

## Chapter 8

# Virtual Machine

(Part II)

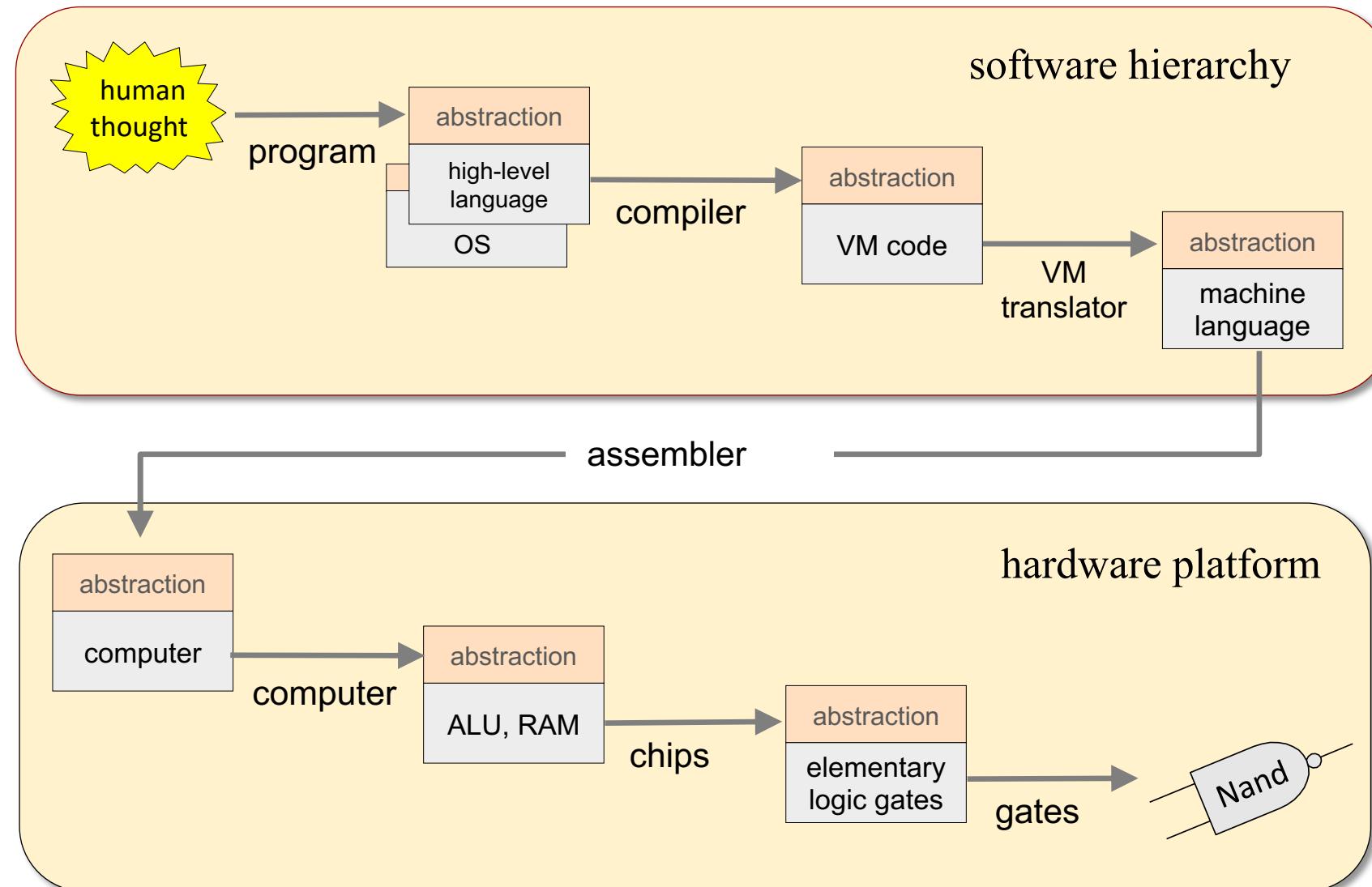
These slides support chapter 8 of the book

*The Elements of Computing Systems*

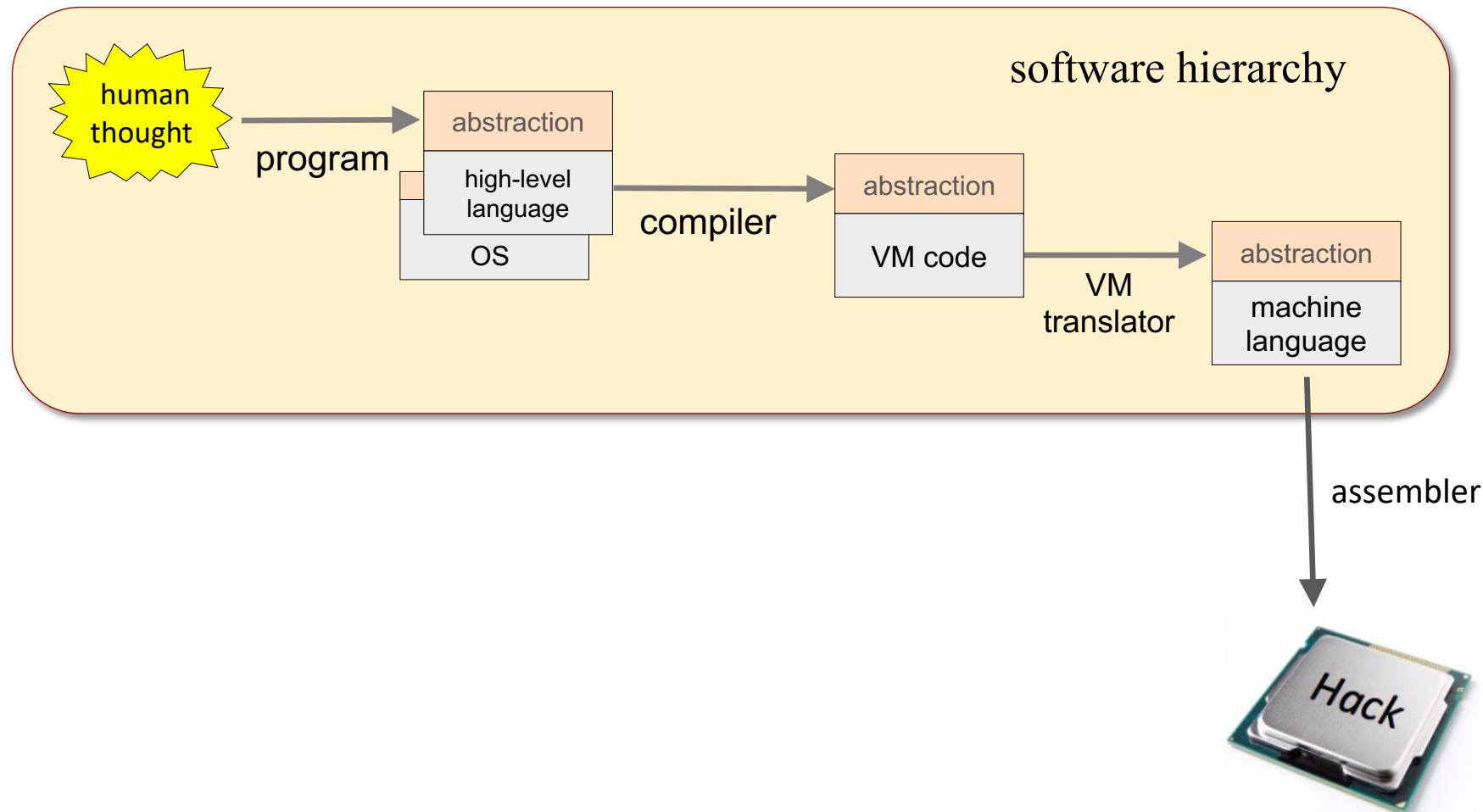
By Noam Nisan and Shimon Schocken

MIT Press, 2021

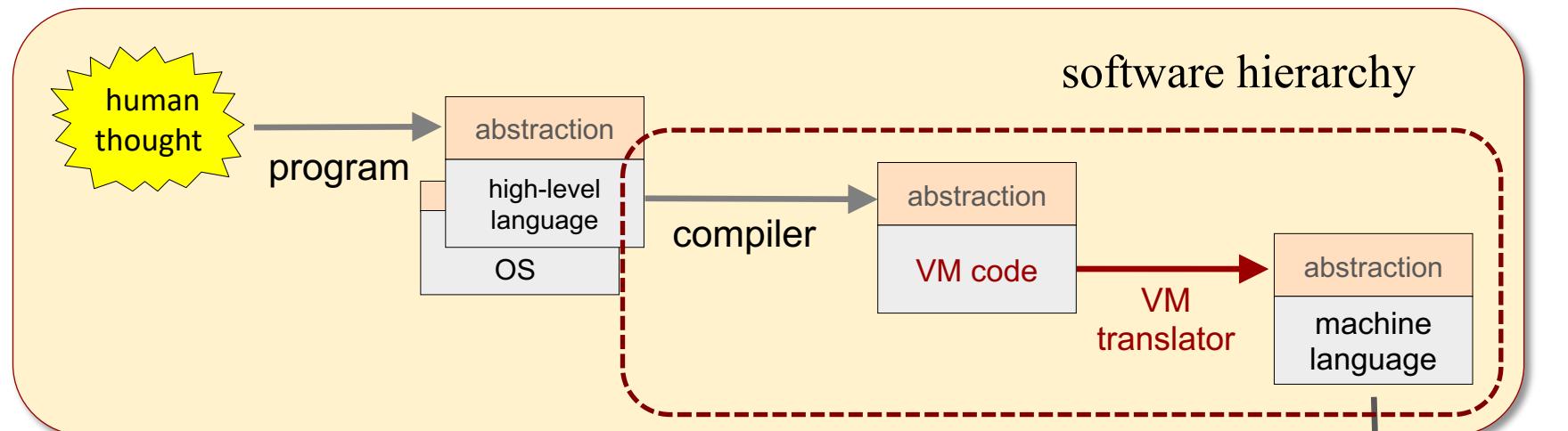
# Nand to Tetris Roadmap



# Nand to Tetris Roadmap: Part II



# Nand to Tetris Roadmap: Part II



## Previous lecture

- Introduced the VM *arithmetic-logical* and *push/pop* commands
- Built a basic VM translator that implements them

## This lecture

- Introduce the VM *branching* and *function* commands
- Complete the VM translator.

# The big picture: Compilation

High-level program

```
// Returns x * y
int mult(int x, int y) {
    int sum = 0;
    int n = 1;
    // sum = sum + x, y times
    while !(n > y) {
        sum += x;
        n++;
    }
    return sum;
}
```



(later in the course)

VM code

```
// Returns x * y
function mult 2
    push 0
    pop sum
    push 1
    pop n
label WHILE_LOOP
    push n
    push y
    gt
    if-goto END_LOOP
    push sum
    push x
    add
    pop sum
    push n
    push 1
    add
    pop n
    goto WHILE_LOOP
label END_LOOP
    push sum
    return
```

## The VM Language

### ✓ Arithmetic / Logical

- add, sub , neg
- eq , gt , lt, and, or , not

### ✓ Memory access

- push
- pop

“imperatives”

### Branching

- label
- goto
- if-goto

“control”

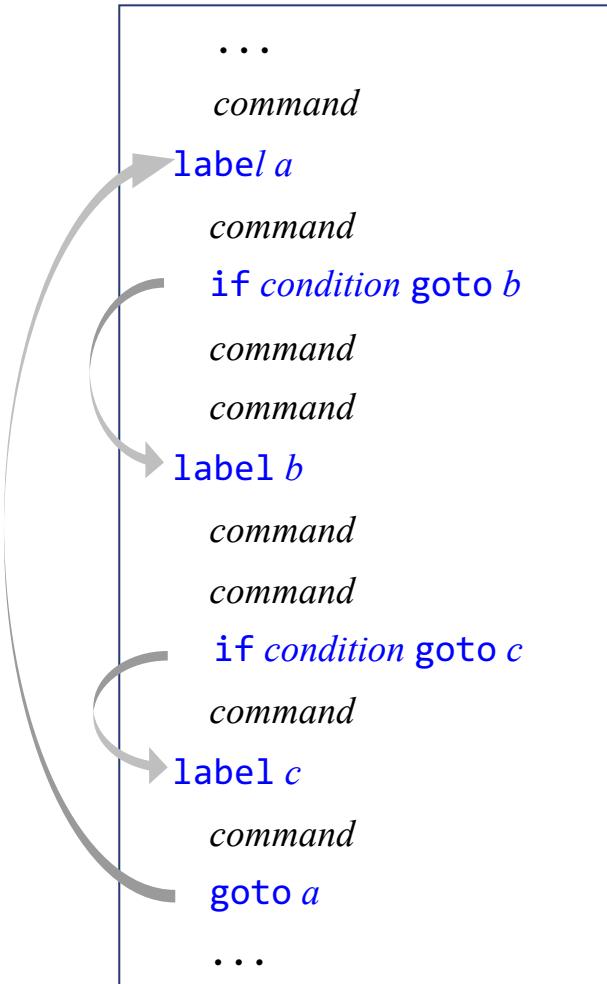
### Function

- function
- call
- return

# Branching

---

Programs typically include branching logic (conditions, loops):



## Branching

Unconditional: `goto label`

Conditional: `if condition goto label`

## Implementation issues

How to realize...

- conditions?
- labels?
- branching operations?

# Functions

---

Programs are typically divided into “*modules*”:

“Subroutines”

“Procedures”

“Methods”

“functions”

Etc.

At the VM level, they all become *functions*



# Functions

---

## Function foo

```
// Some function
function foo
...
// Computes 8 * 5 + 7
push 8
push 5
call mult
push 7
add
...
return
```

caller

## Function mult

```
// Returns x * y
function mult
push 0
pop sum
push 1
pop n
label WHILE_LOOP
push n
push y
gt
if-goto END_LOOP
push sum
push x
add
pop sum
push n
push 1
add
pop n
goto WHILE_LOOP
label END_LOOP
push sum
return
```

callee

### Typical scenario

A function (like `foo`) calls a function (like `mult`) for its effect.

### Implementation issues

How to pass arguments from the caller to the callee?

How to start executing the callee's code?

How to pass the return value from the callee to the caller?

How to resume the execution of the caller's code?

# Take home lessons

---

## Understanding program execution



- Branching
- Function call-and-return
- Recursion

## Related issues

- Compilation
- Run-time system
- Memory management.

# Branching: Abstraction

---

```
// Returns x * y
function mult
    push 0
    pop sum
    push 1
    pop n
label LOOP
    push n
    push y
    gt
    if-goto END
    push sum
    push x
    add
    pop sum
    push n
    push 1
    add
    pop n
    goto LOOP
label END
    push sum
    return
```

## VM branching commands

label

goto

if-goto

# Branching: Abstraction

---

```
// Returns x * y
function mult
    push 0
    pop sum
    push 1
    pop n
label LOOP
    push n
    push y
    gt
    if-goto END
    push sum
    push x
    add
    pop sum
    push n
    push 1
    add
    pop n
    goto LOOP
label END
    push sum
    return
```

## VM branching commands



label

goto

if-goto

Syntax: **label** *label*

## Semantics

Marks the destination of goto commands.

# Branching: Abstraction

---

```
// Returns x * y
function mult
    push 0
    pop sum
    push 1
    pop n
label LOOP
    push n
    push y
    gt
    if-goto END
    push sum
    push x
    add
    pop sum
    push n
    push 1
    add
    pop n
    goto LOOP
label END
    push sum
    return
```

## VM branching commands

label  
→ goto  
if-goto

Syntax: goto *label*

### Semantics

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

# Branching: Abstraction

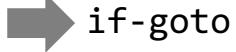
---

```
// Returns x * y
function mult
    push 0
    pop sum
    push 1
    pop n
label LOOP
    push n
    push y
    gt
    if-goto END
    push sum
    push x
    add
    pop sum
    push n
    push 1
    add
    pop n
    goto LOOP
label END
    push sum
    return
```

## VM branching commands

label

goto



Syntax: **if-goto** *label*

## Semantics

1. let *cond* = pop
2. if *cond* jump to execute the command just after the *label*  
else execute the next command.

## Assumption

The code writer is expected to write code that pushes a logical expression onto the stack before the if-goto command. In this example, the highlighted code implements the abstraction:

**if**(*n* > *y*) **goto** END

Note: In this lecture, “code writer” is typically a compiler.

# Branching: Implementation

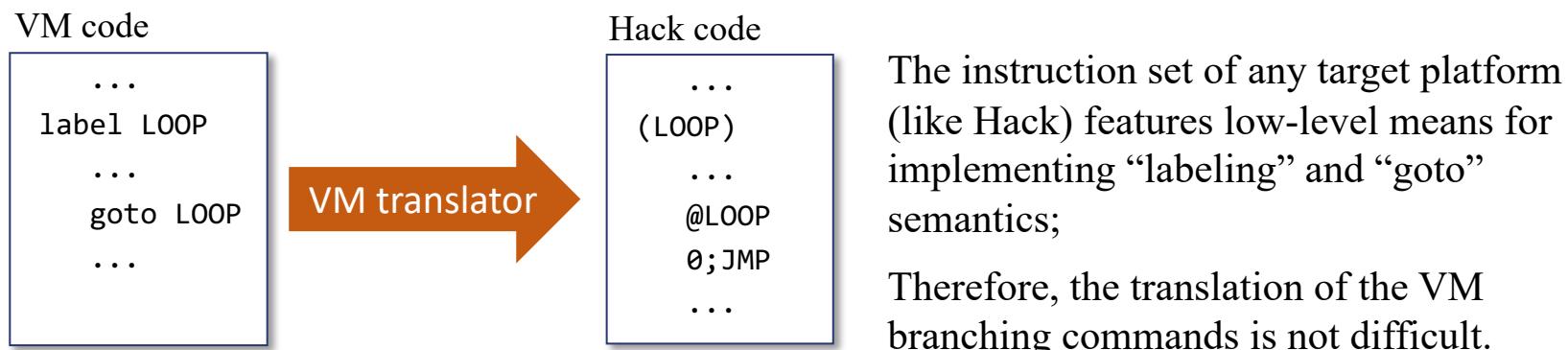
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## Abstraction (recap)

```
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

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



# Lecture plan

---

## ✓ Branching

- Abstraction
- Implementation

## Function call and return



- Implementation

## The Virtual Machine

- Program translation
- Standard mapping
- VM translator
- Project 8

# Functions: Abstraction

caller

```
// Computes 3 + 8 * 5
function foo
    push 3
    push 8
    push 5
    call mult
    add
    ...
```

callee

```
// Returns x * y
function mult
```

```
    push 0
    pop sum
    push 1
    pop n
```

```
label LOOP
    push n
    push y
```

```
    gt
    if-goto END
```

```
    push sum
    push x
```

```
    add
    pop sum
```

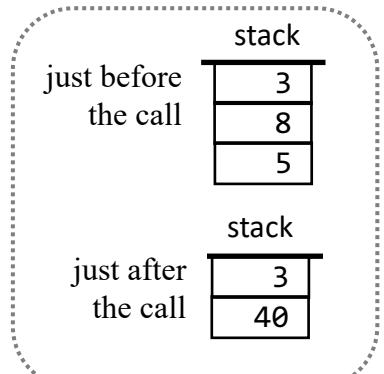
```
    push n
    push 1
```

```
    add
    pop n
```

```
    goto LOOP
label END
```

```
    push sum
    return
```

foo's view:



## Typical scenario

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

# Functions: Abstraction

caller

```
// Computes 3 + 8 * 5
function foo
    push 3
    push 8
    push 5
    call mult
    add
    ...

```

callee

```
// Returns x * y
function mult
```

```
    push 0
    pop sum
    push 1
    pop n
```

```
label LOOP
```

```
    push n
    push y
    gt
```

```
    if-goto END
```

```
    push sum
```

```
    push x
```

```
    add
```

```
    pop sum
```

```
    push n
```

```
    push 1
```

```
    add
```

```
    pop n
```

```
    goto LOOP
```

```
label END
```

```
    push sum
```

```
return
```

foo's view:

just before the call

|       |
|-------|
| stack |
| 3     |
| 8     |
| 5     |

just after the call

|       |
|-------|
| stack |
| 3     |
| 40    |

## VM function commands

call

function

return

We will now switch from  
pseudo VM code to actual  
VM code

# Functions: Abstraction

caller

```
// Computes 3 + 8 * 5
function foo 0
    push constant 3
    push constant 8
    push constant 5
    call mult 2
    add
    ...

```

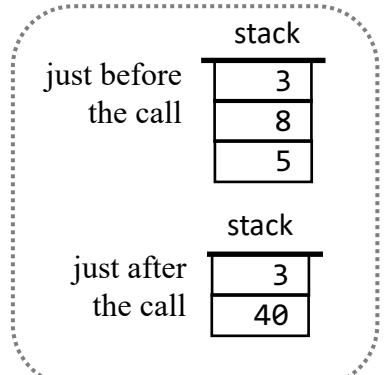
callee

```
// Returns arg 0 * arg 1
```

```
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

```

foo's view:



VM function commands

call

function

return

# Functions: Abstraction

caller

```
// Computes 3 + 8 * 5
function foo 0
    push constant 3
    push constant 8
    push constant 5
    call mult 2
    add
    ...

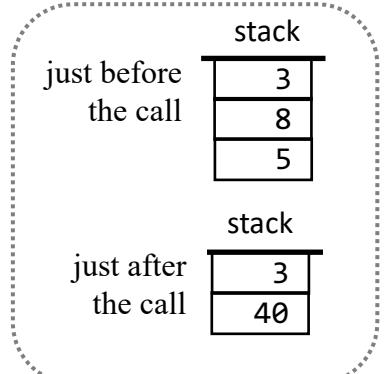
```

callee

```
// Returns arg 0 * arg 1
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

```

foo's view:



VM function commands



call

function

return

# Functions: Abstraction

caller

```
// Computes 3 + 8 * 5
function foo 0
    push constant 3
    push constant 8
    push constant 5
    call mult 2
    add
    ...

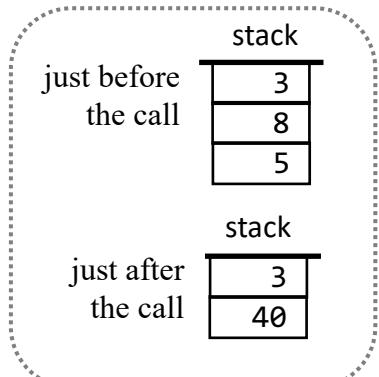
```

callee

```
// Returns arg 0 * arg 1
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

```

foo's view:



## 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

## Assumption

The code writer is expected to push *nArgs* arguments onto the stack before the `call` command.

# Functions: Abstraction

caller

```
// Computes 3 + 8 * 5
function foo 0
    push constant 3
    push constant 8
    push constant 5
    call mult 2
    add
    ...

```

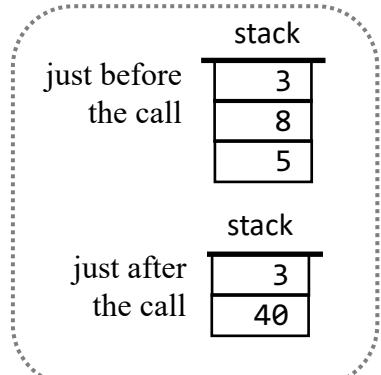
callee

```
// Returns arg 0 * arg 1
```

```
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
```

foo's view:



## 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

# Functions: Abstraction

caller

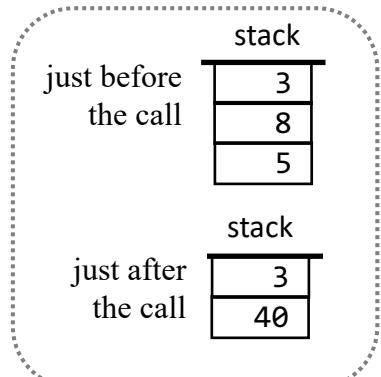
```
// Computes 3 + 8 * 5
function foo 0
    push constant 3
    push constant 8
    push constant 5
    call mult 2
    add
    ...

```

callee

```
// Returns arg 0 * arg 1
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
```

foo's view:



## VM function commands

call

function



Syntax: return

## Assumption

The code writer is expected to push a value onto the stack before the return command

## Semantics

The *return value* will replace (in the stack) the argument values 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.

# Lecture plan

---

## Branching

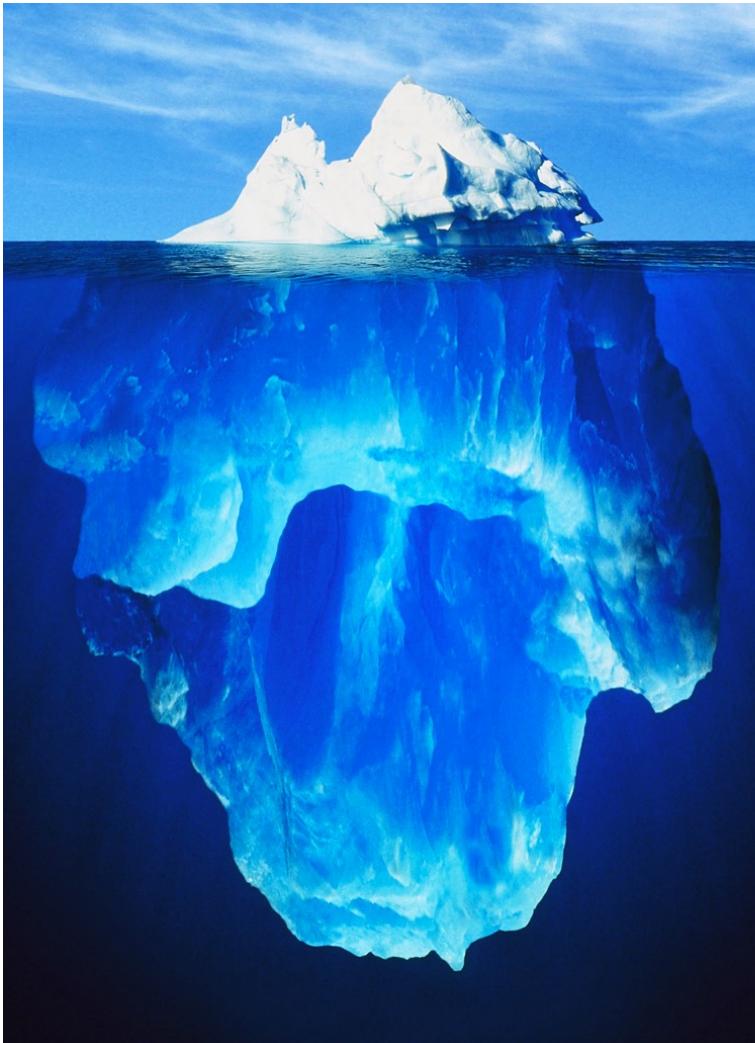
- Abstraction
- Implementation

## Function call and return

- ✓ Abstraction  
→ Implementation

## The Virtual Machine

- Program translation
- Standard mapping
- VM translator
- Project 8



# Function call and return

---

caller

```
// Computes 3 + 8 * 5
function foo 0
    push constant 3
    push constant 8
    push constant 5
    call mult 2
    add
    ...

```

callee

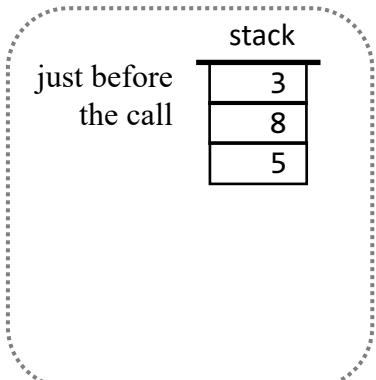
```
// Returns arg 0 * arg 1
function mult 2
    push constant 0
    pop local 0
    push constant 1
    pop local 1
    ...
    push local 0
    return

```

## Typical function-call-and-return scenario

Function `foo` (the *caller*) calls function `mult` (the *callee*) for its effect

`foo`'s view:



# Function call and return

caller

```
// Computes 3 + 8 * 5
function foo 0
    push constant 3
    push constant 8
    push constant 5
    call mult 2
    add
    ...
```

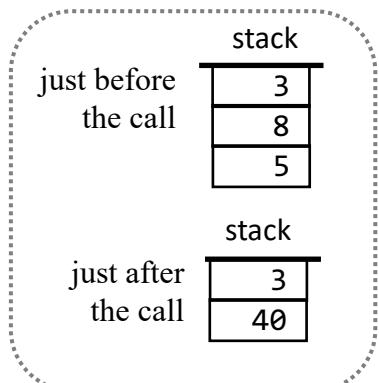
callee

```
// Returns arg 0 * arg 1
function 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` (the *caller*) calls function `mult` (the *callee*) for its effect

`foo`'s view:



Magic!

Let's open  
the black box

# Function call and return

caller

```
// Computes 3 + 8 * 5
function foo 0
    push constant 3
    push constant 8
    push constant 5
    call mult 2
    add
    ...
    ...
```

callee

```
// Returns arg 0 * arg 1
function 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` (the *caller*) calls function `mult` (the *callee*) for its effect

`foo`'s view:

| stack |
|-------|
| 3     |
| 8     |
| 5     |

just before  
the call

Adding line numbers,  
just for reference

The caller's execution  
is suspended

# Function call and return

caller

```
// Computes 3 + 8 * 5
function foo 0
    push constant 3
    push constant 8
    push constant 5
    call mult 2
    add
    ...
    ...
```

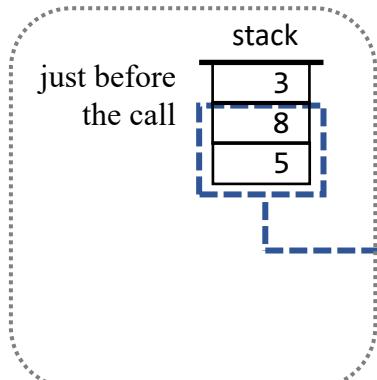
callee

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

## Typical function-call-and-return scenario

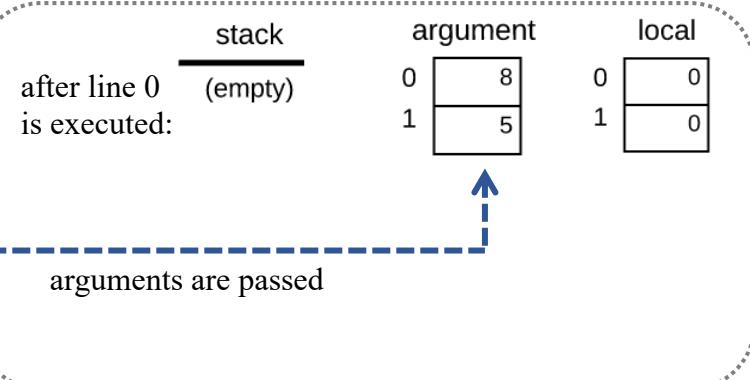
Function `foo` (the *caller*) calls function `mult` (the *callee*) for its effect

`foo`'s view:



The caller's execution is suspended

`mult`'s view:



The callee's stack and segments are being set up

# Function call and return

caller

```
// Computes 3 + 8 * 5
function foo 0
    push constant 3
    push constant 8
    push constant 5
    call mult 2
    add
    ...
    ...
```

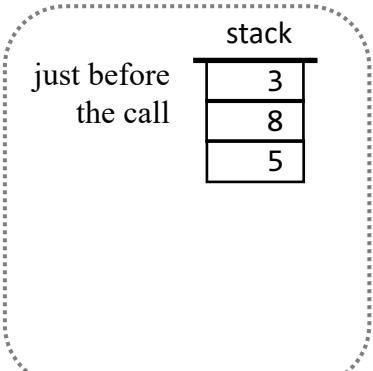
callee

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

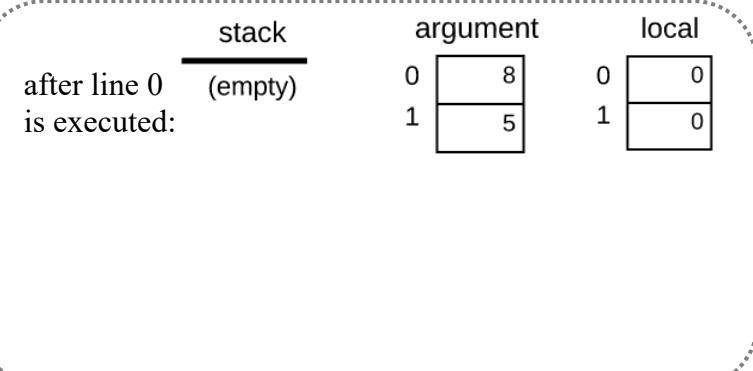
## Typical function-call-and-return scenario

Function `foo` (the *caller*) calls function `mult` (the *callee*) for its effect

`foo`'s view:



`mult`'s view:



The callee's code  
is executed

# Function call and return

caller

```
// Computes 3 + 8 * 5
function foo 0
    push constant 3
    push constant 8
    push constant 5
    call mult 2
    add
    ...
    ...
```

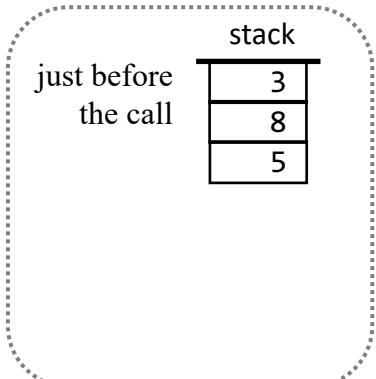
callee

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

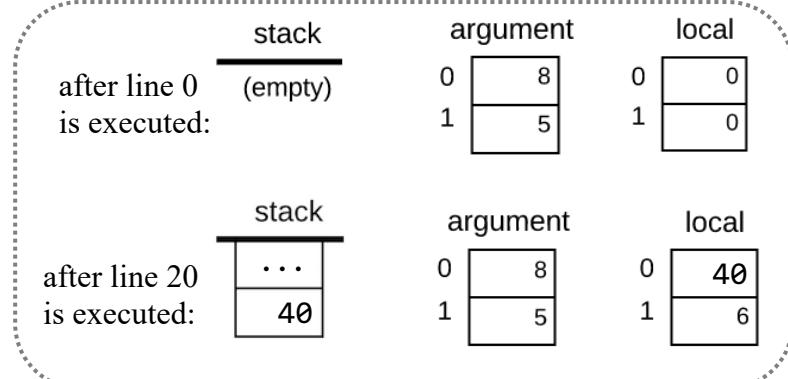
## Typical function-call-and-return scenario

Function `foo` (the *caller*) calls function `mult` (the *callee*) for its effect

`foo`'s view:



`mult`'s view:



The callee's code  
is executed

# Function call and return

caller

```
// Computes 3 + 8 * 5
function foo 0
    push constant 3
    push constant 8
    push constant 5
    call mult 2
    add
    ...
    ...
```

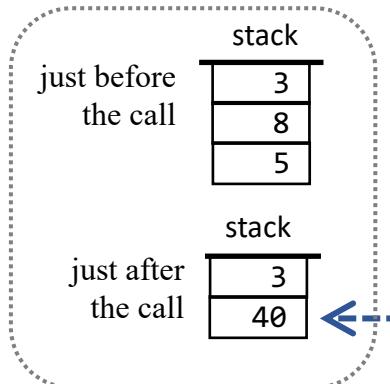
callee

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

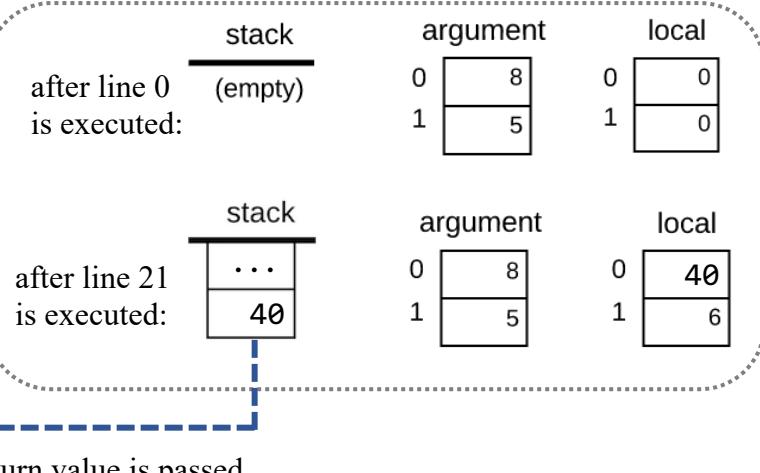
## Typical function-call-and-return scenario

Function `foo` (the *caller*) calls function `mult` (the *callee*) for its effect

`foo`'s view:



`mult`'s view:



The callee's execution is terminated

# Function call and return

caller

```
// Computes 3 + 8 * 5
function foo 0
    push constant 3
    push constant 8
    push constant 5
    call mult 2
    add
    ...

```

callee

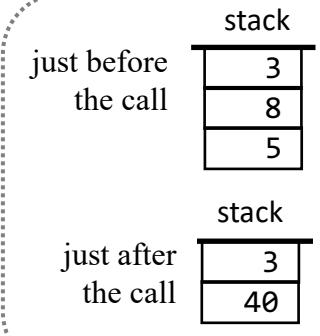
```
// Returns arg 0 * arg 1
function mult 2
    push constant 0
    pop local 0
    push constant 1
    pop local 1
    ...
    push local 0
    return

```

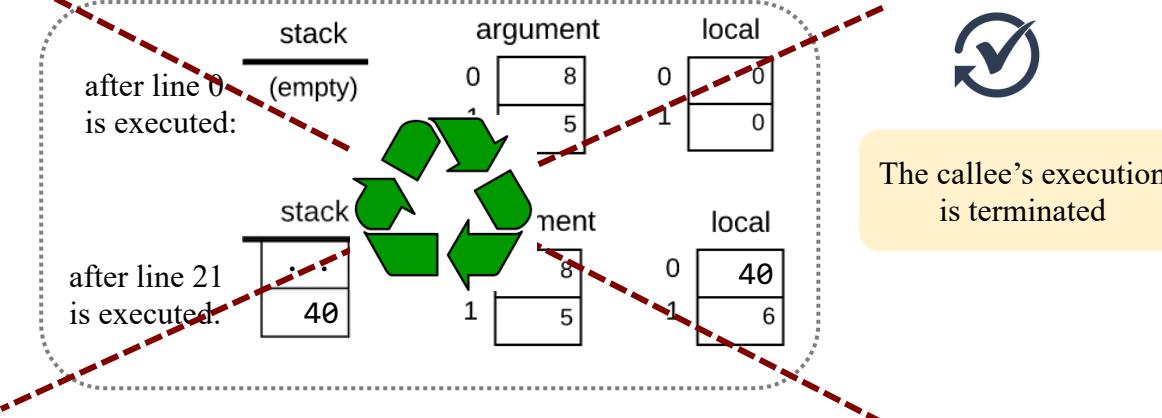
## Typical function-call-and-return scenario

Function `foo` (the *caller*) calls function `mult` (the *callee*) for its effect

`foo`'s view:



`mult`'s view:



# Function call and return

caller

```
// Computes 3 + 8 * 5
function foo 0
    push constant 3
    push constant 8
    push constant 5
    call mult 2
    add
    ...

```

callee

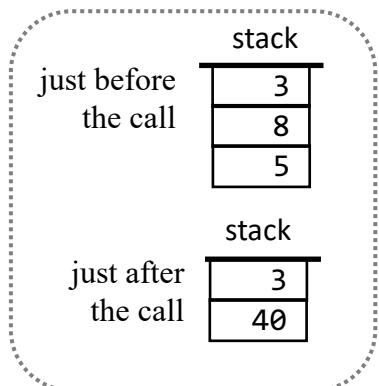
```
// Returns arg 0 * arg 1
function mult 2
    push constant 0
    pop local 0
    push constant 1
    pop local 1
    ...
    push local 0
    return

```

## Typical function-call-and-return scenario

Function `foo` (the *caller*) calls function `mult` (the *callee*) for its effect

`foo`'s view:



The caller's execution  
is resumed

Magic!

# Function call and return

---

## Recap

- A VM program consists of one or more VM functions
- The functions call each other, for their effect (perhaps recursively)
- Each function execution sees its own working stack and memory segments
- Arguments and return values are passed, somehow

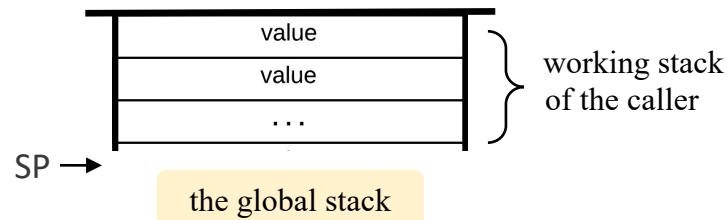
## Implementation

- We will build a run-time system that realizes this abstraction
- The run-time system will manage the working stacks and memory segments of all the running functions on a single, global stack, stored on the host RAM
- For every occurrence of `call`, `function`, and `return` command, the VM translator will generate machine language code that, when executed, will realize this run-time system
- And now for the gory details.

# Implementing `call` / function / return

---

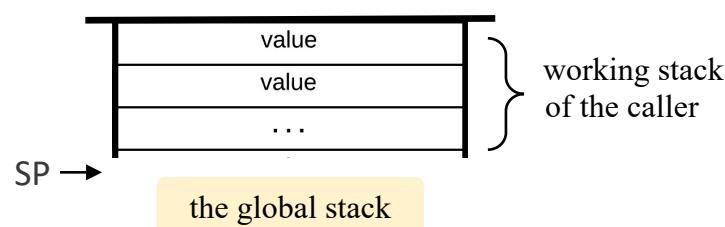
The caller is running,  
doing various things



# Implementing `call` / function / return

---

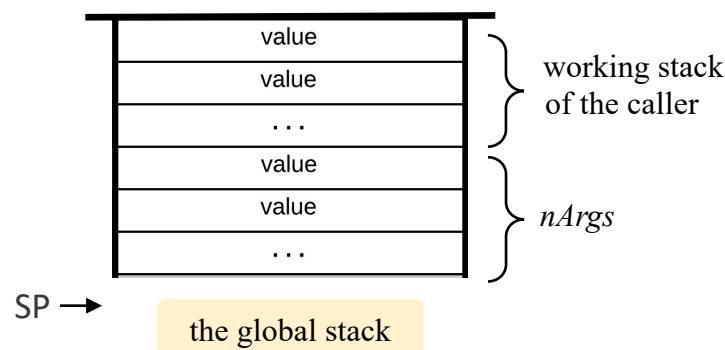
The caller prepares to call another function;  
It pushes 0 or more arguments onto the stack



# Implementing `call` / function / return

---

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

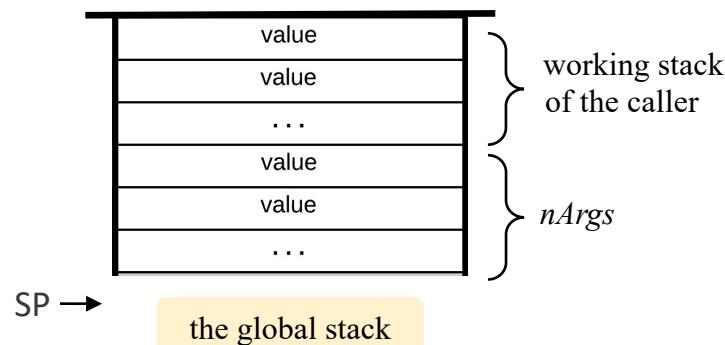


# Implementing `call` / function / return

---

The caller says:

`call functionName nArgs`



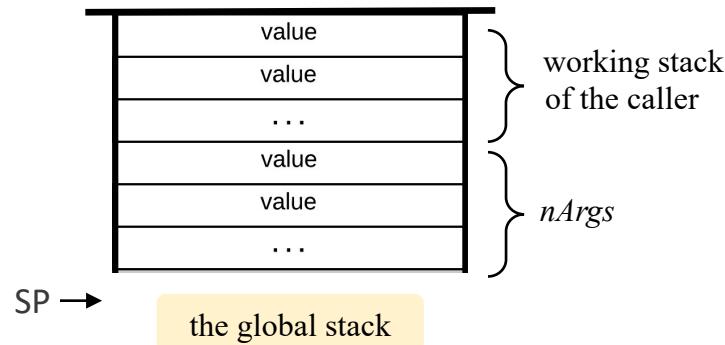
Handling `call functionName nArgs`

We have to:

# Implementing `call` / function / return

The caller says:

`call functionName nArgs`



## Handling `call functionName nArgs`

We have to:

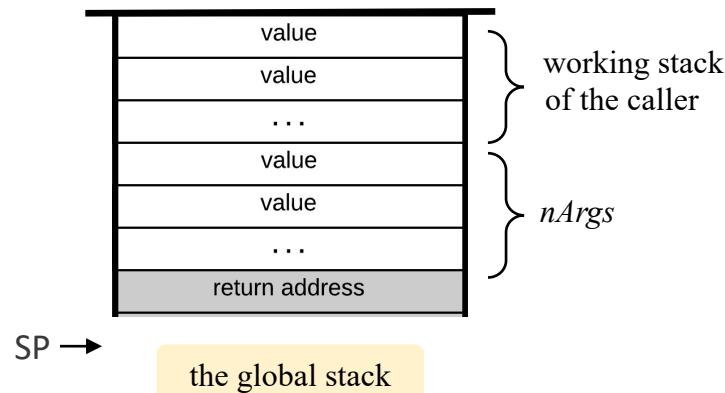
- Save the return address

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

# Implementing `call` / function / return

The caller says:

`call functionName nArgs`



Handling `call functionName nArgs`

We have to:

- Save the return address

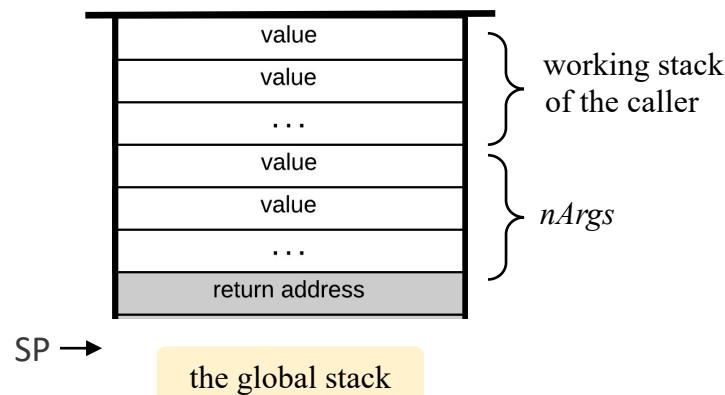
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# Implementing `call` / function / return

---

The caller says:

`call functionName nArgs`



Handling `call functionName nArgs`

We have to:

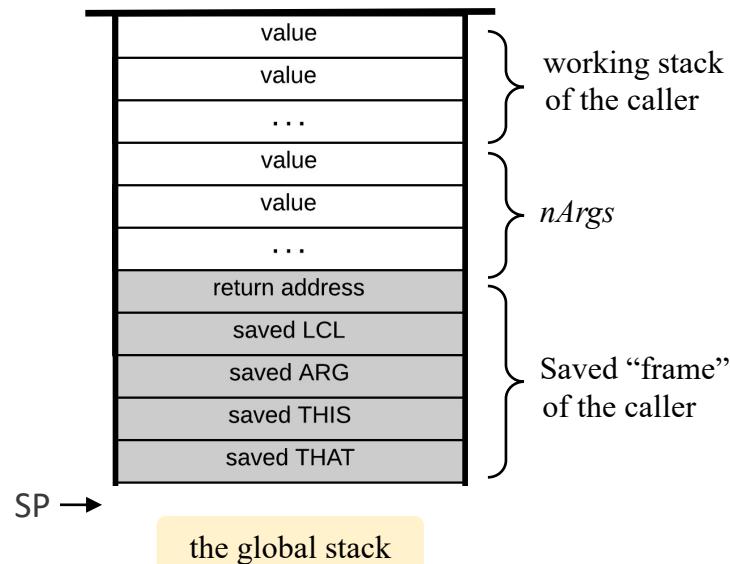
- Save the return address
- Save the caller's segment pointers

# Implementing `call` / function / return

---

The caller says:

`call functionName nArgs`



Handling `call functionName nArgs`

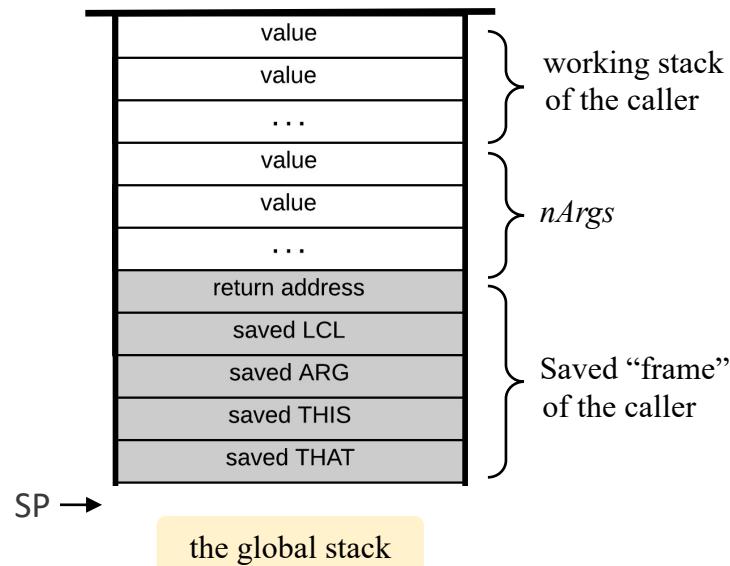
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# Implementing `call` / function / return

The caller says:

`call functionName nArgs`



Handling `call functionName nArgs`

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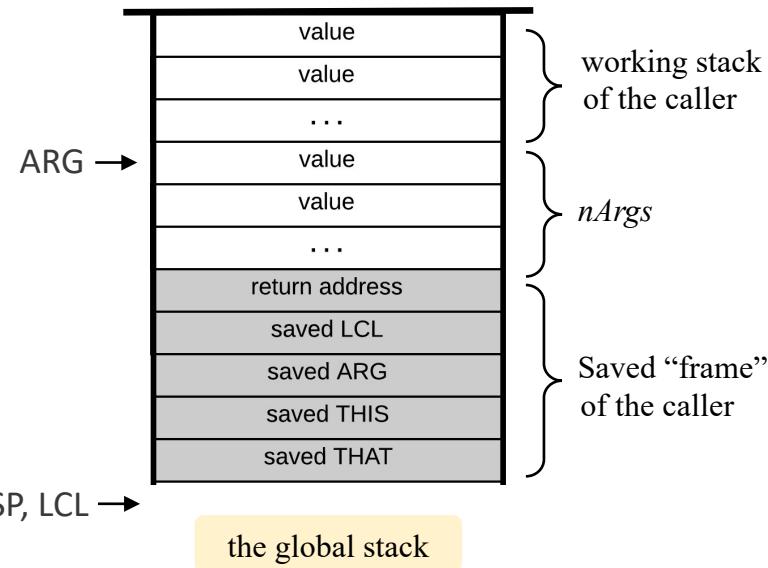
- Save the return address
- Save the caller's segment pointers
- Reposition ARG (for the callee)
- Reposition LCL (for the callee)

# Implementing `call` / function / return

---

The caller says:

`call functionName nArgs`



Handling `call functionName nArgs`

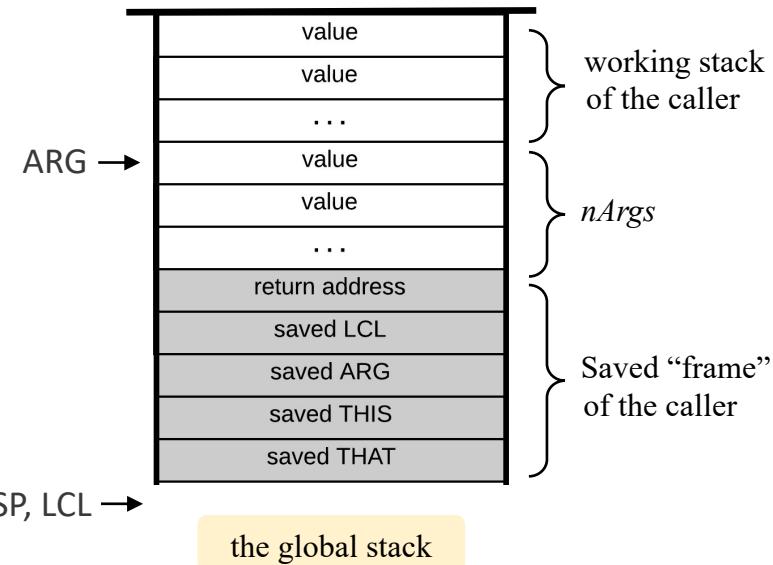
We have to:

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

# Implementing `call` / function / return

The caller says:

`call functionName nArgs`



Handling `call functionName nArgs`

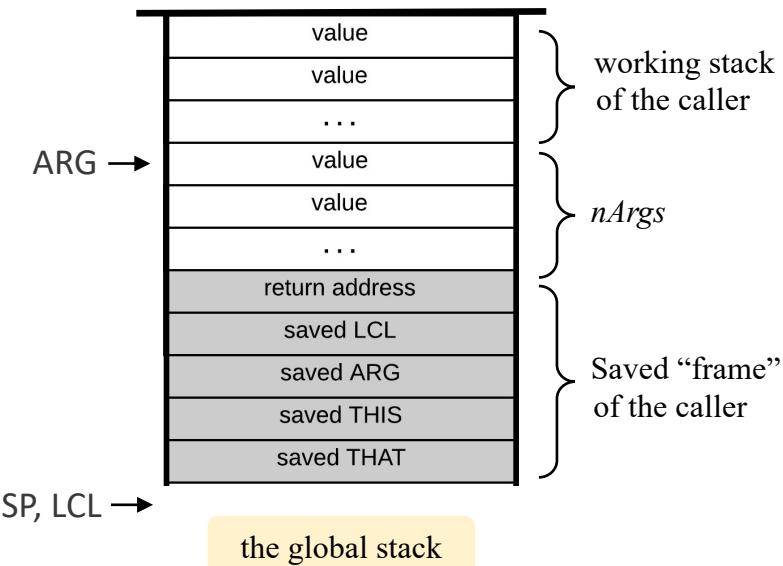
We have to:

- 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

# Implementing `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

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
```

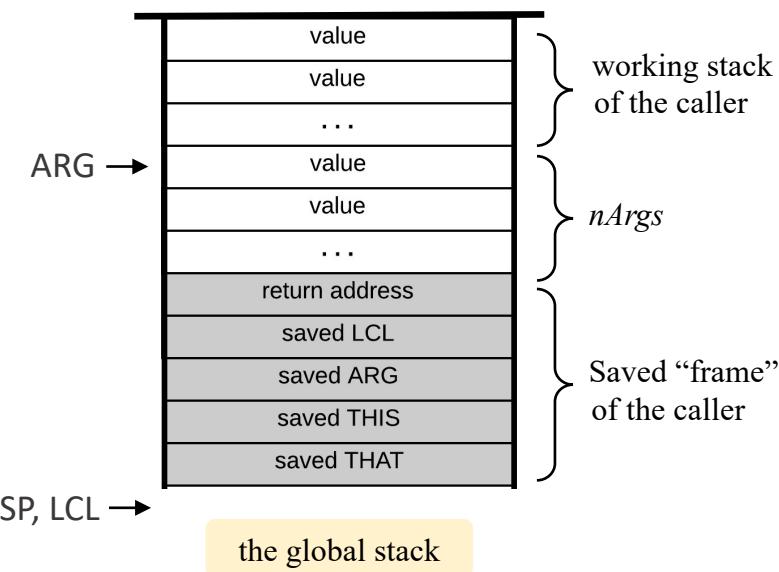
(The VM translator should generate this code in assembly)

# Implementing `call` / `function` / `return`

---

The callee is entered:

`function functionName nVars`



Handling `functionName nVars`

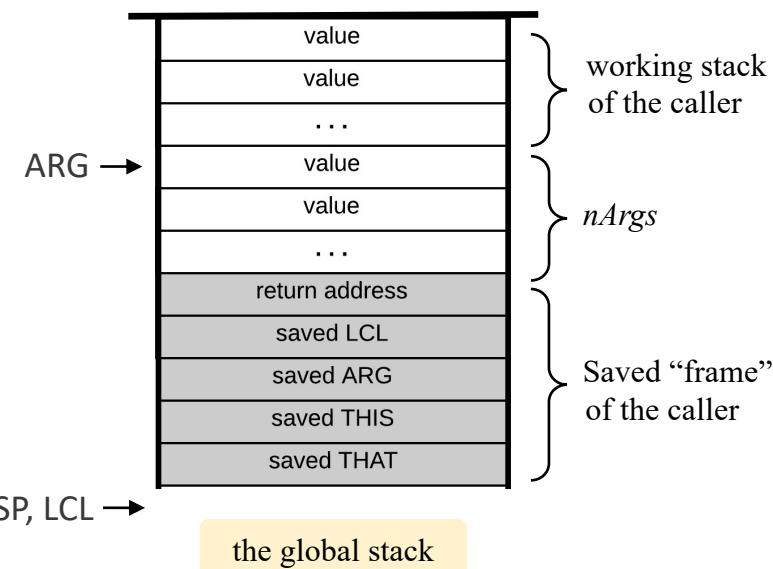
We have to:

# Implementing `call` / `function` / `return`

---

The callee is entered:

`function functionName nVars`



Handling function `functionName nVars`

We have to:

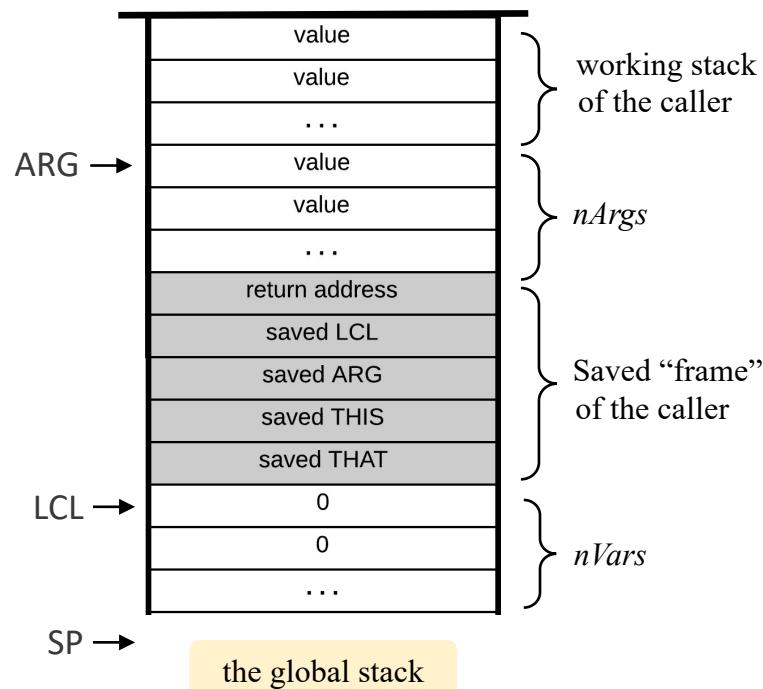
- Inject an entry point label into the code
- Initialize the local segment of the callee

# Implementing `call` / `function` / `return`

---

The callee is entered:

`function functionName nVars`



Handling `function functionName nVars`

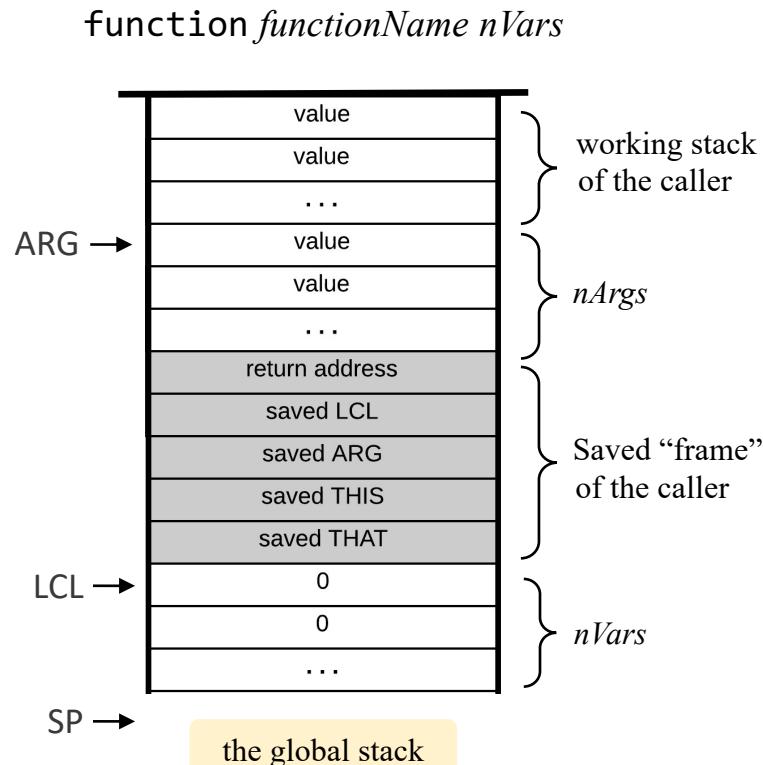
We have to:

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

# Implementing `call` / `function` / `return`

---

The callee is entered:



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

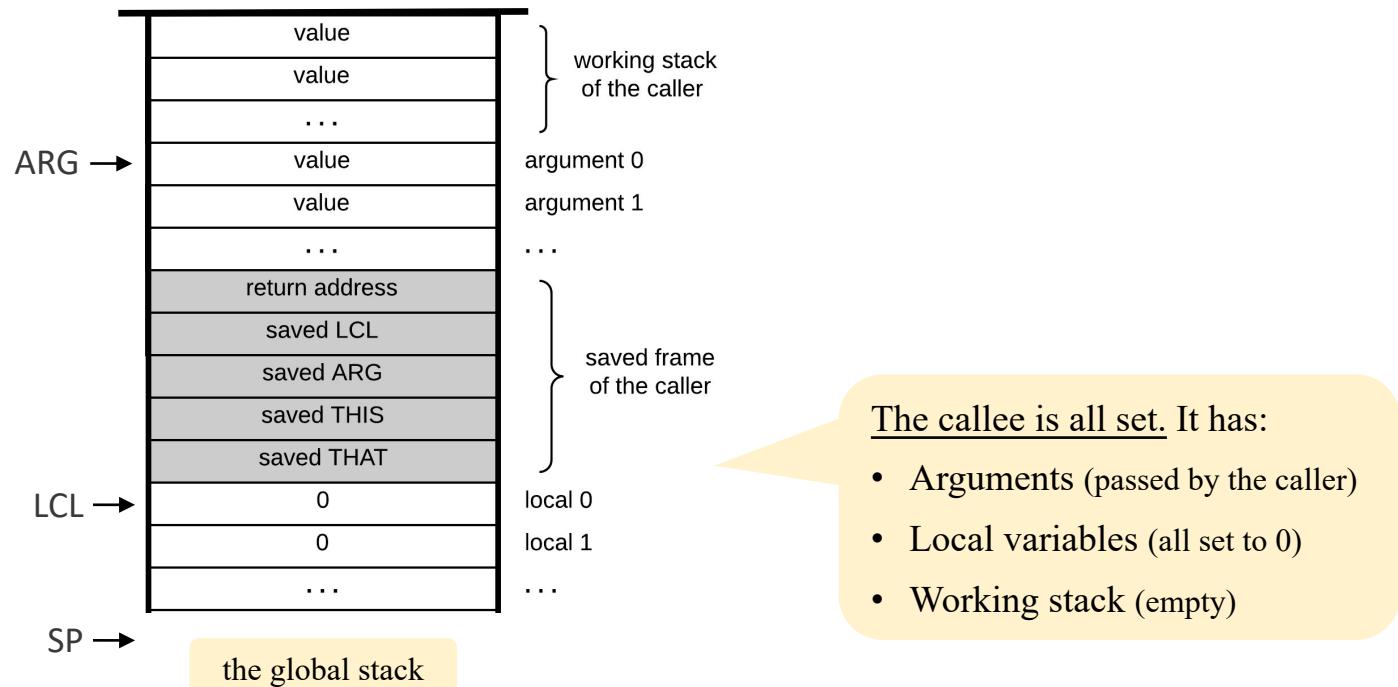
(The VM translator should generate this code in assembly)

# Implementing `call` / `function` / `return`

---

The callee is entered:

`function functionName nVars`



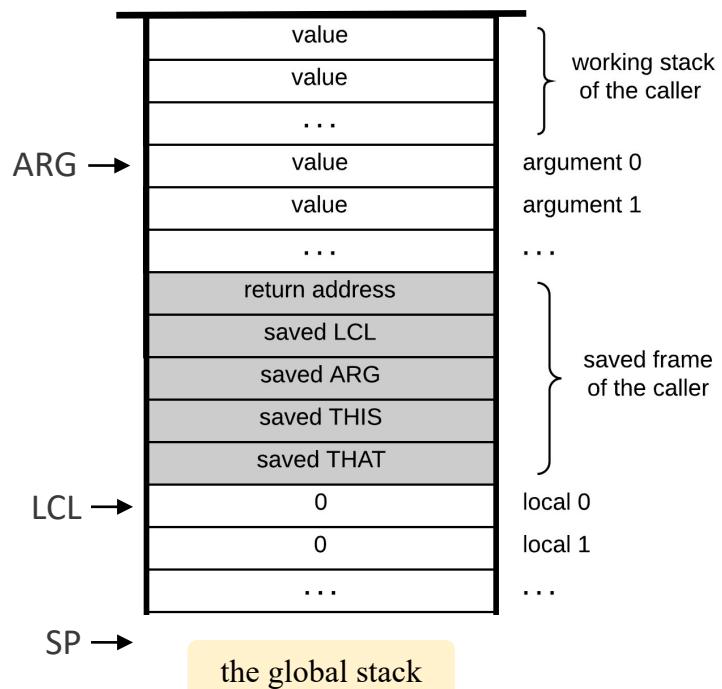
The callee is all set. It has:

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

# Implementing `call` / `function` / `return`

---

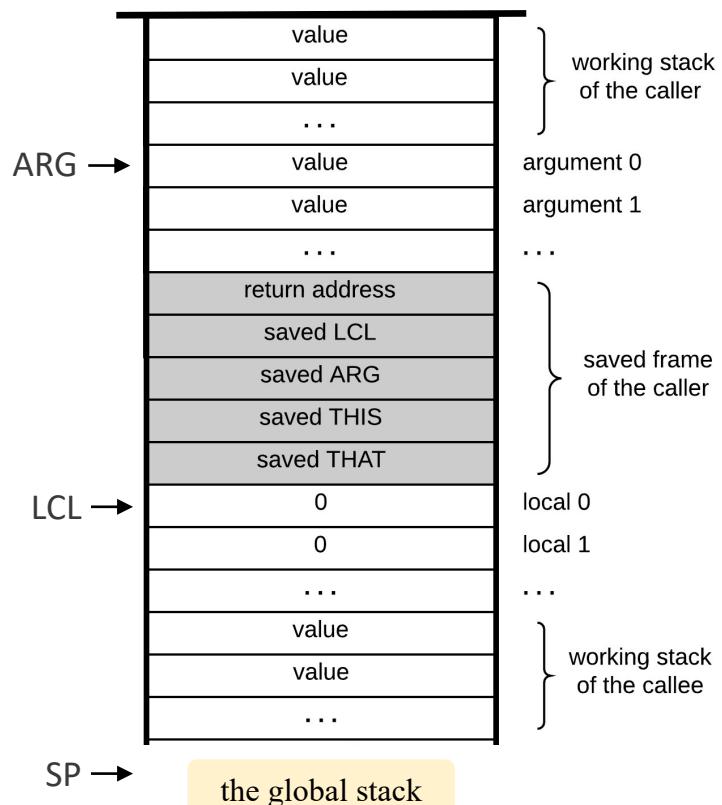
The callee executes,  
doing various things



# Implementing `call` / `function` / `return`

---

The callee executes,  
doing various things

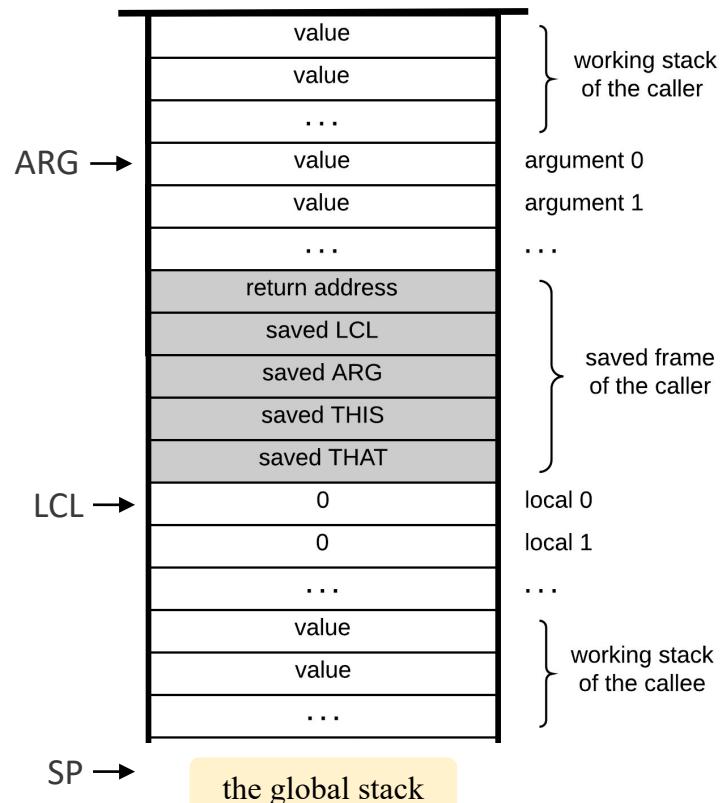


# Implementing `call` / `function` / `return`

---

The callee prepares to return:

It pushes a *return value*

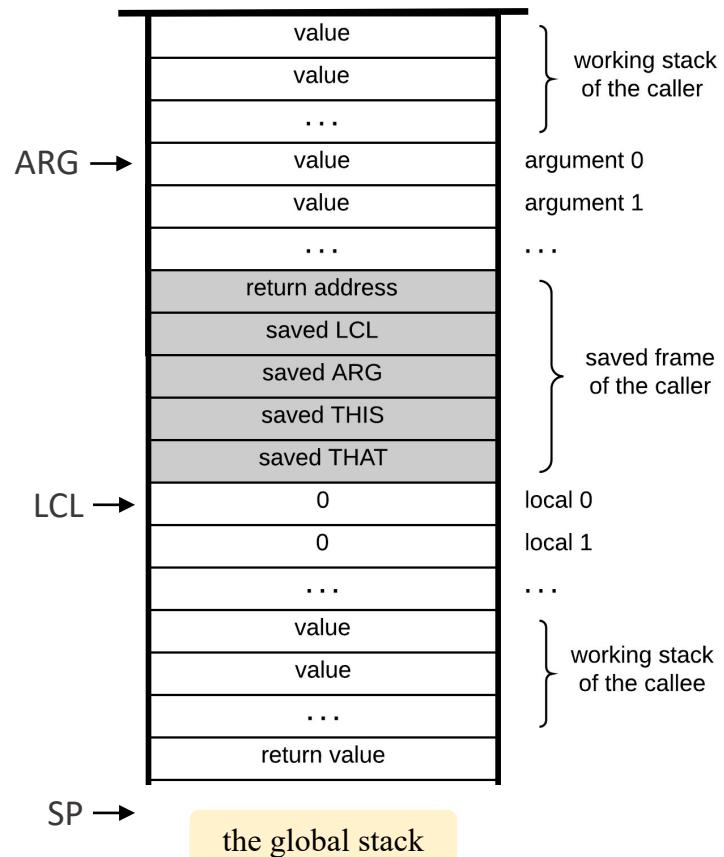


# Implementing `call` / `function` / `return`

---

The callee prepares to return:

It pushes a *return value*

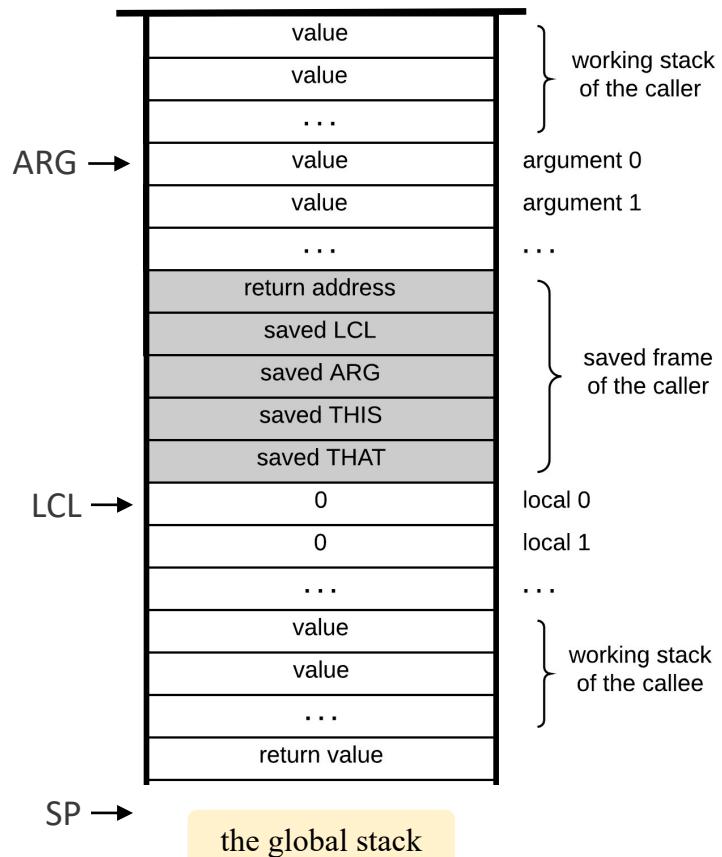


# Implementing `call` / `function` / `return`

---

The callee says:

`return`



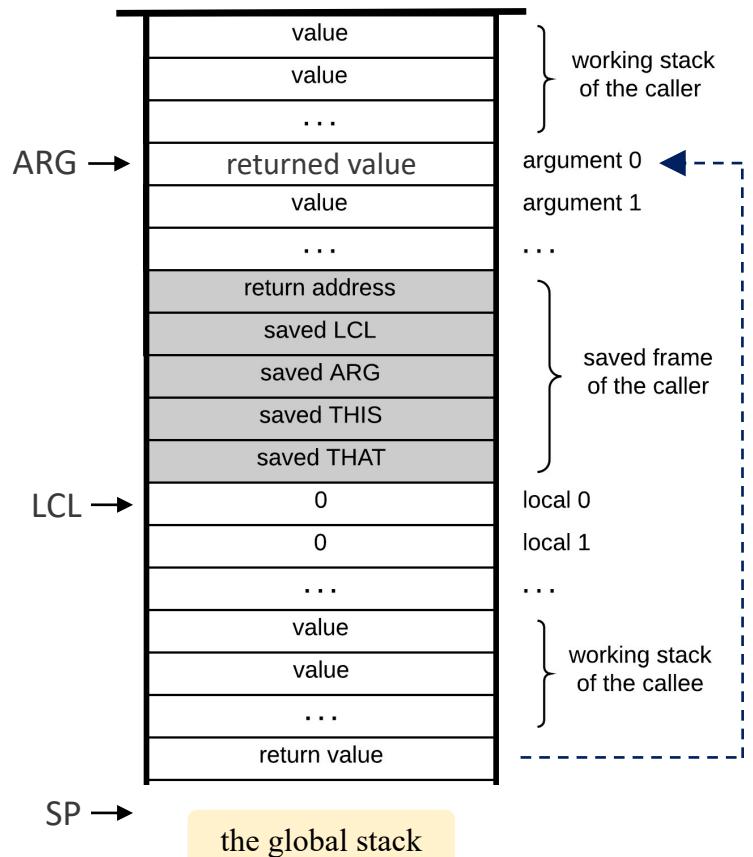
Handling return:

We have to:

# Implementing `call` / `function` / `return`

The callee says:

`return`



## Handling return:

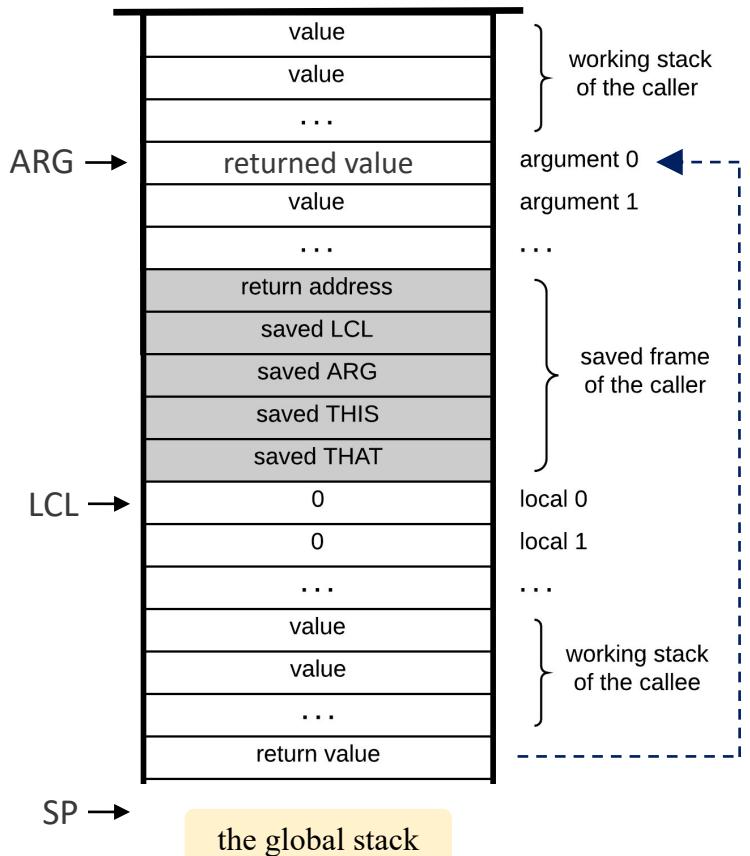
We have to:

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

# Implementing `call` / `function` / `return`

The callee says:

`return`



## Handling return:

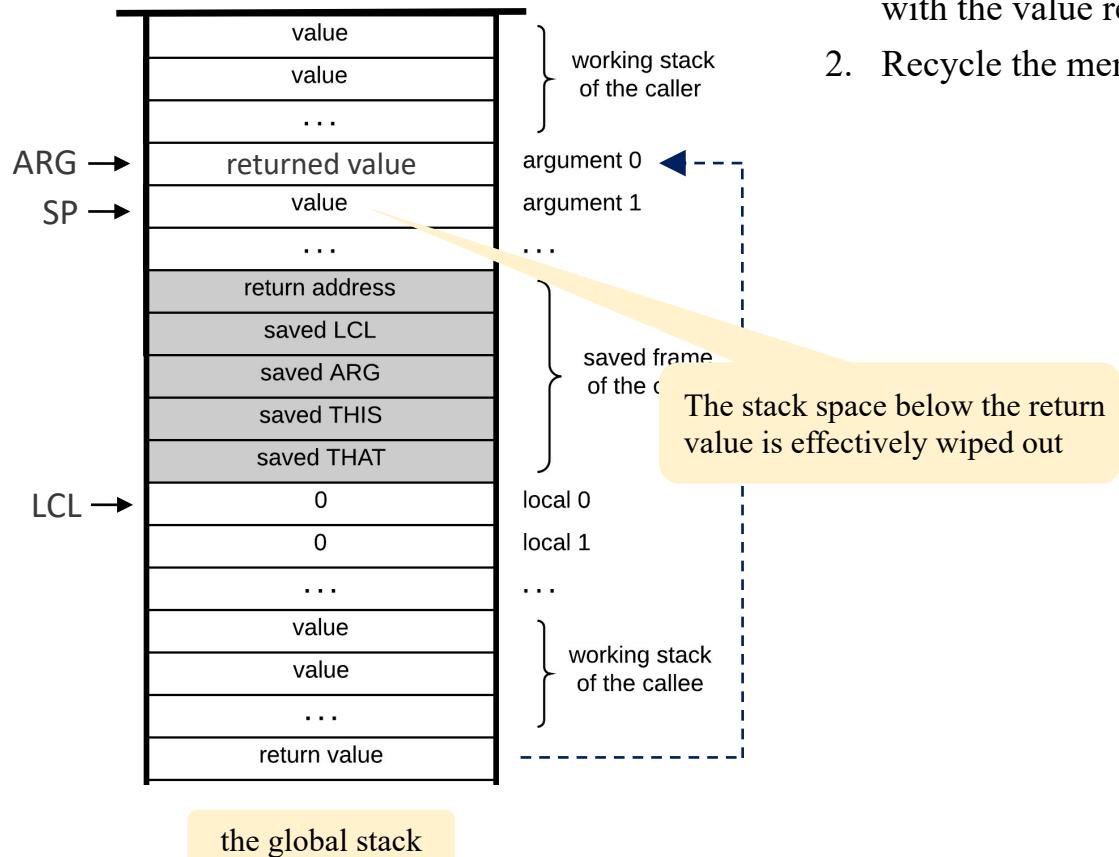
We have to:

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

# Implementing `call` / `function` / `return`

The callee says:

`return`



## Handling return:

We have to:

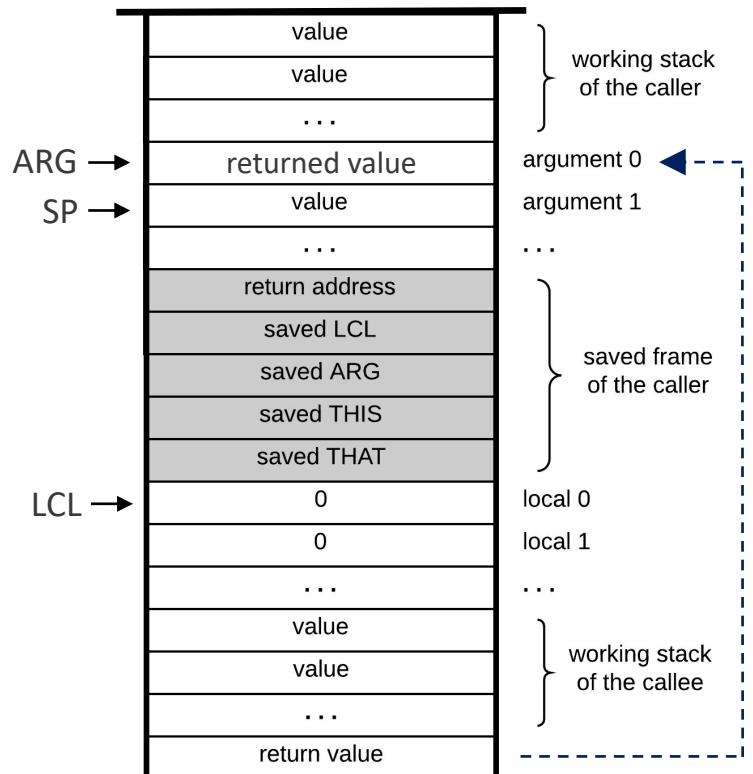
1. Replace the arguments that the caller pushed with the value returned by the callee
2. Recycle the memory used by the callee

# Implementing `call` / `function` / `return`

---

The callee says:

`return`



## Handling return:

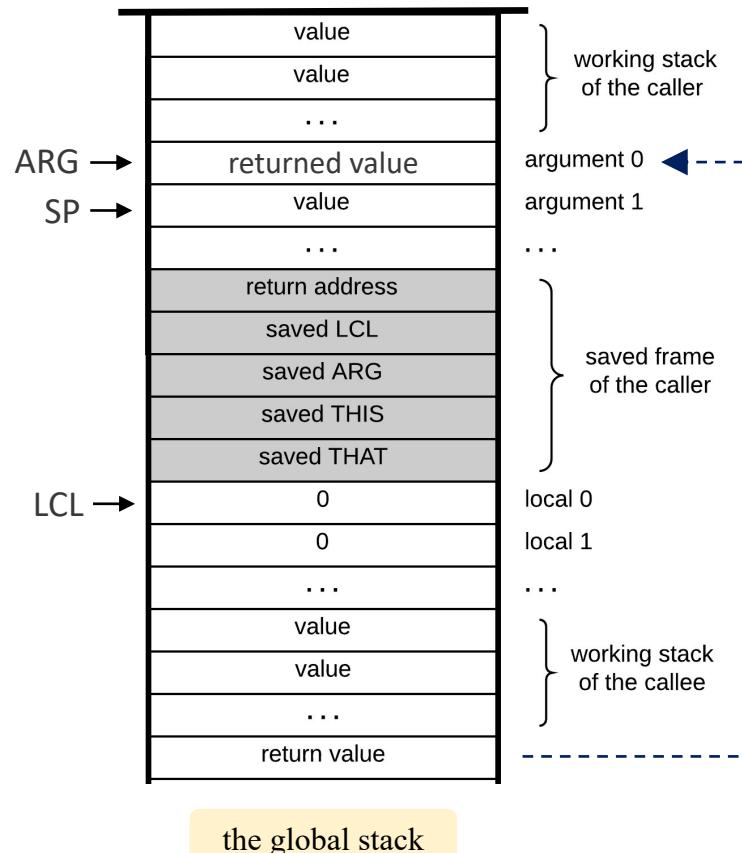
We have to:

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

# Implementing `call` / `function` / `return`

The callee says:

`return`



## 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. Reinstate the caller's segment pointers
4. Jump to the return address

## Generated code

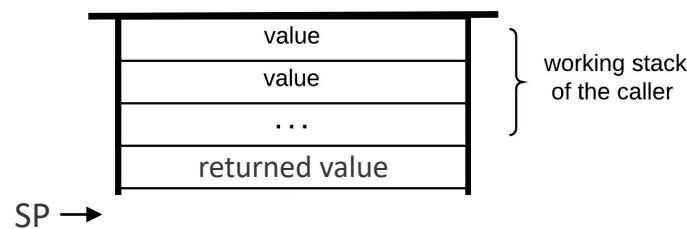
```
// endFrame and retAddr are temporary variables.  
// The pointer notation *addr denotes RAM[addr].  
  
endFrame = LCL           // gets the address at the frame's end  
retAddr = *(endFrame - 5) // gets the return address  
  
*ARG = pop()             // puts the return value for the caller  
SP = 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 should generate this code in assembly)

# Implementing `call` / `function` / `return`

---

The caller resumes  
its execution



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.

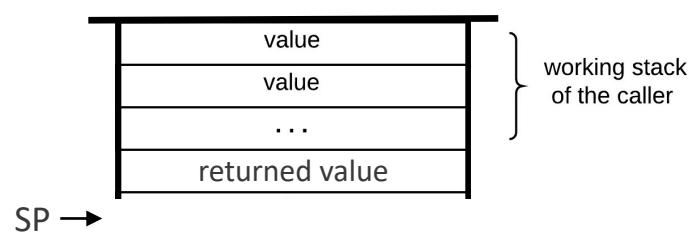
*Any sufficiently advanced technology is indistinguishable from magic.*

– Arthur C. Clarke, 1962

# Implementing `call` / `function` / `return`

---

The caller resumes  
its execution



What if the calling chain consists  
of multiple calls?

`foo` calls `bar`, then `bar` calls `baz`, etc.

And what about recursion?

## Solution

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

The global stack will grow and shrink as needed: *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

# Lecture plan

---

## ✓ Abstraction

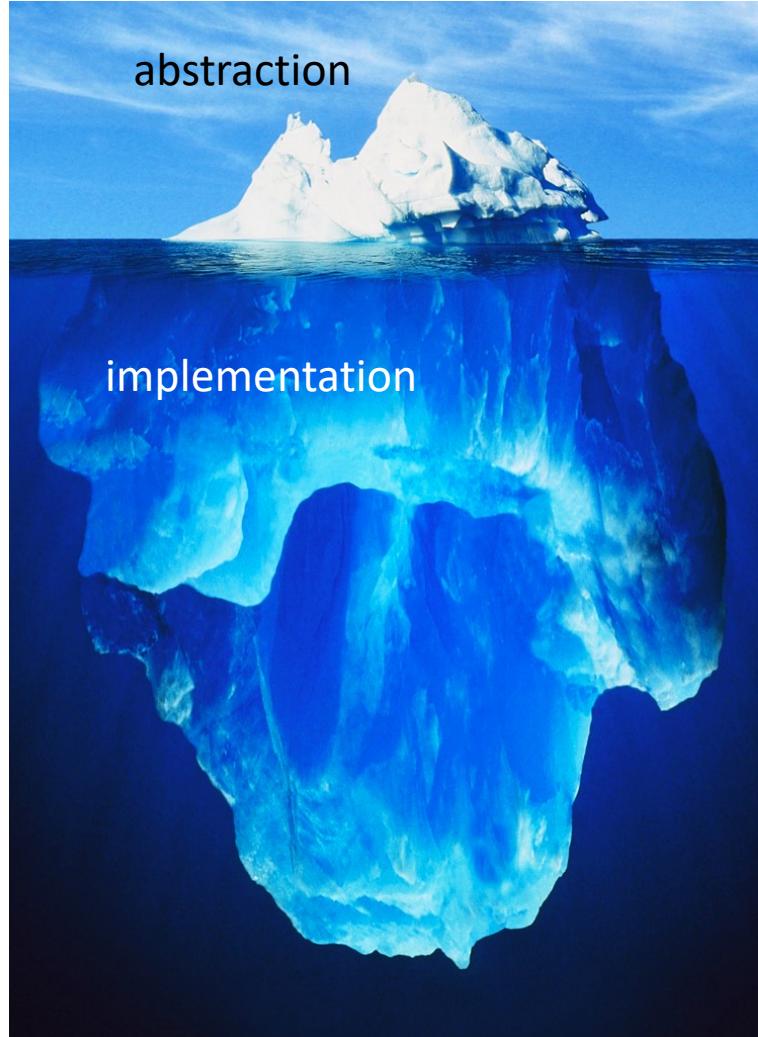
- VM branching commands
- VM function commands

## ✓ Implementation (conceptual)

- VM branching commands
- VM function commands

## → Implementation (nuts and bolts)

- Run-time system
- Standard mapping
- VM translator
- Project 8

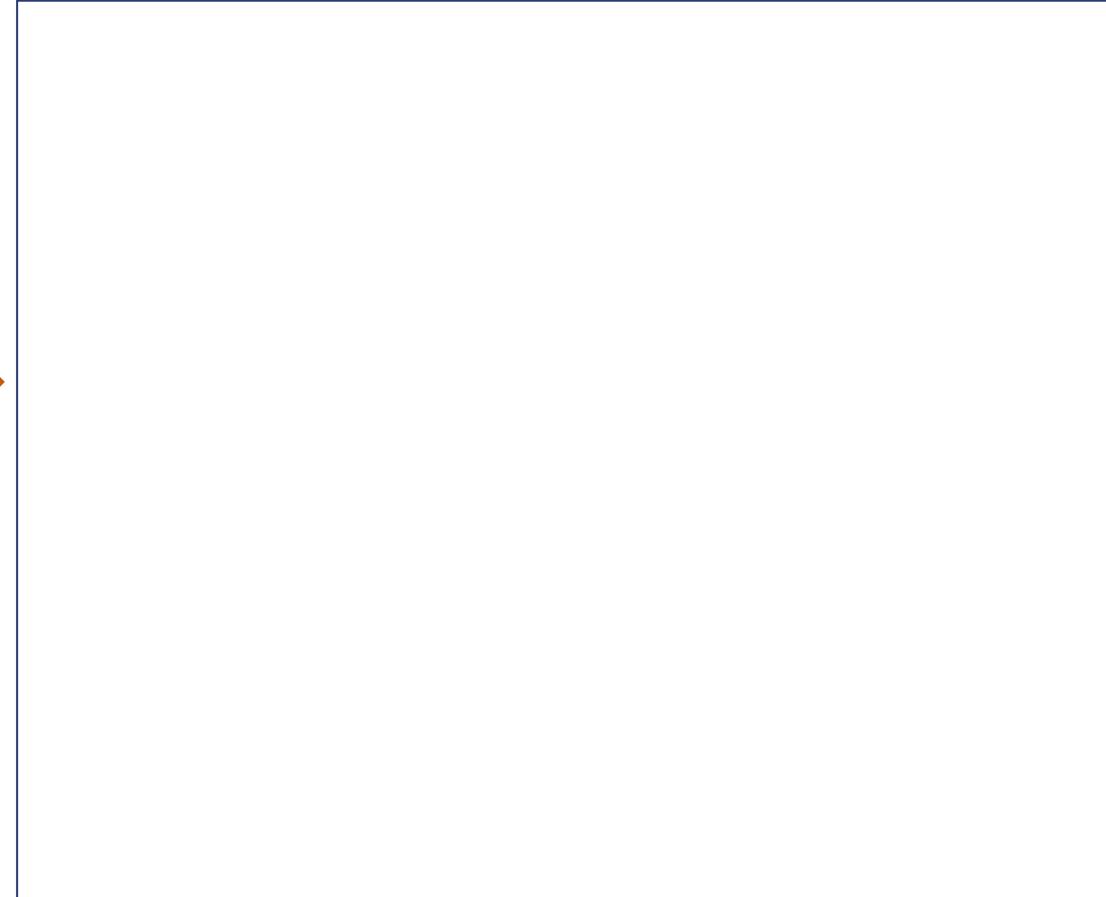


# VM translator in action

VM code

```
function Foo.main 4
...
// Computes 8 * 5 + 7
push constant 8
push constant 5
call Foo.mult 2
push constant 7
add
...
// Returns 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
```

Generated code (in assembly)



# VM translator in action

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Generated code (in assembly)

```
(Foo.main) // function's entry point label, injected by the VM translator
// assembly code that initializes the function's local variables
```

VM translator



# VM translator in action

VM code

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VM translator



# VM translator in action

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

Generated code (in assembly)

```
(Foo.main) // function's entry point label, injected by the VM translator
// assembly code that initializes the function's local variables
...
// assembly code that handles push constant 8
```

VM translator



# VM translator in action

VM code

```
function Foo.main 4
  ...
  // Computes 8 * 5 + 7
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  push constant 7
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  ...
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function Foo.mult 2
  push constant 0
  pop local 0
  push constant 1
  pop local 1
  ...
  // Returns the result
  push local 0
  return
```

Generated code (in assembly)

```
(Foo.main) // function's entry point label, injected by the VM translator
// assembly code that initializes the function's local variables
...
// assembly code that handles push constant 8
```

VM translator



# VM translator in action

VM code

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function Foo.main 4
  ...
  // Computes 8 * 5 + 7
  push constant 8
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  push constant 7
  add
  ...
  // Returns 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
```

Generated code (in assembly)

```
(Foo.main) // function's entry point label, injected by the VM translator
// assembly code that initializes the function's local variables
...
// assembly code that handles push constant 8
// assembly code that handles push constant 5
```

VM translator



# VM translator in action

VM code

```
function Foo.main 4
  ...
  // Computes 8 * 5 + 7
  push constant 8
  push constant 5
  call Foo.mult 2
  push constant 7
  add
  ...
  // Returns 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
```

Generated code (in assembly)

```
(Foo.main) // function's entry point label, injected by the VM translator
// assembly code that initializes the function's local variables
...
// assembly code that handles push constant 8
// assembly code that handles push constant 5
// assembly code that handles call Foo.mult 2: creates and saves a return
// address label (Foo$ret.1), saves the segment pointers, and then generates:
goto Foo.mult // (in assembly)
(Foo$ret.1) // return address label, injected by the VM translator
// assembly code that handles push constant 7
...
(Foo.mult) // function's entry point label, injected by the VM translator
// assembly code that initializes the function's local variables.
```

VM translator

# VM translator in action

## VM code

```
function Foo.main 4
  ...
  // Computes 8 * 5 + 7
  push constant 8
  push constant 5
  call Foo.mult 2
  push constant 7
  add
  ...
  // Returns 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
```

## Generated code (in assembly)

```
(Foo.main) // function's entry point label, injected by the VM translator
  // assembly code that initializes the function's local variables
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(Foo$ret.1) // return address label, injected by the VM translator
  // assembly code that handles push constant 7
  ...
(Foo.mult) // function's entry point label, injected by the VM translator
  // assembly code that initializes the function's local variables.
  ...
  // Assembly code that handles push local 0
```

VM translator



# VM translator in action

## VM code

```
function Foo.main 4
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function Foo.mult 2
  push constant 0
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  pop local 1
  ...
  // Returns the result
  push local 0
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```

VM translator

## Generated code (in assembly)

```
(Foo.main) // function's entry point label, injected by the VM translator
// assembly code that initializes the function's local variables
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// address label (Foo$ret.1), saves the segment pointers, and then generates:
goto Foo.mult // (in assembly)
(Foo$ret.1) // return address label, injected by the VM translator
// assembly code that handles push constant 7
...
(Foo.mult) // function's entry point label, injected by the VM translator
// assembly code that initializes the function's local variables.
...
// Assembly code that handles push local 0
// Assembly code that handles return: gets the return address (which happens
// to be Foo$ret.1), copies the return value, reinstates the segment pointers
// of Foo.main, and then generates:
goto Foo$ret.1 // (in assembly)
```

# VM translator in action

## The translation creates a run-time system

When executed, the generated code realizes the program semantics, as well as the function **call-and-return overhead** (passing arguments and return values, saving and reinstating function frames).

Notice: At the generated code level, functions no longer exist: The generated code is one long sequence of assembly instructions.

### Generated code (in assembly)

```
(Foo.main) // function's entry point label, injected by the VM translator
    // assembly code that initializes the function's local variables
    ...
    // assembly code that handles push constant 8
    // assembly code that handles push constant 5
    // assembly code that handles call Foo.mult 2: creates and saves a return
    // address label (Foo$ret.1), saves the segment pointers, and then generates:
    goto Foo.mult // (in assembly)
(Foo$ret.1)      // return address label, injected by the VM translator
    // assembly code that handles push constant 7
    ...
(Foo.mult) // function's entry point label, injected by the VM translator
    // assembly code that initializes the function's local variables.
    ...
    // Assembly code that handles push local 0
    // Assembly code that handles return: gets the return address (which happens
    // to be Foo$ret.1), copies the return value, reinstates the segment pointers
    // of Foo.main, and then generates:
    goto Foo$ret.1 // (in assembly)
```

# Lecture plan

---

## ✓ Abstraction

- VM branching commands
- VM function commands

## ✓ Implementation (conceptual)

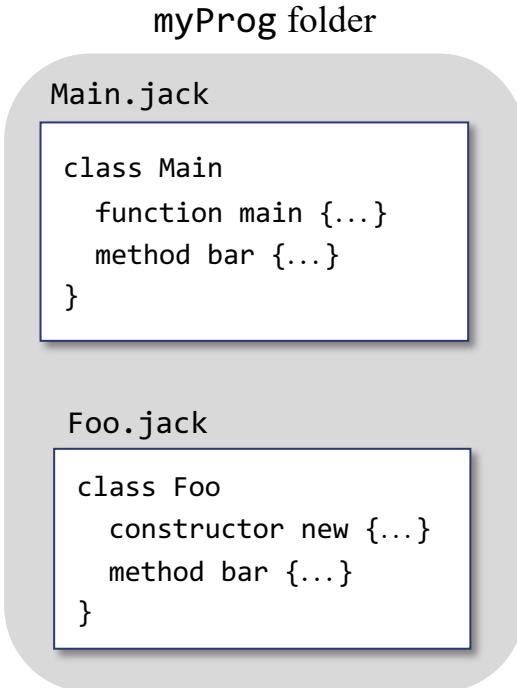
- VM branching commands
- VM function commands

## Implementation (nuts and bolts)

- Run-time system
- Standard mapping
- VM translator
  - Project 8

# The big picture: Compilation

---

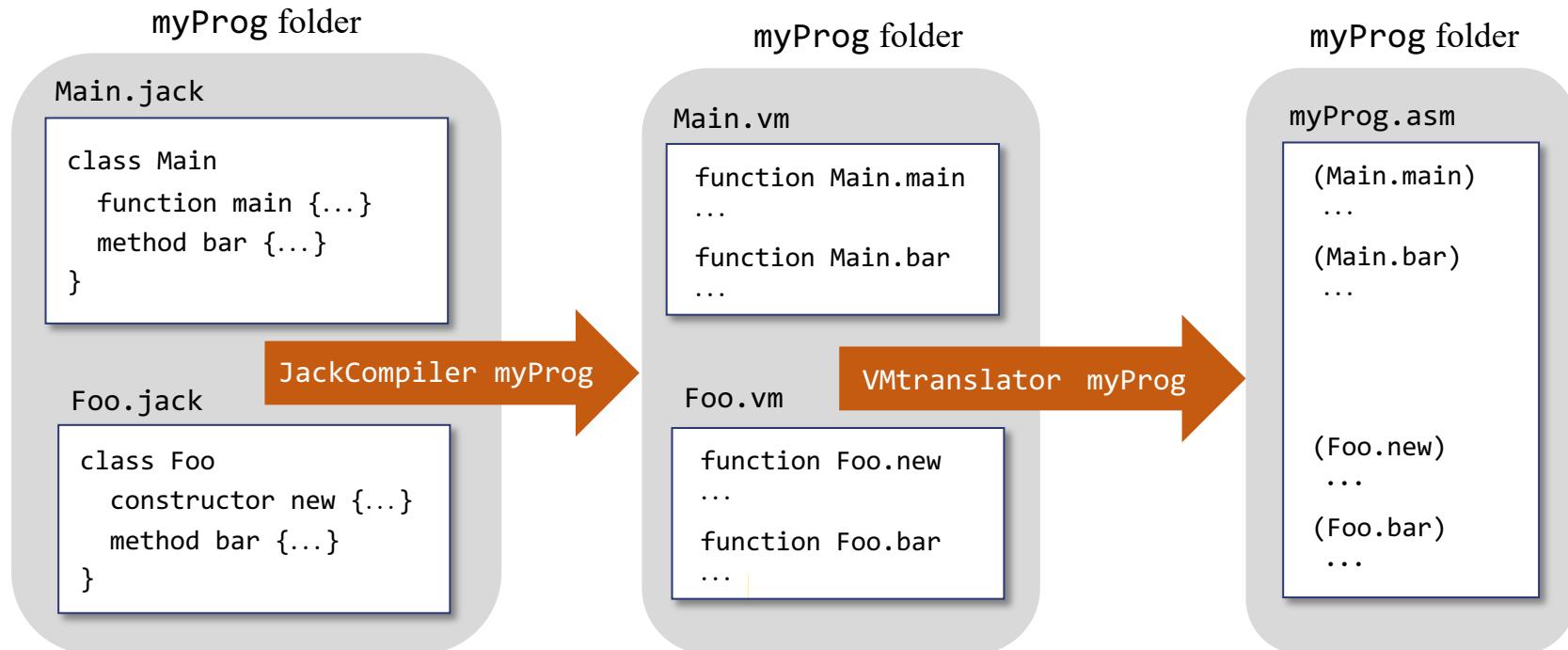


## Jack program:

One or more class files, stored in the same folder;  
The program name is taken to be the folder's name.

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

# The big picture: Compilation



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

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

All the VM functions  
are translated into a  
**single assembly file**

## Program conventions

One class file in any Jack program is expected to be named `Main.Jack`

The `Main.jack` file is expected to have at least one function, named `main`

# Bootstrap code

---

## Run-time conventions (of Jack programs on the Hack platform)

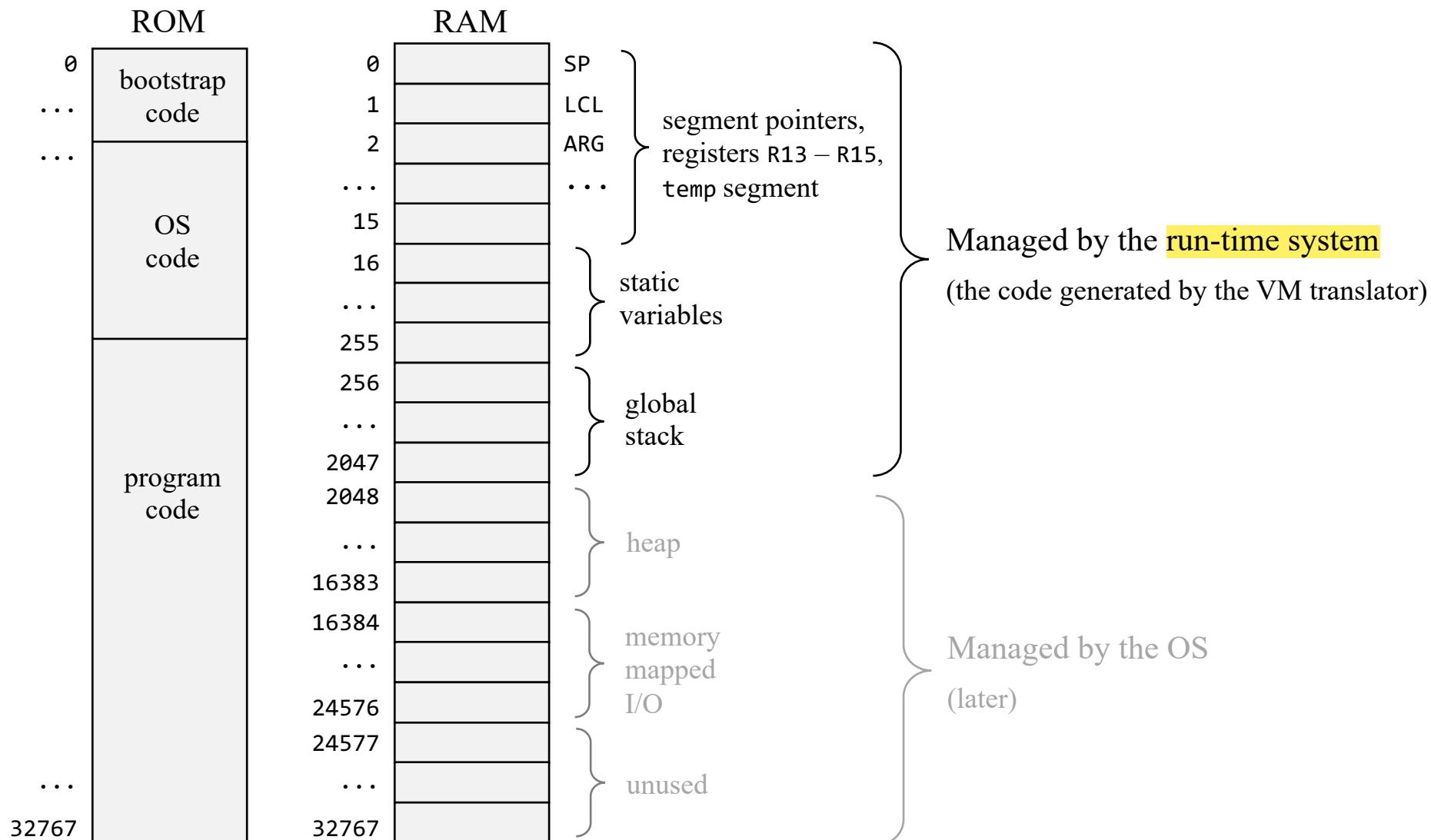
- The *stack* is stored in the RAM, starting at address 256
- In addition to the program functions, there should be an OS function named `sys.init`
- `Sys.init` initializes the operating system, calls `Main.main`, and enters an infinite loop.

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

(The VM translator should generate this code in assembly)

This code should be stored in the Hack ROM, starting at address 0.

# Standard mapping of the VM on the Hack platform



## Standard mapping of the VM on the Hack platform

---

| <i>Symbol</i>  | <i>Usage</i>  |                          |
|--|---|--------------------------|
| SP   | This predefined symbol points to the memory address within the host RAM just following the address containing the topmost stack value.  | Implemented in project 7 |
| LCL, ARG, THIS, THAT                                       | These predefined symbols point, respectively, to the base RAM addresses of the virtual segments <code>local</code> , <code>argument</code> , <code>this</code> , and <code>that</code> of the currently running VM function.  |                          |
| <code>Xxx.i</code> symbols<br>(represent static variables) | Each reference to <code>static i</code> appearing in file <code>Xxx.vm</code> is translated to the assembly symbol <code>Xxx.i</code> . In the subsequent assembly process, the Hack assembler will allocate these symbolic variables to the RAM, starting at address 16. |                          |

# Standard mapping of the VM on the Hack platform

| 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 <code>local</code> , <code>argument</code> , <code>this</code> , and that of the currently running VM function.  |
| <code>Xxx.i</code> symbols<br>(represent static variables)           | Each reference to <code>static i</code> appearing in file <code>Xxx.vm</code> is translated to the assembly symbol <code>Xxx.i</code> . In the subsequent assembly process, the Hack assembler will allocate these symbolic variables to the RAM, starting at address 16.  |
| <code>functionName \$label</code><br>(destinations of goto commands) | Let <code>foo</code> be a function within the file <code>Xxx.vm</code> . The handling of each <code>label bar</code> command within <code>foo</code> generates, and injects into the assembly code stream, the symbol <code>Xxx.foo\$bar</code> .<br>When translating <code>goto bar</code> and <code>if-goto bar</code> commands (within <code>foo</code> ) into assembly, the label <code>Xxx.foo\$bar</code> must be used instead of <code>bar</code> .   |
| <code>functionName</code><br>(function entry point symbols)          | The handling of each <code>function foo</code> command within the file <code>Xxx.vm</code> generates, and injects into the assembly code stream, a symbol <code>Xxx.foo</code> 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.  |
| <code>functionName \$ret.i</code><br>(return address symbols)        | Let <code>foo</code> be a function within the file <code>Xxx.vm</code> .<br>The handling of each <code>call</code> command within <code>foo</code> 's code generates, and injects into the assembly code stream, a symbol <code>Xxx.foo\$ret.i</code> , where <code>i</code> is a running integer (one such symbol is generated for each <code>call</code> command within <code>foo</code> ).<br>This symbol is used to mark the return address within the caller's code.<br>In the subsequent assembly process, the assembler translates this symbol into the physical memory address of the command immediately following the <code>call</code> 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.  |

Complete specification of all the special symbols that the VM translator must use, and generate.

Read carefully, for project 8.

# Lecture plan

---

## ✓ Abstraction

- VM branching commands
- VM function commands

## ✓ Implementation (conceptual)

- VM branching commands
- VM function commands

## Implementation (nuts and bolts)

✓ Run-time system

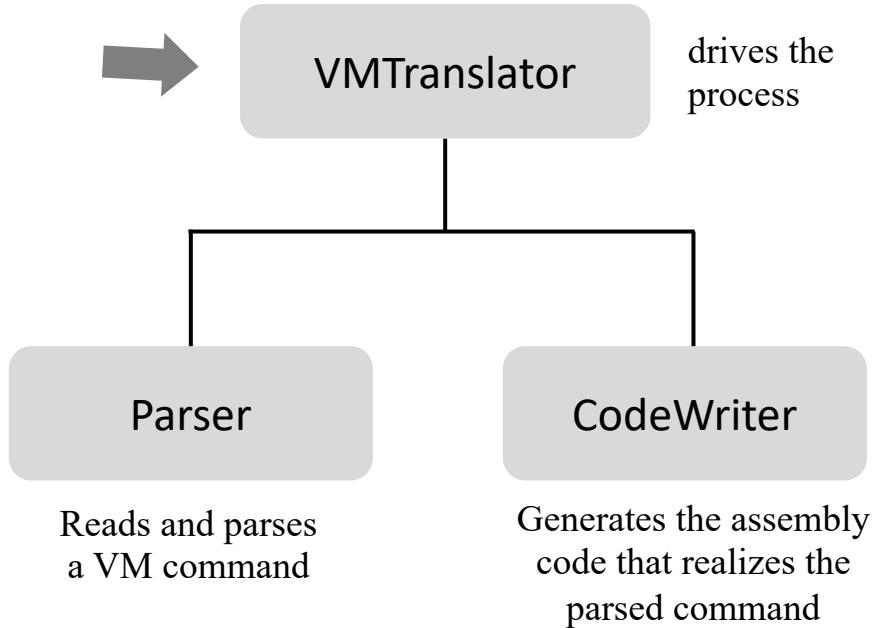
✓ Standard mapping

→ VM translator

- Project 8

# VM translator: Proposed design

---



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

# VMTranslator

---

Usage: % VMtranslator *input*

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

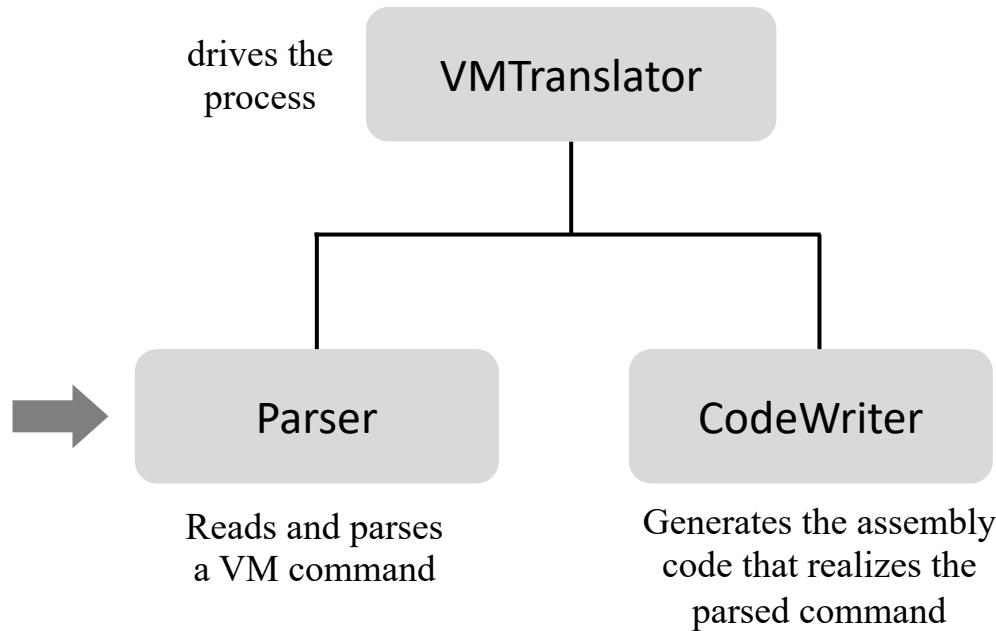
Output: A single assembly file named *input.asm*

## Process

- Constructs a `CodeWriter`
- If the input 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 the input is a folder:
  - Handles every *.vm* file in the folder in the manner described above.

# VM translator: Proposed design

---



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

# Parser

---

The same Parser developed in project 7:

- Handles the parsing of a single .vm file
- Reads a VM command, parses the command into its lexical components, and provides convenient access to these components
- Skips white space and comments.

# 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 <i>current command</i> .<br>This method should be called only if <code>hasMoreLines</code> is true.<br>Initially there is no current command.                        |
| commandType  | —                   | <code>C_ARITHMETIC</code> , <code>C_PUSH</code> ,<br><code>C_POP</code> , <code>C_LABEL</code> , <code>C_GOTO</code> ,<br><code>C_IF</code> , <code>C_FUNCTION</code> ,<br><code>C_RETURN</code> , <code>C_CALL</code><br>(constant) | Returns a constant representing the type of the current command.<br>If the current command is an arithmetic-logical command, returns <code>C_ARITHMETIC</code> .  |
| arg1         | —                   | string   | Returns the first argument of the current command.<br>In the case of <code>C_ARITHMETIC</code> , the command itself (add, sub, etc.) is returned.<br>Should not be called if the current command is <code>C_RETURN</code> . |
| arg2         | —                   | int  | Returns the second argument of the current command.<br>Should be called only if the current command is <code>C_PUSH</code> , <code>C_POP</code> , <code>C_FUNCTION</code> , or <code>C_CALL</code> .                        |

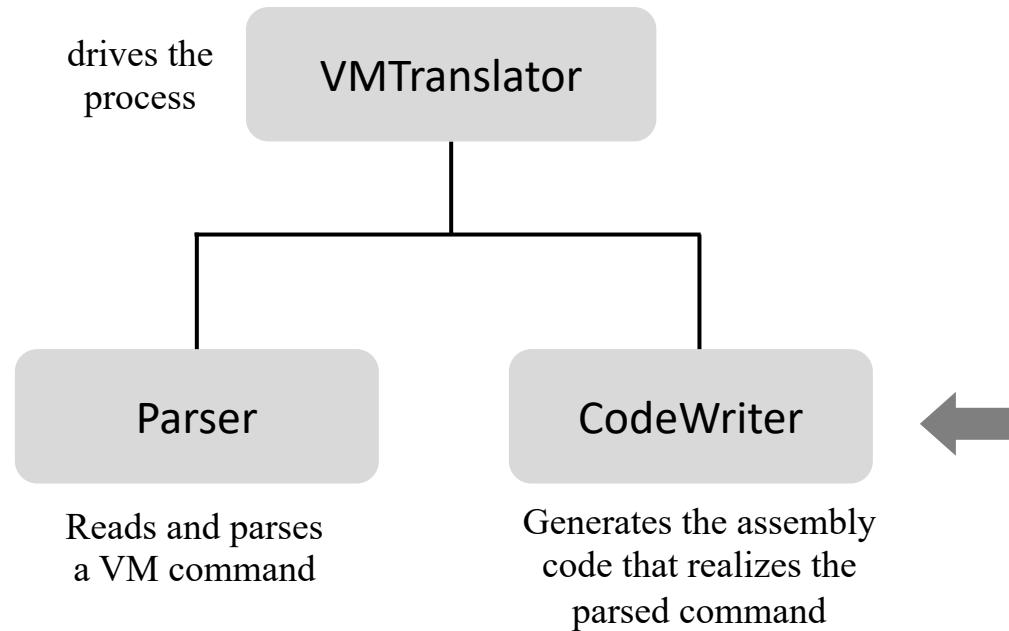
Same API as in project 7;

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

goto, if-goto, label, call, function, and return,  
add this parsing functionality now.

# VM translator: Proposed design

---



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

# CodeWriter

---

| <b>Routine</b>                              | <b>Arguments</b>   | <b>Returns</b> | <b>Function</b>   |
|---|--|----------------|---|
| constructor                                 | output file / stream                                     | —              | Opens an output file / stream and gets ready to write into it.<br><br>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<br>(developed in project 7) | command (string)   | —              | Writes to the output file the assembly code that implements the given arithmetic-logical command.   |
| WritePushPop<br>(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

---

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

The generated assembly code must follow the guidelines and symbols described in the Standard Mapping of the VM on the Hack Platform.

# Lecture plan

---

## Abstraction

- VM branching commands
- VM function commands

## Implementation (conceptual)

- VM branching commands
- VM function commands

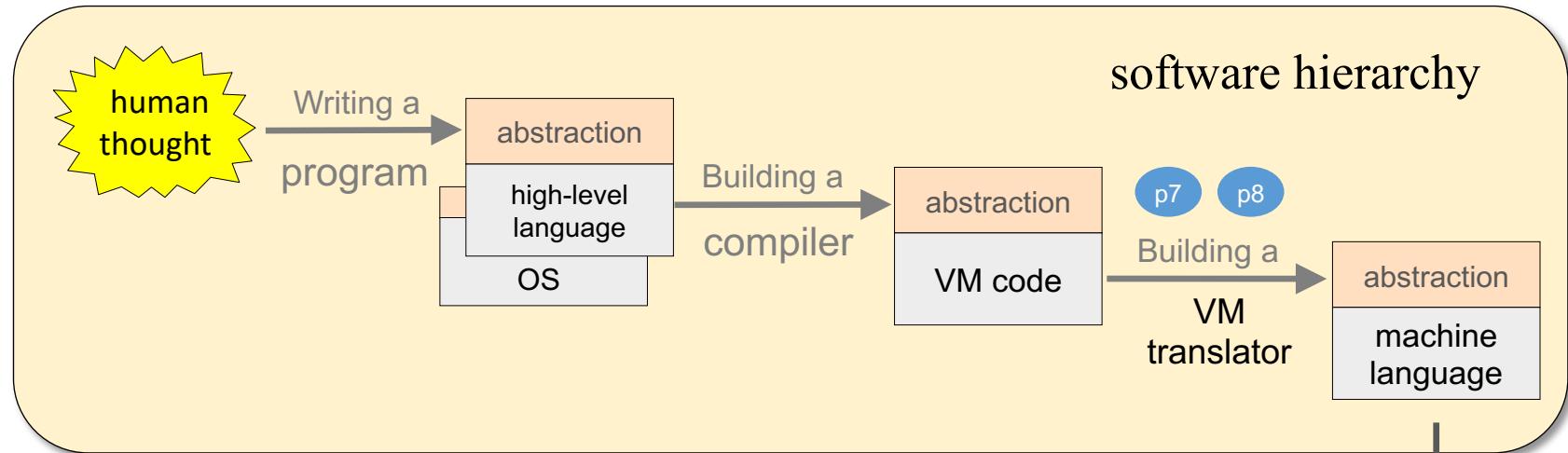
## Implementation (nuts and bolts)

- Run-time system
- Standard mapping
- VM translator



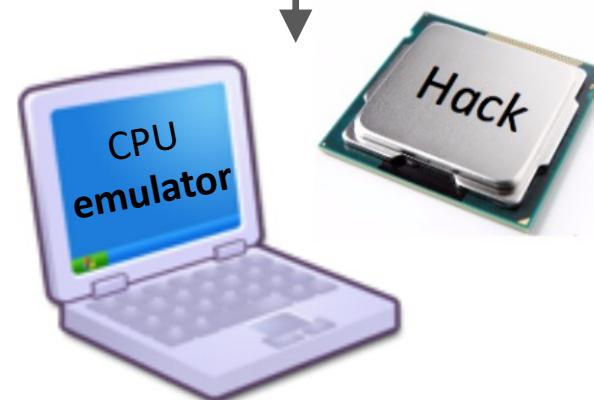
Project 8

# 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
- NestedCall
- FibonacciElement
- StaticsTest

# Test programs: BasicLoop

---

## ProgramFlow:

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

## FunctionCalls:

- SimpleFunction
- NestedCall
- 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: FibonacciSeries

---

ProgramFlow:

- BasicLoop

 **FibonacciSeries**

- **FibSeries.vm**

- **FibSeriesVME.tst**

- **FibSeries.tst**

- **FibSeries.cmp**

FunctionCalls:

- SimpleFunction

- NestedCall

- FibonacciElement

- StaticsTest

# Test programs: FibonacciSeries

## ProgramFlow:

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

## FunctionCalls:

- SimpleFunction
- NestedCall
- 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: SimpleFunction

## ProgramFlow:

- BasicLoop
- FibonacciSeries

## FunctionCalls:

- ➡ SimpleFunction
  - SimpleFunction.vm
  - SimpleFunctionVME.tst
  - SimpleFunction.tst
  - SimpleFunction.cmp
- NestedCall
- 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: FibonacciElement

---

## ProgramFlow:

- BasicLoop
- FibonacciSeries

Usage: % VMTranslator FibonacciElement (translates a *folder*)

Generates a single output file: `FibonacciElement.asm`

## FunctionCalls:

- SimpleFunction
- NestedCall
- ➡ **FibonacciElement**
  - Main.vm**
  - Sys.vm**
  - FibElementVME.tst
  - FibElement.tst
  - FibElement.cmp
- StaticsTest

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

# Test programs: FibonacciElement

ProgramFlow:

- BasicLoop
- FibonacciSeries

FunctionCalls:

- SimpleFunction
- NestedCall

→ **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
```

# Test programs: FibonacciElement

ProgramFlow:

- BasicLoop
- FibonacciSeries

FunctionCalls:

- SimpleFunction
- NestedCall

→ **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
```

Normally, Sys.init is used to call Main.main.  
In Project 8 we use Sys.init to call test functions, directly.

Sys.vm

```
// Sys.init: pushes n onto the stack,  
// and calls Main.fibonaci 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: NestedCall

---

## ProgramFlow:

- BasicLoop
- FibonacciSeries

## FunctionCalls:

- SimpleFunction

## NestedCall

- Sys.vm
- NestedCallVME.tst
- NestedCall.tst
- NestedCall.cmp
- NestedCall.html
- NestedCallStack.html
- FibonacciElement
- StaticsTest

- Closes testing gaps between SimpleFunction and FibonacciElement
- Recommended when SimpleFunction tests successfully and FibonacciElement fails or crashes
- Self-documented

# Test programs: staticsTest

---

## ProgramFlow:

- BasicLoop
- FibonacciSeries

## FunctionCalls:

- SimpleFunction
- NestedCall
- FibonacciElement

## StaticsTest

Class1.vm  
Class2.vm  
Sys.vm

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

Usage: % VMTranslator StaticTest (translates a *folder*)  
Generates a single output file: StaticTest.asm

StaticsTestVME.tst  
StaticsTest.tst  
StaticsTest.cmp

# Test programs: staticsTest

ProgramFlow:

- BasicLoop
- FibonacciSeries

FunctionCalls:

- SimpleFunction
- NestedCall
- FibonacciElement

## StaticsTest

- Class1.vm
- Class2.vm
- Sys.vm
- StaticsTestVME.tst
- StaticsTest.tst
- StaticsTest.cmp

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
    return
```

Sys.vm

```
function Sys.init 0
    push
    pop s
    push
    pop s
    push
    return

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

## FunctionCalls:

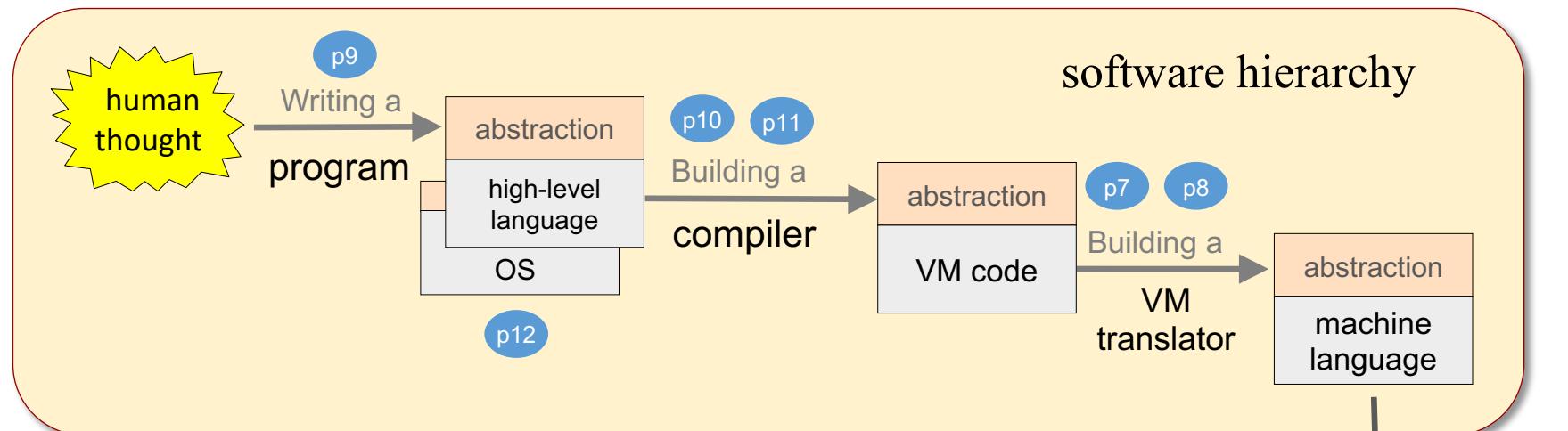
- SimpleFunction
- NestedCall
- FibonacciElement
- StaticsTest

## Testing routine for every test program *xxx*:

0. Recommended: Load and run *xxxVME.tst* on the VM emulator; This script loads the *xxx.vm* test program into the VM emulator, allowing you to experiment with its code
1. Use your VM translator to translate *xxx.vm* generating a file named *xxx.asm*
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 these files are supplied, except for *xxx.asm*

# Recap / Next



## Work plan

✓ Projects 7,8: VM translator (compiler's backend)

- Projects 10,11: Compiler (compiler's frontend)

→ Project 9: High-level language

- Project 12: Operating system.

