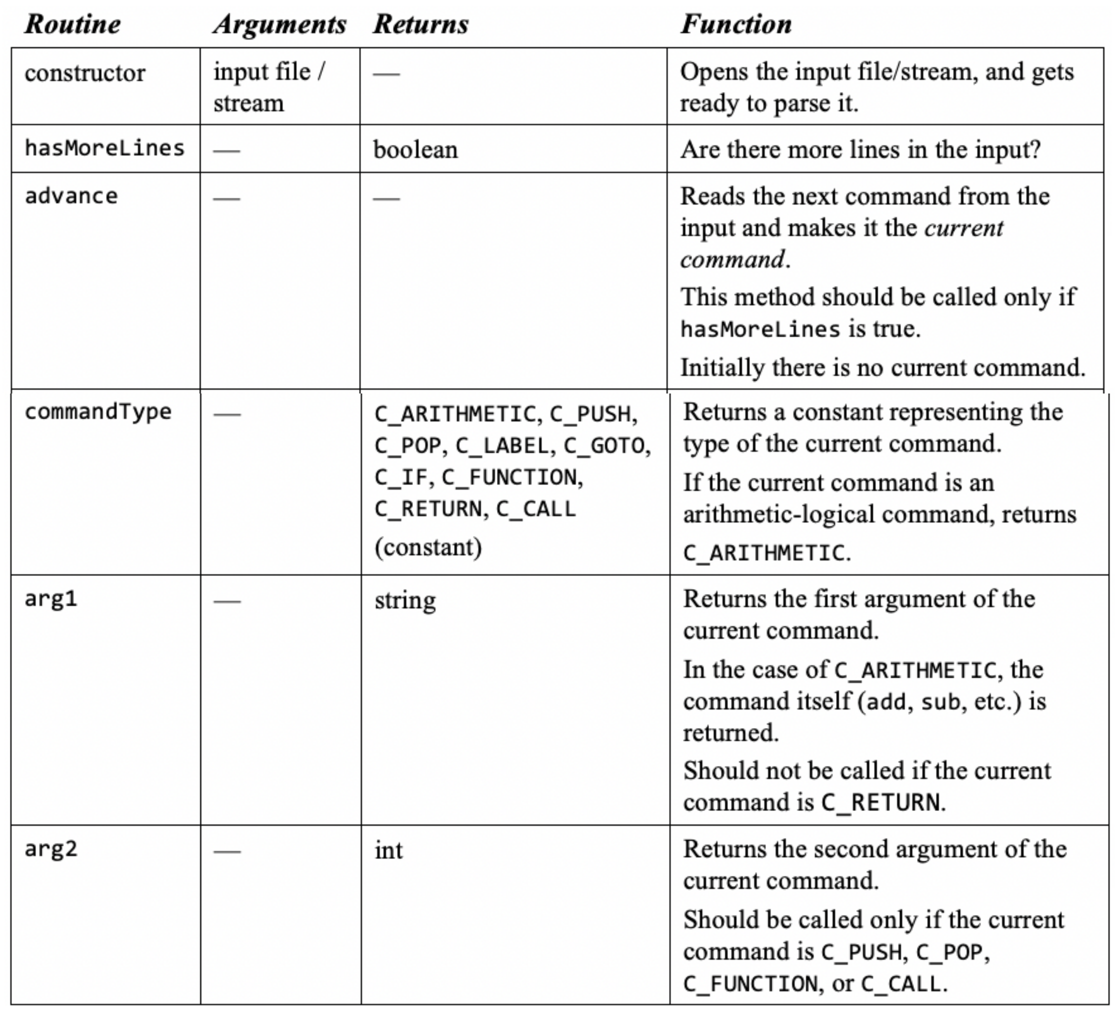

drives the process
VMTranslator
Parser
CodeWriter
Reads and parses a VM command
Generates the assembly code that realizes the parsed command

Same `Parser` developed in project 7

Handles the parsing of a `.vm` file:

- Skips white space and comments;
- Reads a VM command, parses the command into its lexical components, and provides convenient access to these components.

Parser



Routine	*Arguments*	*Returns*	*Function*
constructor	input file / stream	—	Opens the input file/stream, and gets ready to parse it.
`hasMoreLines`	—	boolean	Are there more lines in the input?
`advance`	—	—	Reads the next command from the input and makes it the *current command*. This method should be called only if `hasMoreLines` 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` (constant)	Returns a constant representing the type of the current command. If the current command is an arithmetic-logical command, returns `C_ARITHMETIC`.
`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`.

Same API as in project 7;

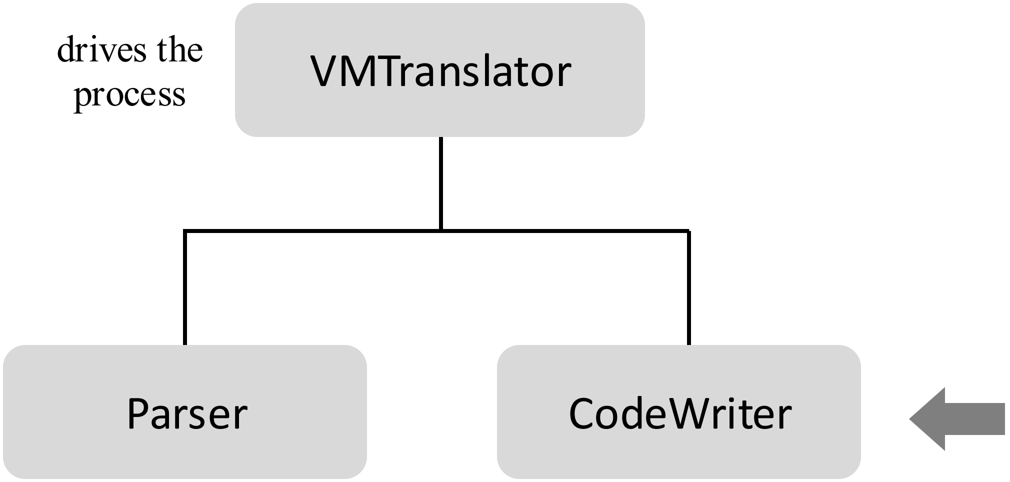
If your project 7 `Parser` did not handle the parsing of the VM commands:

`goto`, `if-goto`, `label`,

`call`, `function`, `return`,

add this parsing functionality now.

VM translator: Proposed design



drives the process

VMTranslator

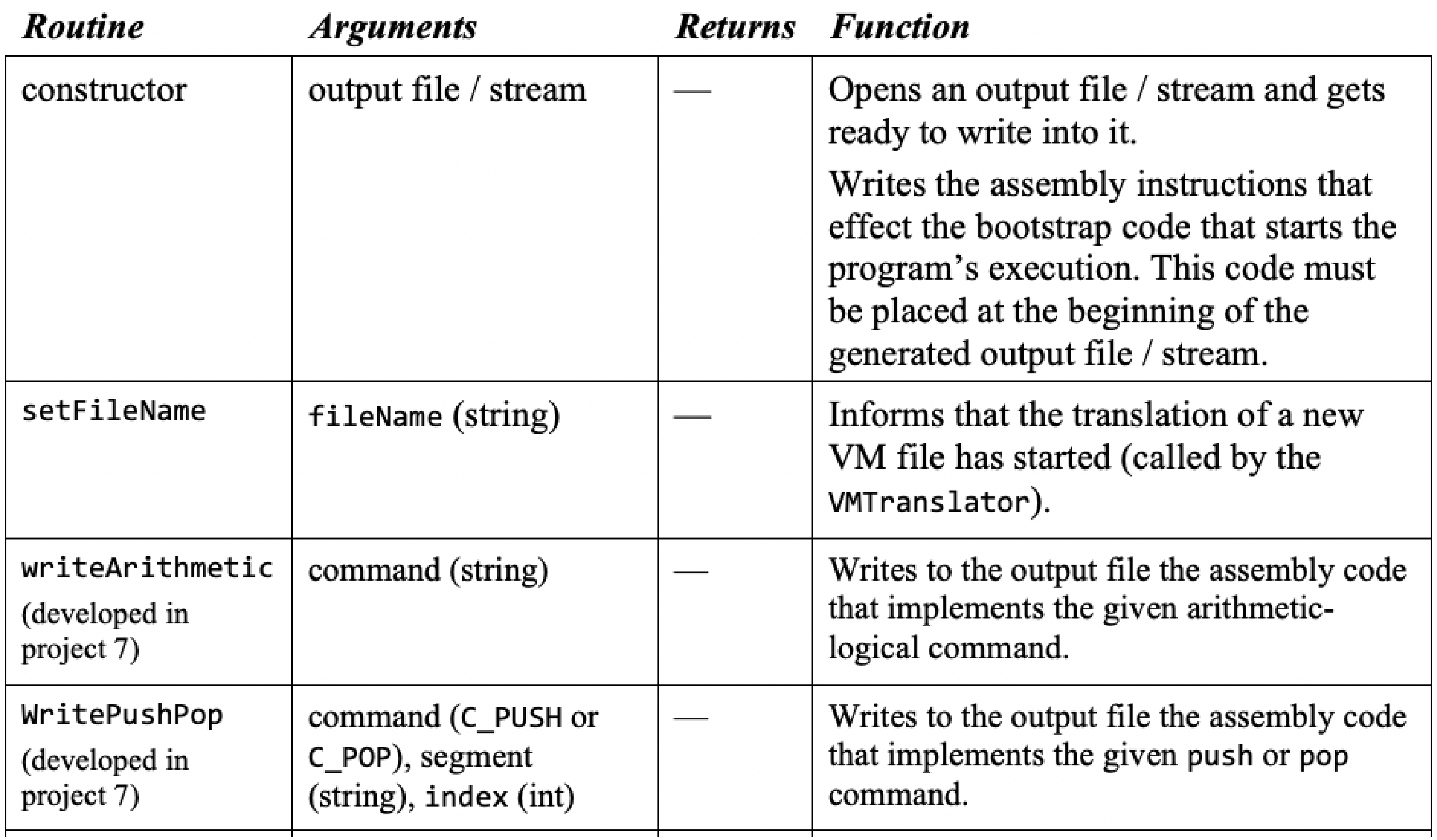
Parser

CodeWriter

Reads and parses a VM command

Generates the assembly code that realizes the parsed command

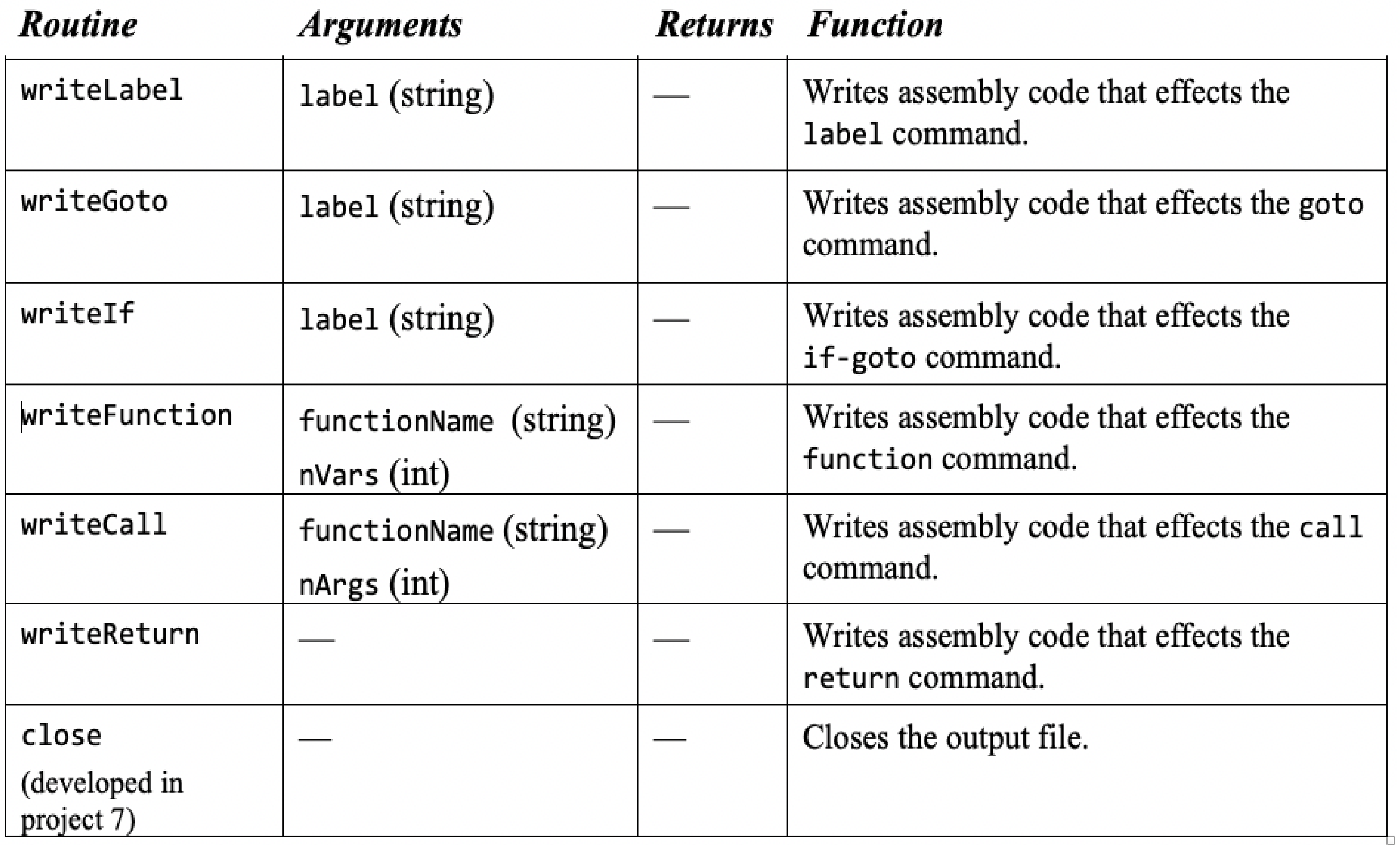
CodeWriter



Routine	*Arguments*	*Returns*	*Function*
constructor	output file / stream	—	Opens an output file / stream and gets ready to write into it. Writes the assembly instructions that effect the bootstrap code that starts the program's execution. This code must be placed at the beginning of the generated output file / stream.
`setFileName`	`fileName` (string)	—	Informs that the translation of a new VM file has started (called by the `VMTranslator`).
`writeArithmetic` (developed in project 7)	command (string)	—	Writes to the output file the assembly code that implements the given arithmetic-logical command.
`WritePushPop` (developed in project 7)	command (`C_PUSH` or `C_POP`), segment (string), `index` (int)	—	Writes to the output file the assembly code that implements the given `push` or `pop` command.

(API continues in the next slide)

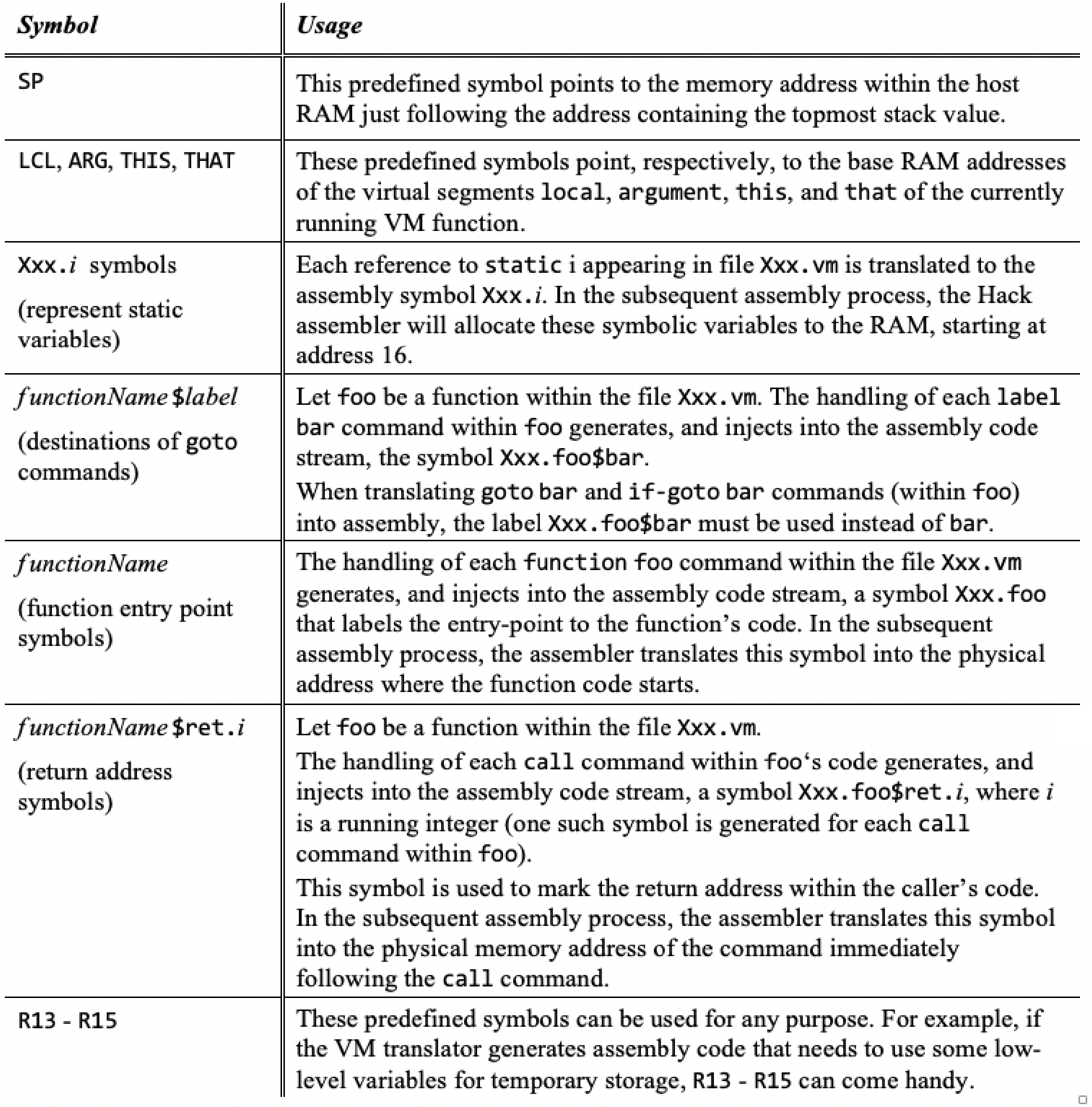
CodeWriter



Routine	*Arguments*	*Returns*	*Function*
`writeLabel`	`label` (string)	—	Writes assembly code that effects the `label` command.
`writeGoto`	`label` (string)	—	Writes assembly code that effects the `goto` command.
`writeIf`	`label` (string)	—	Writes assembly code that effects the `if-goto` command.
`writeFunction`	`functionName` (string) `nVars` (int)	—	Writes assembly code that effects the `function` command.
`writeCall`	`functionName` (string) `nArgs` (int)	—	Writes assembly code that effects the `call` command.
`writeReturn`	—	—	Writes assembly code that effects the `return` command.
`close` (developed in project 7)	—	—	Closes the output file.

Note: The generated assembly code uses *symbols* that must follow symbol naming conventions (next slide).

Symbols



Symbol	*Usage*
SP	This predefined symbol points to the memory address within the host RAM just following the address containing the topmost stack value.
LCL, ARG, THIS, THAT	These predefined symbols point, respectively, to the base RAM addresses of the virtual segments `local`, `argument`, `this`, and `that` of the currently running VM function.
`Xxx.`*i* symbols (represent static variables)	Each reference to `static` i appearing in file `Xxx.vm` is translated to the assembly symbol `Xxx.`*i*. In the subsequent assembly process, the Hack assembler will allocate these symbolic variables to the RAM, starting at address 16.
functionName`$`*label* (destinations of `goto` commands)	Let `foo` be a function within the file `Xxx.vm`. The handling of each `label bar` command within `foo` generates, and injects into the assembly code stream, the symbol `Xxx.foo$bar`. When translating `goto bar` and `if-goto bar` commands (within `foo`) into assembly, the label `Xxx.foo$bar` must be used instead of `bar`.
functionName (function entry point symbols)	The handling of each `function foo` command within the file `Xxx.vm` generates, and injects into the assembly code stream, a symbol `Xxx.foo` that labels the entry-point to the function's code. In the subsequent assembly process, the assembler translates this symbol into the physical address where the function code starts.
functionName`$ret.`*i* (return address symbols)	Let `foo` be a function within the file `Xxx.vm`. The handling of each `call` command within `foo`'s code generates, and injects into the assembly code stream, a symbol `Xxx.foo$ret.`*i*, where *i* is a running integer (one such symbol is generated for each `call` command within `foo`). This symbol is used to mark the return address within the caller's code. In the subsequent assembly process, the assembler translates this symbol into the physical memory address of the command immediately following the `call` command.
R13 - R15	These predefined symbols can be used for any purpose. For example, if the VM translator generates assembly code that needs to use some low-level variables for temporary storage, `R13 - R15` can come handy.

Symbol naming conventions,

Read carefully for project 8.

Lecture plan

✓ VM language

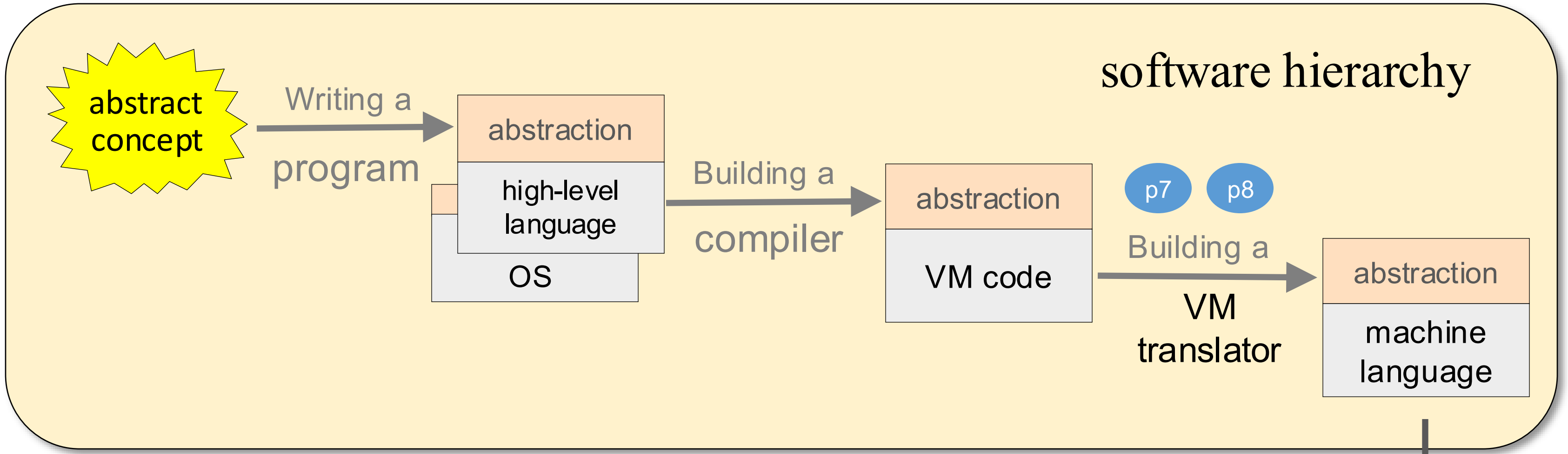
- Branching commands (abstraction / implementation)
- Function commands (abstraction / implementation)

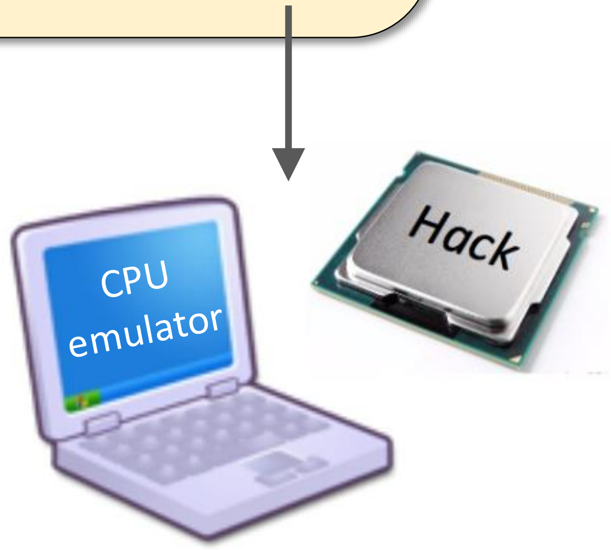
VM translator

- Bootstrap
- Standard mapping
- Architecture

➡ Project 8

The Big Picture





Objective: build a VM translator that translates programs written in the VM language into programs written in Hack's assembly language

Testing: Run the generated code on the target platform.

Test programs

ProgramFlow:

- ❑ BasicLoop
- ❑ FibonacciSeries

FunctionCalls:

- ❑ SimpleFunction
- ❑ FibonacciElement
- ❑ StaticsTest

Test programs: BasicLoop

ProgramFlow:

- BasicLoop
  - **BasicLoop.vm**
  - BasicLoopVME.tst
  - BasicLoop.tst
  - BasicLoop.cmp
- ❑ FibonacciSeries

FunctionCalls:

- ❑ SimpleFunction
- ❑ FibonacciElement
- ❑ StaticsTest

BasicLoop.vm

```
// Computes the sum 1 + 2 + ... + argument[0],
// and pushes the  result onto the stack.
   push constant 0
   pop local 0
label LOOP_START
   push argument 0
   push local 0
   add
   pop local 0
   push argument 0
   push constant 1
   sub
   pop argument 0
   push argument 0
if-goto LOOP_START
   push local 0
```

Tests the handling of the VM commands:

`label`

`if-goto`

Test programs

`ProgramFlow:`

- `BasicLoop`
- `FibonacciSeries`

`FunctionCalls:`

- `SimpleFunction`
- `FibonacciElement`
- `StaticsTest`

Test programs: `FibonacciSeries`

`ProgramFlow:`

- ❑ `BasicLoop`
- `FibonacciSeries`
  - **`FibSeries.vm`**
  - `FibSeriesVME.tst`
  - `FibSeries.tst`
  - `FibSeries.cmp`

`FunctionCalls:`

- ❑ `SimpleFunction`
- ❑ `FibonacciElement`
- ❑ `StaticsTest`

`FibSeries.vm`

```
// Computes the first argument[0] elements of the Fibonacci series.
// Puts the elements in the RAM, starting at the address given in argument[1].
   push argument 1
   pop pointer 1
   push constant 0
   pop that 0
   push constant 1
   pop that 1
   ...
label MAIN_LOOP_START
   push argument 0
   if-goto COMPUTE_ELEMENT
   goto END_PROGRAM
label COMPUTE_ELEMENT
   push that 0
   push that 1
   add
   ...
   goto MAIN_LOOP_START
label END_PROGRAM
```

A more elaborate test of handling the VM commands:

`label`

`goto`

`if-goto`

Test programs

`ProgramFlow:`

- `BasicLoop`
- `FibonacciSeries`

`FunctionCalls:`

- `SimpleFunction`
- `FibonacciElement`
- `StaticsTest`

Test programs: `SimpleFunction`

ProgramFlow:

- ❑ BasicLoop
- ❑ FibonacciSeries

FunctionCalls:

- ➡ SimpleFunction
  - **SimpleFunction.vm**
  - SimpleFunctionVME.tst
  - SimpleFunction.tst
  - SimpleFunction.cmp
- ❑ FibonacciElement
- ❑ StaticsTest

SimpleFunction.vm

```
// Performs a simple (and meaningless) calculation involving local
// and argument values, and returns the result.

function SimpleFunction.test 2
   push local 0
   push local 1
   add
   not
   push argument 0
   add
   push argument 1
   sub
   return
```

Tests the handling of the VM commands

```
function
return
```

Basic test, involving no caller

Test programs

`ProgramFlow:`

- `BasicLoop`
- `FibonacciSeries`

`FunctionCalls:`

- `SimpleFunction`
- `FibonacciElement`
- `StaticsTest`

Test programs: `FibonacciElement`

ProgramFlow:

- ❑ BasicLoop
- ❑ FibonacciSeries

FunctionCalls:

- ❑ SimpleFunction
- ◆ FibonacciElement
  - **Main.vm**
  - **Sys.vm**
  - FibElementVME.tst
  - FibElement.tst
  - FibElement.cmp
- ❑ StaticsTest

Main.vm

```
// Main.fibonacci: computes the n'th element of the Fibonacci series,
// recursively. The n value is supplied by the caller, and stored in
// argument 0.
function Main.fibonacci 0
   push argument 0
   push constant 2
   lt
   if-goto IF_TRUE
   goto IF_FALSE
label IF_TRUE
   push argument 0
   return
label IF_FALSE
   push argument 0
   push constant 2
   sub
   call Main.fibonacci 1
   push argument 0
   push constant 1
   sub
   call Main.fibonacci 1
   add
   return
```

Tests ...

- that the VM translator can handle more than one VM file
- the handling of `function`, `return`, `call`
- that the VM translator initializes the memory segments
- that the bootstrap code initializes the stack and calls `Sys.init`

Sys.vm

```
// Sys.init: pushes n onto the stack,
// and calls Main.fibonacii to compute
// the n'th Fibonacci element.

// (Called by the bootstrap code generated
// by the VM translator ).

function Sys.init 0
   push constant 4
   call Main.fibonacci 1
label WHILE
   goto WHILE
```

Normally, `Sys.init` is used to call `Main.main`;

In Project 8 we use `Sys.init` to call test functions, as needed.

Test programs: `FibonacciElement`

ProgramFlow:

- ❑ BasicLoop
- ❑ FibonacciSeries

FunctionCalls:

- ❑ SimpleFunction
- ◆ FibonacciElement
  - **Main.vm**
  - **Sys.vm**
  - FibElementVME.tst
  - FibElement.tst
  - FibElement.cmp
- ❑ StaticsTest

Main.vm

```
// Main.fibonacci: computes the n'th element of the Fibonacci series,
// recursively. The n value is supplied by the caller, and stored in
// argument 0.
function Main.fibonacci 0
   push argument 0
   push constant 2
   lt
   if-goto IF_TRUE
   goto IF_FALSE
label IF_TRUE
   push argument 0
   return
label IF_FALSE
   push argument 0
   push constant 2
   sub
   call Main.fibonacci 1
   push argument 0
   push constant 1
   sub
   call Main.fibonacci 1
   add
   return
```

Usage: `$ VMTranslator FibonacciElement` (translates a *folder*)

(Should generate a single output file: `FibonacciElement.asm`)

Sys.vm

```
// Sys.init: pushes n onto the stack,
// and calls Main.fibonacii to compute
// the n'th Fibonacci element.
// (Called by the bootstrap code generated
// by the VM translator ).
function Sys.init 0
   push constant 4
   call Main.fibonacci 1
label WHILE
   goto WHILE
```

Test programs

`ProgramFlow:`

- ❑ `BasicLoop`
- ❑ `FibonacciSeries`

`FunctionCalls:`

- ❑ `SimpleFunction`
- ❑ `FibonacciElement`
- ❑ `StaticsTest`

Test programs: `StaticsTest`

ProgramFlow:

- ❑ BasicLoop
- ❑ FibonacciSeries

FunctionCalls:

- ❑ SimpleFunction
- ❑ FibonacciElement
- ◆ StaticsTest
  - **Class1.vm**
  - **Class2.vm**
  - **Sys.vm**
  - StaticsTestVME.tst
  - StaticsTest.tst
  - StaticsTest.cmp

Tests the handling of static variables in a program consisting of more than one VM file

Class1.vm

```
// Stores two supplied arguments in
// static 0 and static 1
function Class1.set 0
    push a
    pop st
    push a
    pop st
    push c
    return

// Returns (s
function
    push s
    push s
    sub
    return
```

Class2.vm

```
// Stores two supplied arguments in
 static 0 and static 1
function Class2.set 0
    push
    pop s
    push
    pop s
    push
    retur

// Returns
functior
    push
    push
    sub
    retur
```

Sys.vm

```
function Sys.init 0
  // Calls Class1.set with 6 and 8
    push constant 6
    push constant 8
    call Class1.set 2
    pop temp 0      // dumps the return value
   // Calls Class2.set with 23 and 15
    push constant 23
    push constant 15
    call Class2.set 2
    pop temp 0      // dumps the return value
    // Checks the two resulting static segments
    call Class1.get 0
    call Class2.get 0
label WHILE
    goto WHILE
```

Test programs

`ProgramFlow:`

- `BasicLoop`
- `FibonacciSeries`

`FunctionCalls:`

- `SimpleFunction`
- `FibonacciElement`
- `StaticsTest`

Testing routine for every test program `Xxx`:

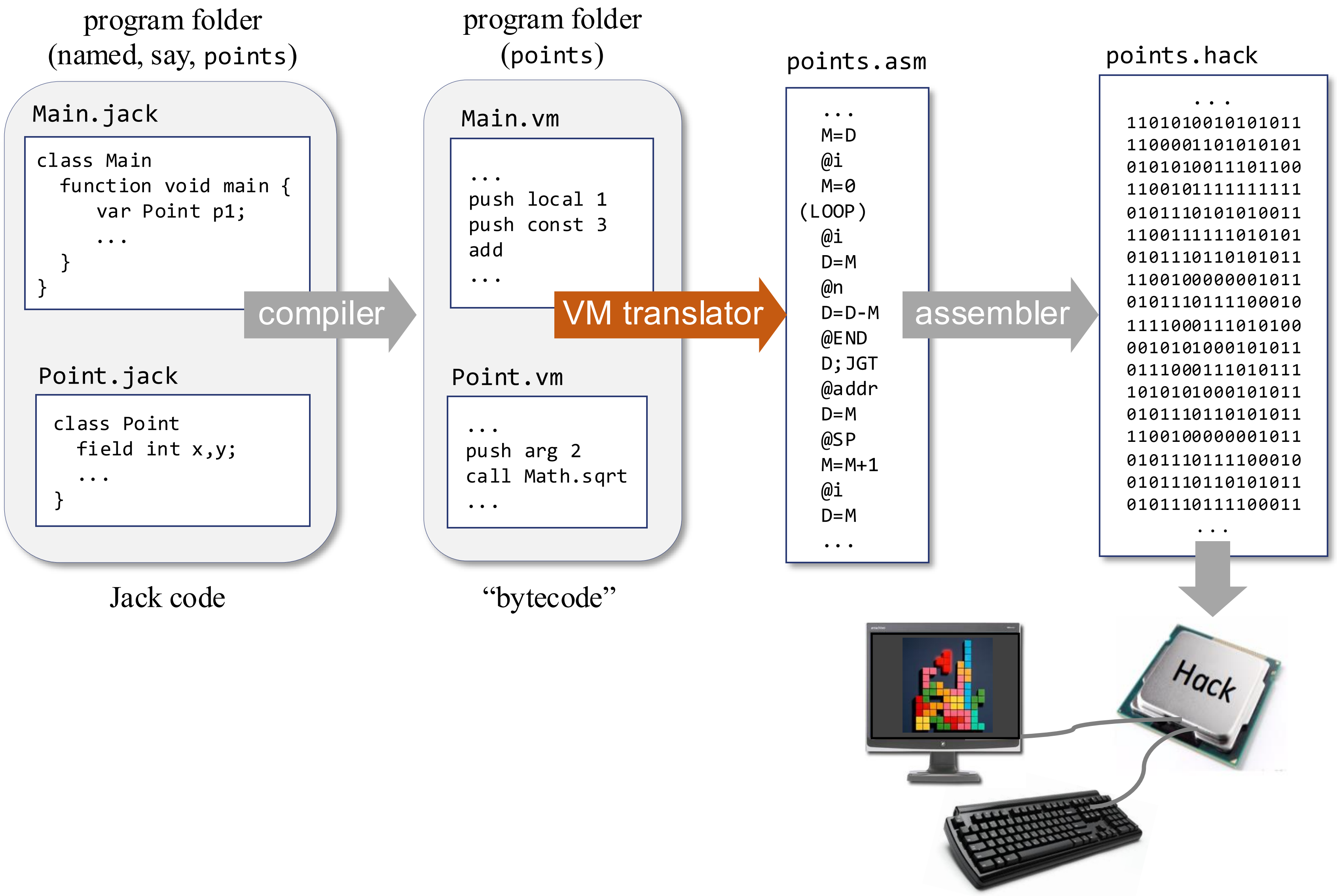
0. Recommended: Load and run `XxxVME.tst` on the VM emulator;
   This script loads the `Xxx` test program into the VM emulator, allowing you to experiment with its VM code

1. Use your VM translator to translate `Xxx.vm`, generating a file named `Xxx.asm` (if the test includes more than one `.vm` file, apply your translator to the folder name)

2. Load and run `Xxx.tst` on the CPU emulator;
   This script loads `Xxx.asm` into the emulator, executes it, and compares the output to `Xxx.cmp`

Note: All the files mentioned above are supplied, except for `Xxx.asm`, which must be generated by your VM translator.

The Big Picture



program folder
(named, say, points)

Main.jack

```
class Main
  function void main {
     var Point p1;
     ...
  }
}
```

Point.jack

```
class Point
  field int x,y;
  ...
}
```

Jack code

compiler

program folder
(points)

Main.vm

```
...
push local 1
push const 3
add
...
```

Point.vm

```
...
push arg 2
call Math.sqrt
...
```

“bytecode”

VM translator

points.asm

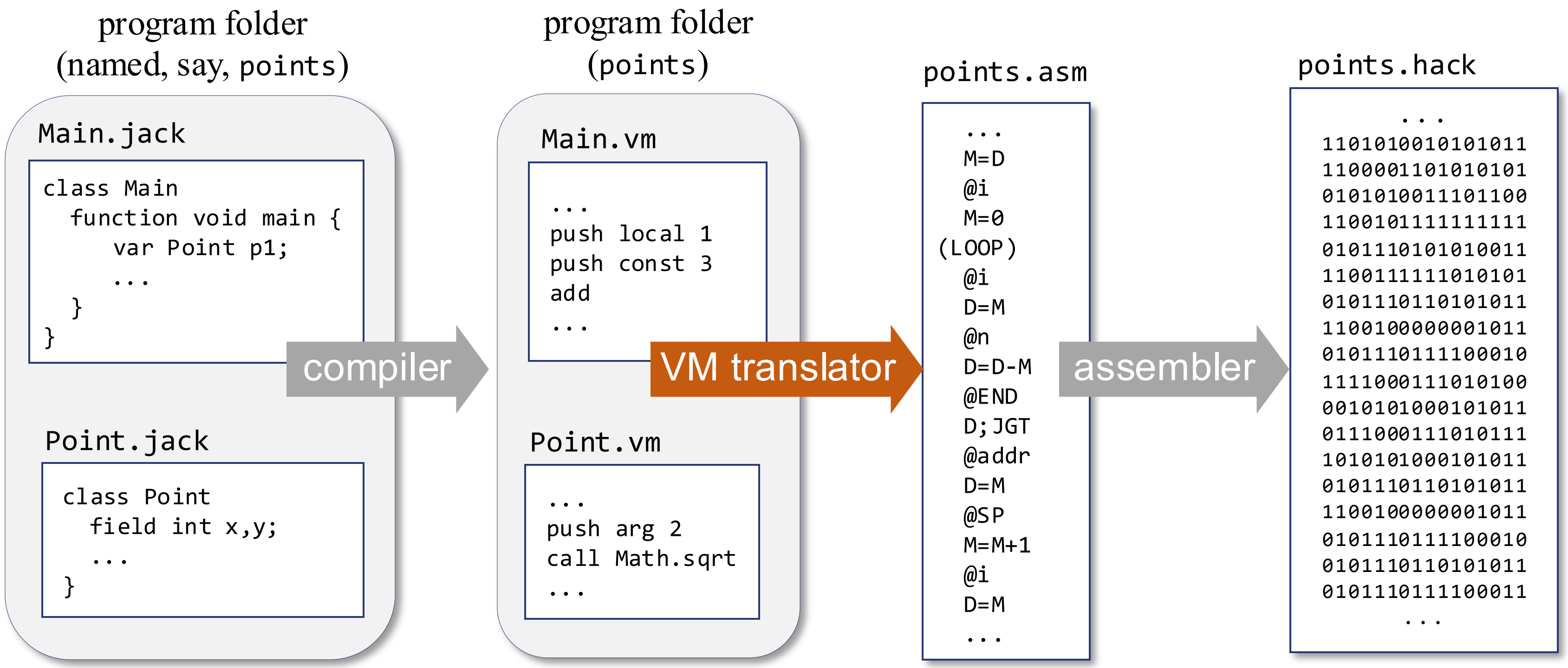
```
  ...
  M=D
  @i
  M=0
(LOOP)
  @i
  D=M
  @n
  D=D-M
  @END
  D;JGT
  @addr
  D=M
  @SP
  M=M+1
  @i
  D=M
  ...
```

assembler

points.hack

```
      ...
1101010010101011
1100001101010101
0101010011101100
1100101111111111
0101110101010011
1100111111010101
0101110110101011
1100100000001011
0101110111100010
1111000111010100
0010101000101011
0111000111010111
1010101000101011
0101110110101011
1100100000001011
0101110111100010
0101110110101011
0101110111100011
      ...
```

The Big Picture



program folder
(named, say, points)

Main.jack

```
class Main
  function void main {
     var Point p1;
     ...
  }
}
```

Point.jack

```
class Point
  field int x,y;
  ...
}
```

program folder
(points)

Main.vm

```
...
push local 1
push const 3
add
...
```

Point.vm

```
...
push arg 2
call Math.sqrt
...
```

points.asm

```
  ...
  M=D
  @i
  M=0
(LOOP)
  @i
  D=M
  @n
  D=D-M
  @END
  D;JGT
  @addr
  D=M
  @SP
  M=M+1
  @i
  D=M
  ...
```

points.hack

```
       ...
1101010010101011
1100001101010101
0101010011101100
1100101111111111
0101110101010011
1100111111010101
0101110110101011
1100100000001011
0101110111100010
1111000111010100
0010101000101011
0111000111010111
1010101000101011
0101110110101011
1100100000001011
0101110111100010
0101110110101011
0101110111100011
       ...
```

The VM translator developed in projects 7 – 8 is the *compiler's backend*

<u>Next:</u>

- Introducing the Jack language (project 9)
- Completing the *compiler's frontend* (projects 10 – 11).