University of Nottingham
UK | CHINA | MALAYSIA

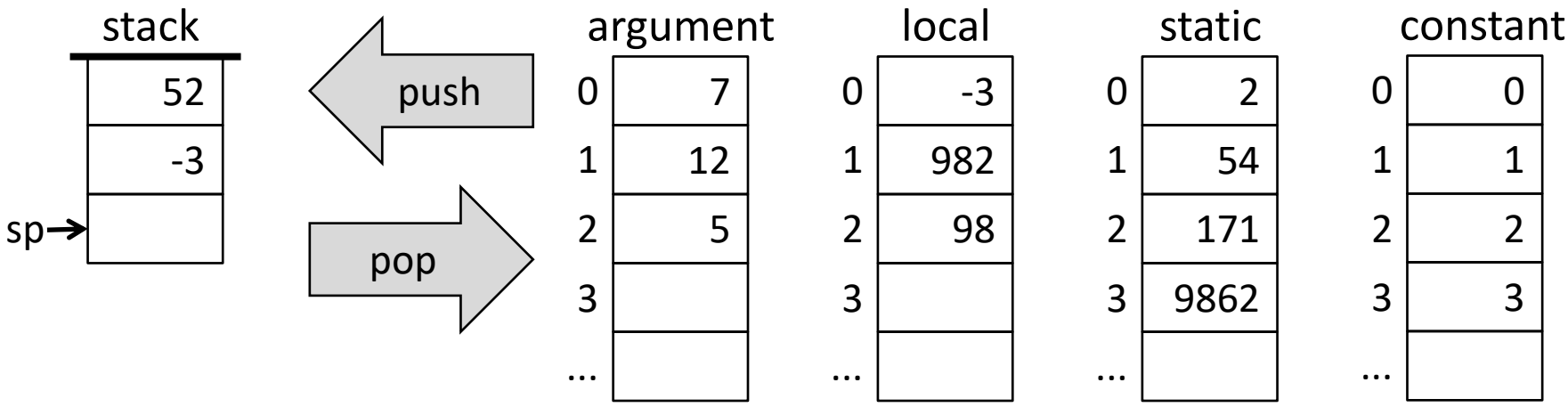
# Virtual Machine (Part 2)

Dr. Wooi Ping Cheah

# Outlines

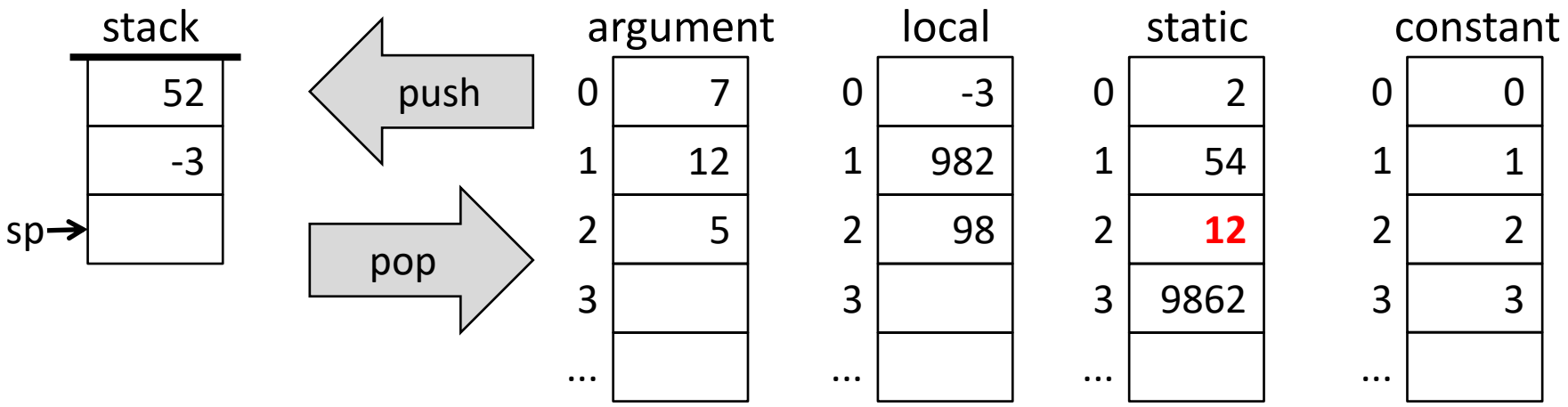
- Introduction to virtual machine
- VM abstraction
- VM implementation
  - Stack
  - Memory segment commands
  - Branching commands
  - Function commands
- VM translator

# VM abstraction




let static 2 = argument 1

```
push argument 1
pop  static 2
```



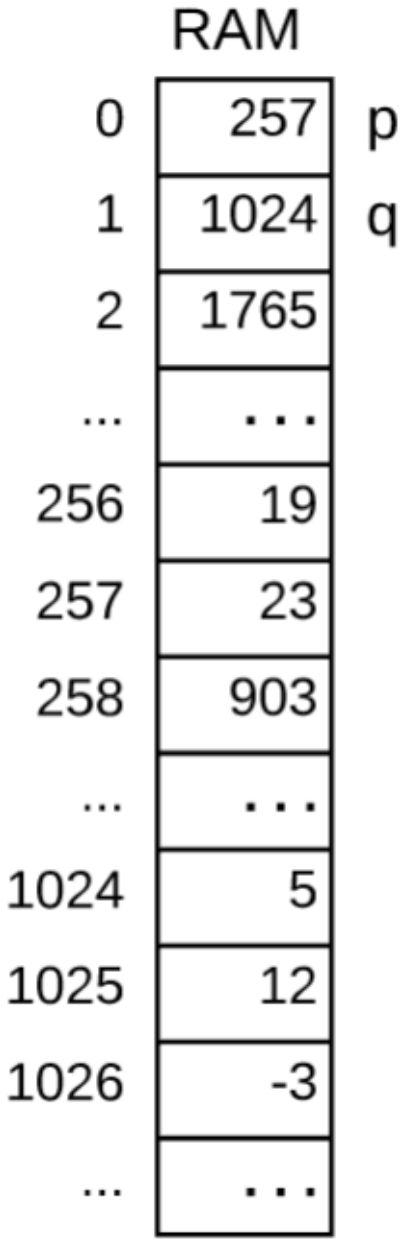
# Pointer manipulation

Pseudo assembly code

```
D = *p // D becomes 23

p--    // RAM[0] becomes 256
D = *p // D becomes 19

*q = 9 // RAM[1024] becomes 9
q++    // RAM[1] becomes 1025
```

In Hack:

```
@p
A=M
D=M
```




Notation:

*p // the memory content that p points at

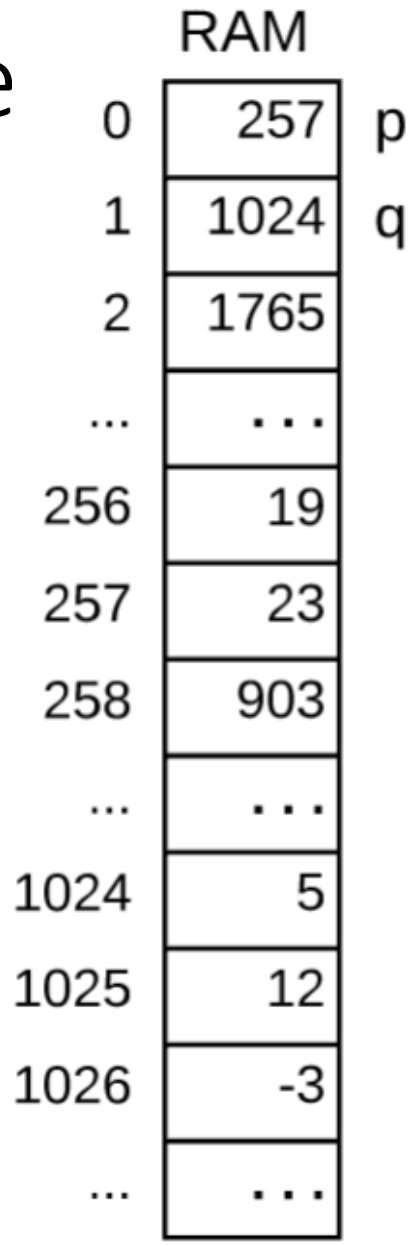
x-- // decrement: x = x - 1

x++ // increment: x = x + 1

# Pointer manipulation - exercise

Given the initial memory status shown on the right, find:

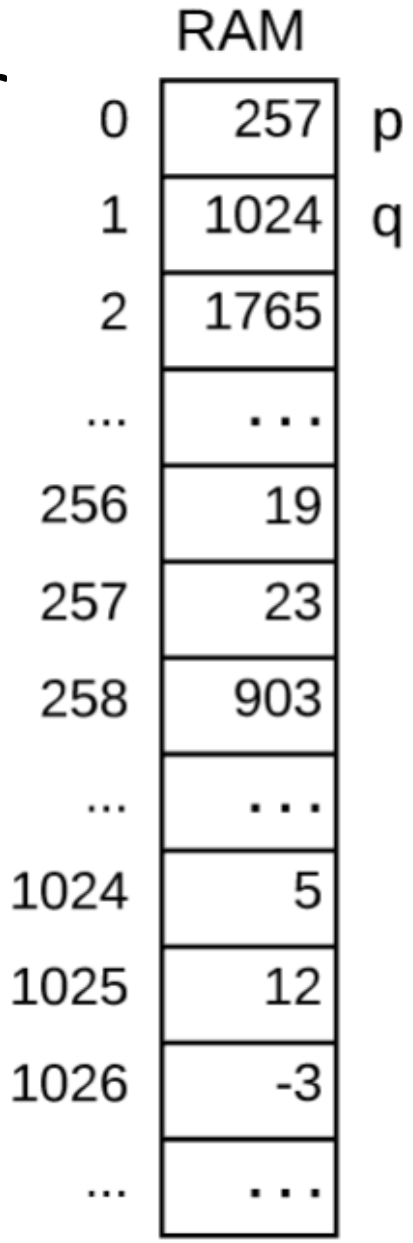
```
p++ // What is RAM[0]?

D = *p //What is D?

*q = D // What is *q?

q++    //What is RAM[1]?

*p = *q //What is *p?
```



# Pointer manipulation - answer

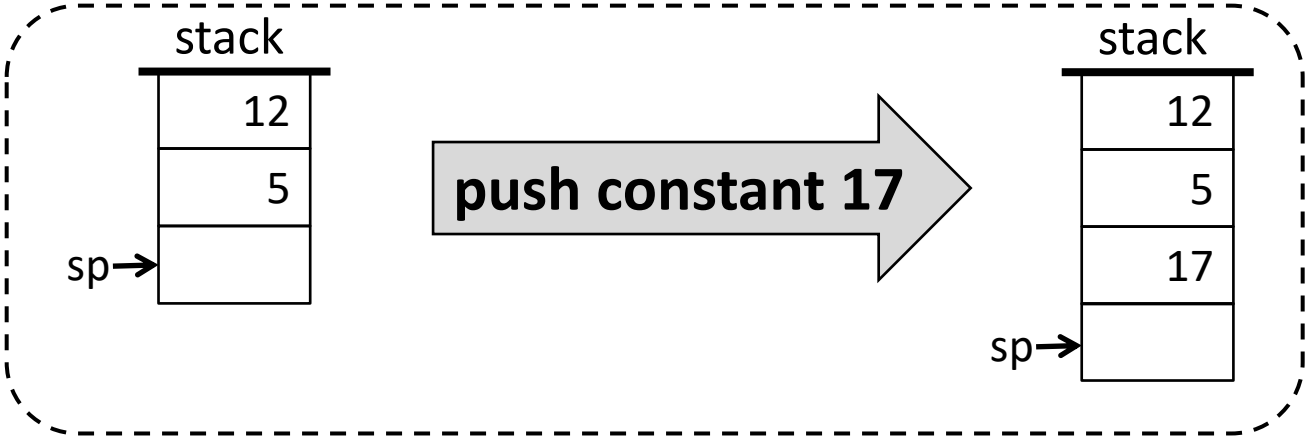
Given the initial memory status shown on the right, find:

```
p++ // What is RAM[0]? 258

D = *p //What is D? 903

*q = D // What is *q? 903

q++    //What is RAM[1]? 1025

*p = *q //What is *p? 12
```



# Stack implementation

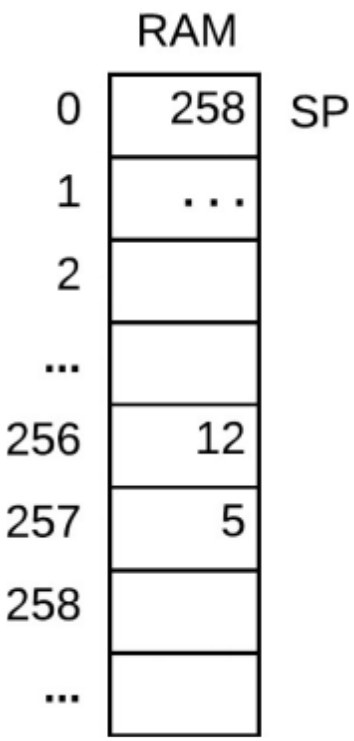
## Abstraction:




## Implementation:

Assumptions:

- SP stored in RAM[0],
- Stack base addr = 256.

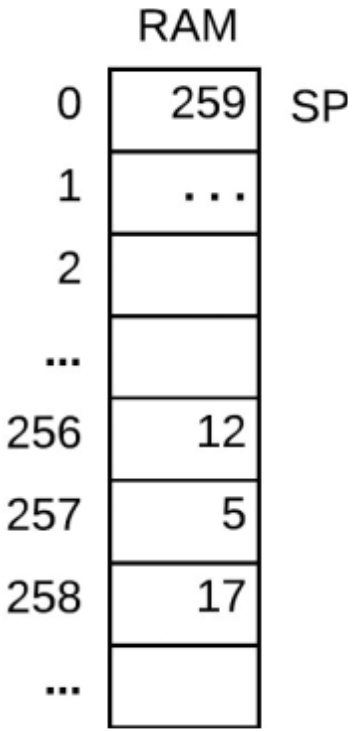



Logic:

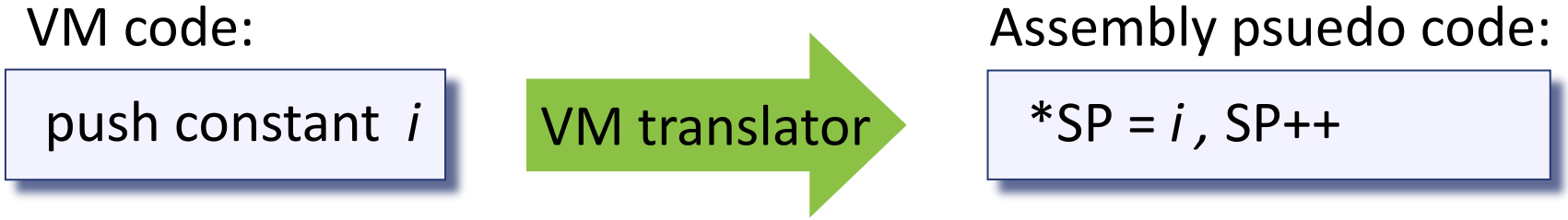
```
*SP = 17
SP++
```

Hack assembly:

```
@17   // D=17
D=A
@SP   // *SP=D
A=M
M=D
@SP   // SP++
M=M+1
```



# Stack implementation



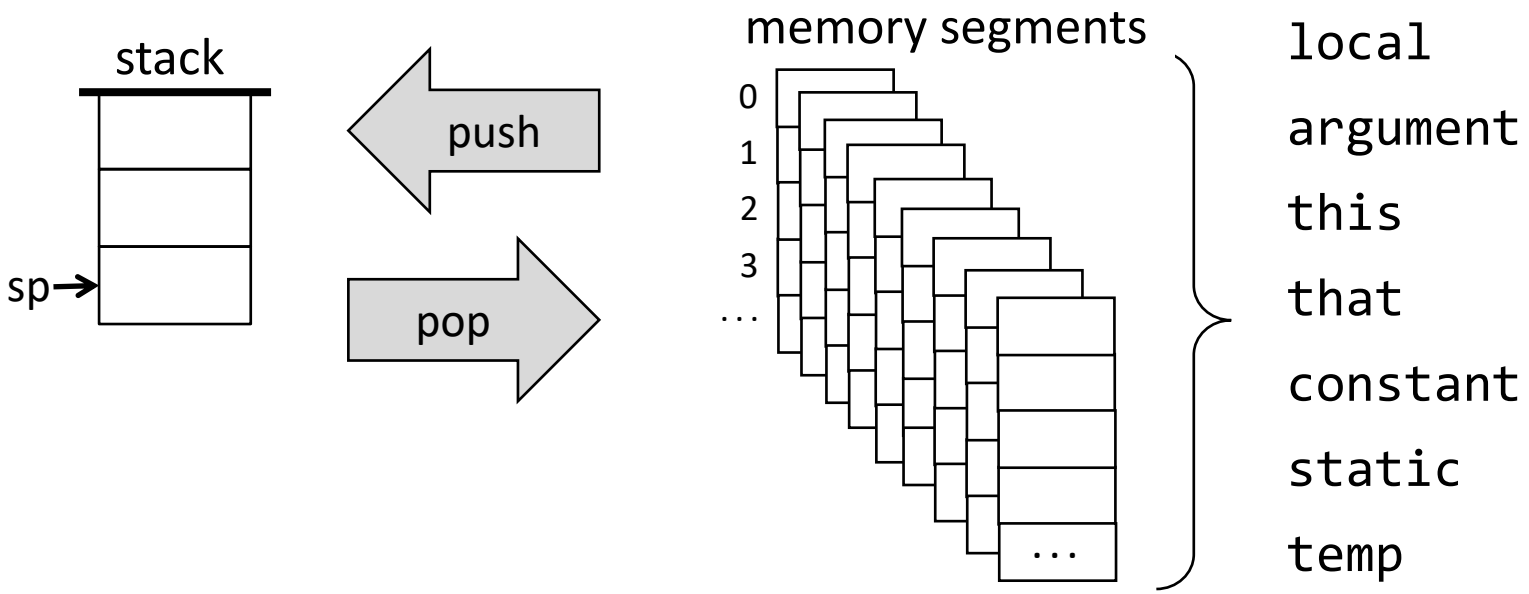

## VM Translator

- A program that **translates** VM commands into lower-level commands of some host platform (like the Hack computer).
- Each VM command **generates** one or more low-level commands.
- The low-level commands **realize** the stack and the memory segments on the host platform.

# Outlines

- Introduction to virtual machine
- VM abstraction
- VM implementation
  - Stack
  - Memory segment commands
  - Branching commands
  - Function commands
- VM translator

# Memory segments (abstraction)

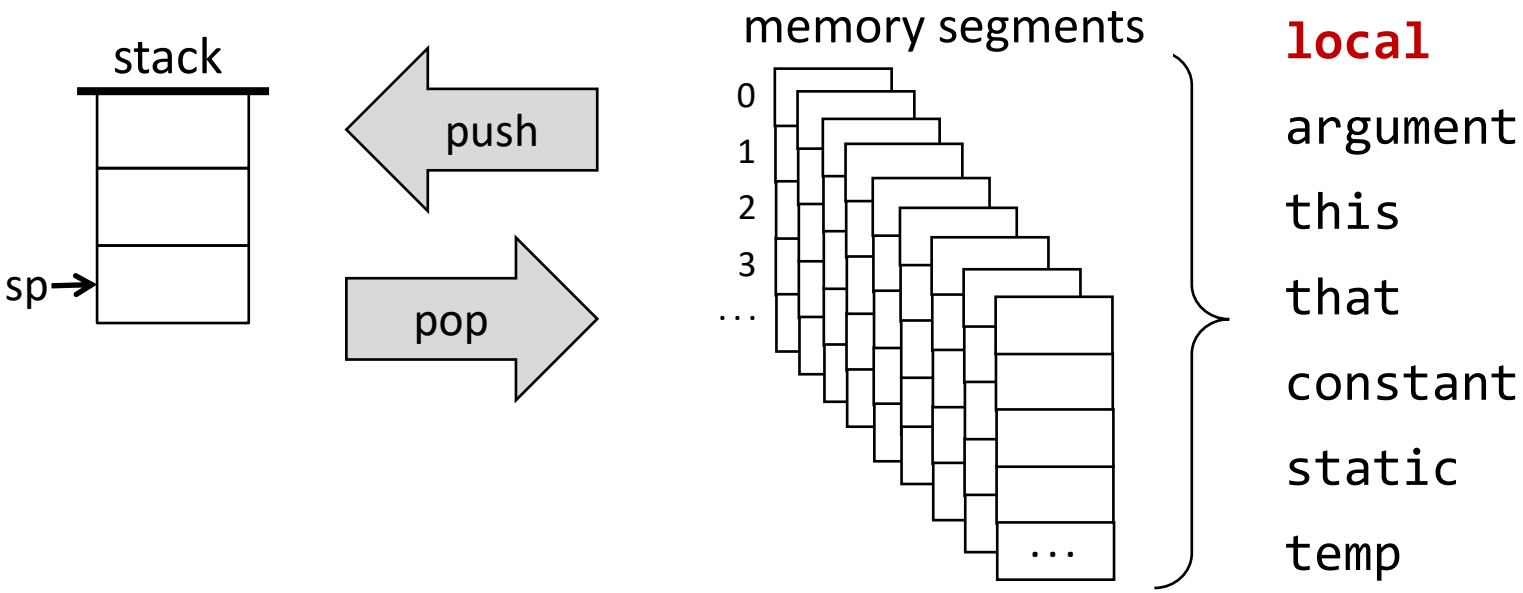



Syntax: push / pop segment i

Examples:

- push constant 17
- pop local 2
- pop static 5
- push argument 3

# Implement `push/pop local` *i*



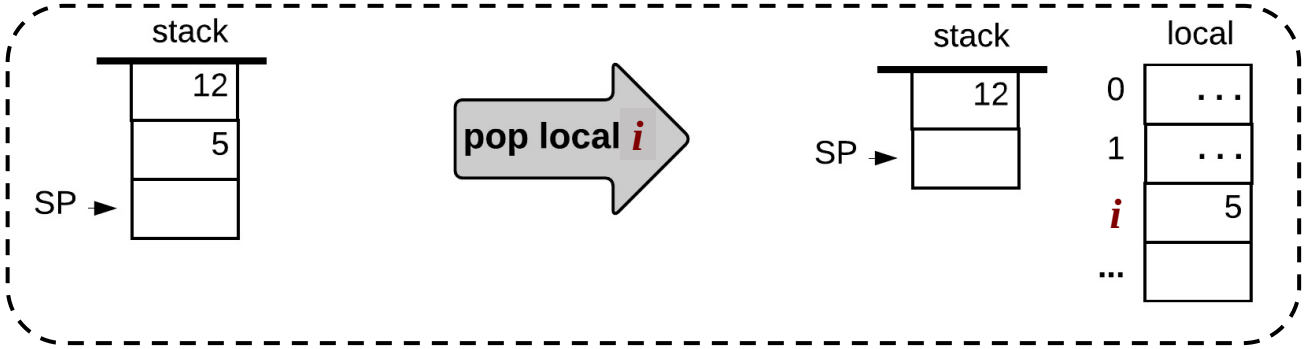

Syntax: push/pop local *i*

Why do we need a local segment?

- High-level code on ***local variables*** are translated into VM operations on the entries of the segment ***local***.

# Implement pop local *i*

Abstraction:

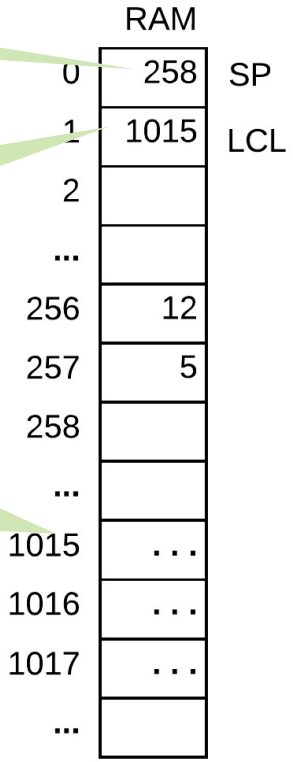



stack pointer

base address of the local segment

Implementation:

the local segment is stored some-where in the RAM

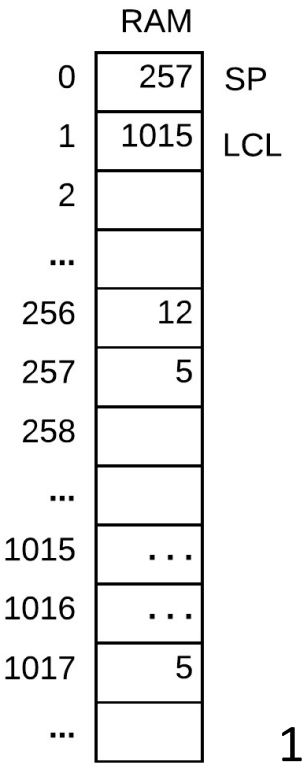



Implementation:

addr=LCL+ *i*, SP--, *addr=*SP

Hack assembly:

On next slide!



# Implement pop local *i*

Abstraction

pop local ***i***

Implementation:

addr=LCL+ ***i***, SP--, *addr=*SP

***i* is a constant here!!!**
**but LCL is a variable.**

Hack assembly:

```
@i      // addr=LCL+i
D=A
@LCL
D=D+M
@addr
M=D
@SP     // SP--
M=M-1
@SP     // D=*SP
A=M
D=M
@addr   // *addr=D
A=M
M=D
```

# Implement `push/pop local i`

VM code:

```
pop local i
```

```
push local i
```

VM Translator

Assembly pseudo code:

```
addr = LCL+ i, SP--, *addr = *SP
```

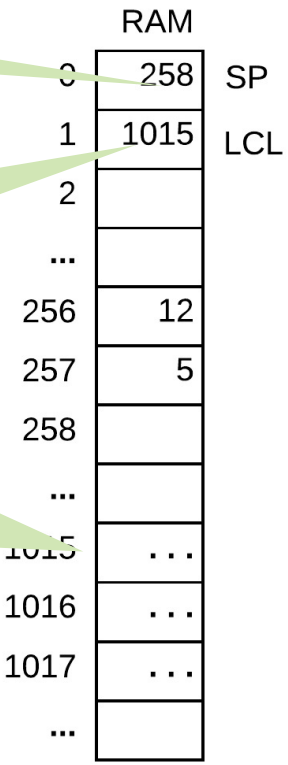
```
addr = LCL+ i, *SP = *addr, SP++
```

Stack pointer

Base address of the local segment

Implementation:

The local segment is stored some-where in the RAM

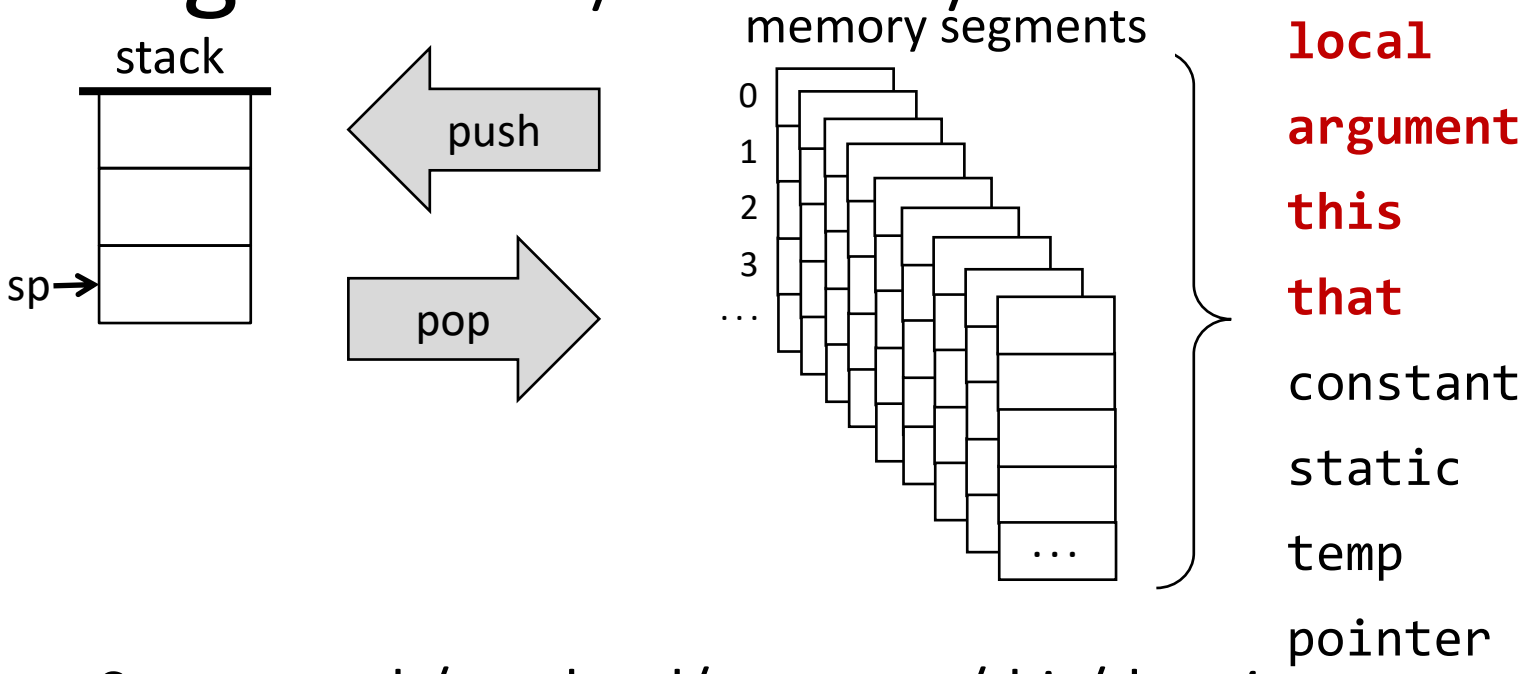



Hack assembly:

```
// implement
// push local i
// addr=LCL+i
@i
D=A
@LCL
D=D+M
@addr
M=D
```

```
// *SP = *addr
@addr// D=*addr
A=M
D=M
@SP  // *SP=D
A=M
M=D
// SP++
@SP
M=M+1
```

# Implement `push / pop local / argument / this / that` *i*




Syntax: push/pop local/argument/this/that *i*

| | High-level language | VM code |
|---|---|---|
| local | *local* variable | *local i* |
| argument | *argument* in a function call | *argument i* |
| this | *field* variables of the current object | *this i* |
| that | *array entries* | *that i* |

# Implement `push / pop local / argument / this / that` *i*

VM code:

`push` *segment i*

`pop` *segment i*

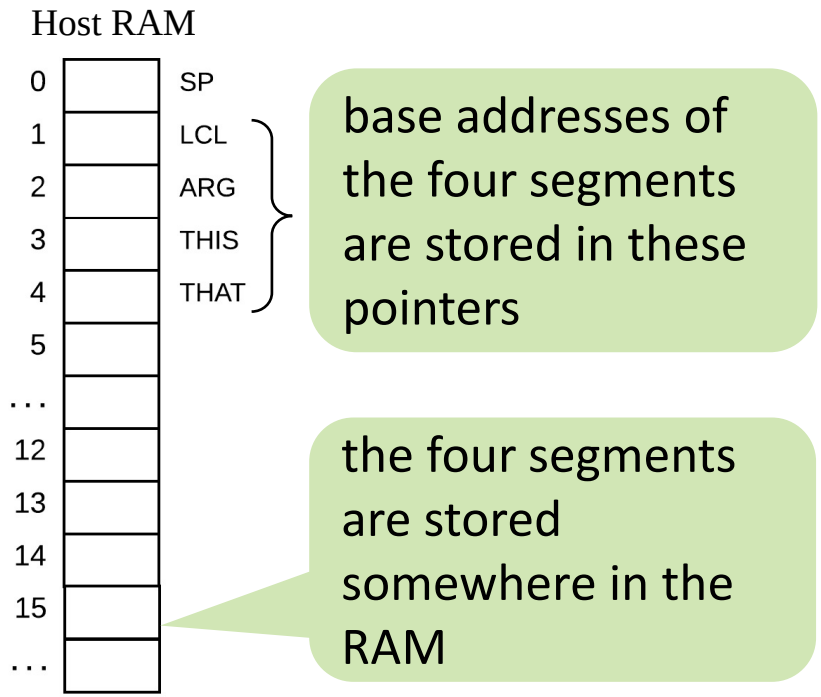
VM translator

Assembly pseudo code:

`addr` = *segmentPointer* + *i*, `*SP = *addr, SP++`

`addr` = *segmentPointer* + *i*, `SP--, *addr = *SP`

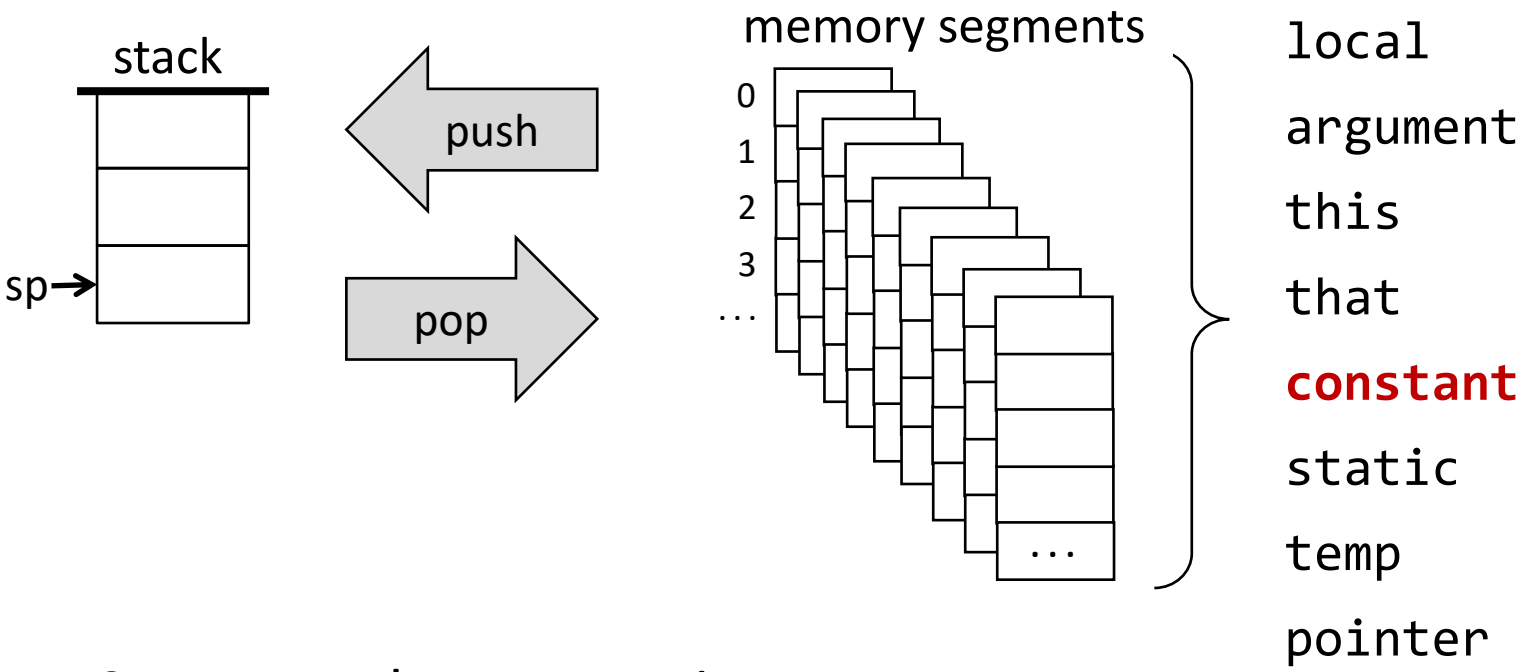
*segment* = {`local, argument, this, that`}




- `push/pop local` *i*
- `push/pop argument` *i*
- `push/pop this` *i*
- `push/pop that` *i*

implemented precisely the same way.

# Implement `push constant` *i*




Syntax: push constant *i*

Why do we need a constant segment?

- High-level code on the *constant i* are translated into VM operations on the segment entry constant *i.*

# Implement `push constant` *i*

VM code:

```
push constant i
```


Assembly psuedo code:

```
*SP = i, SP++
```

(no pop constant operation)

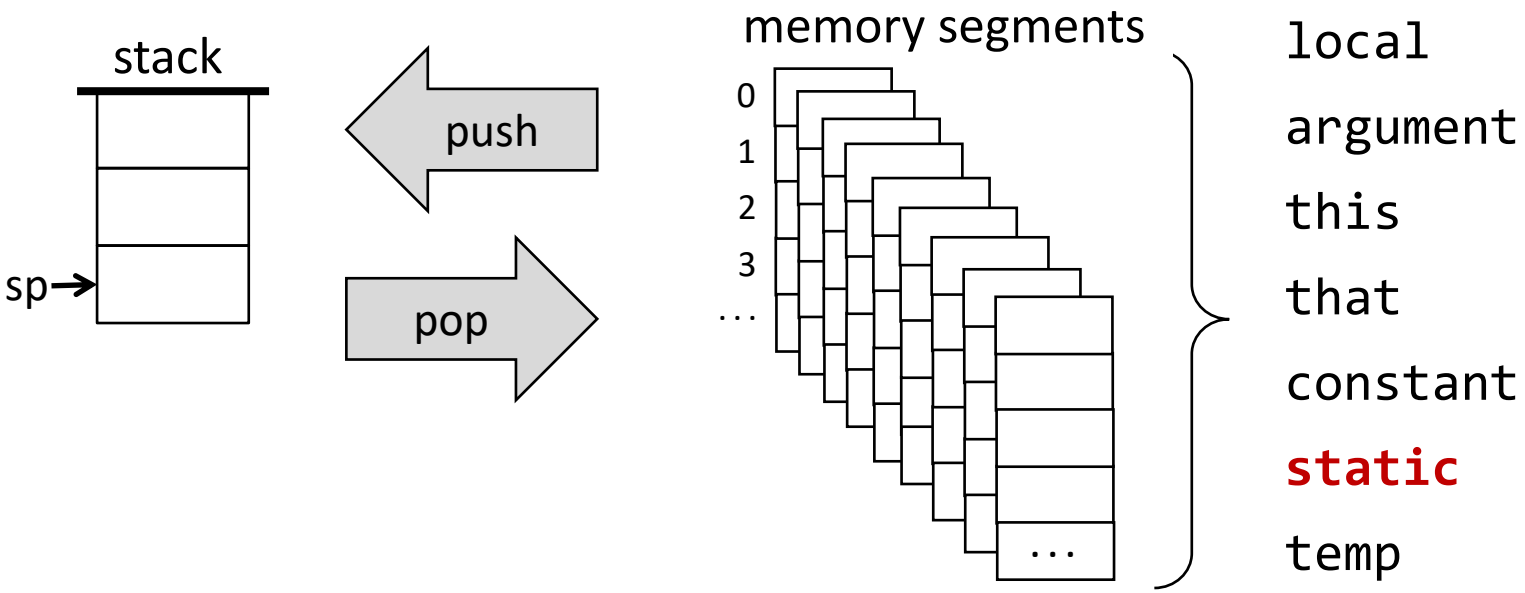
Hack assembly:

```
// D = i
@i
D=A
// *SP=D
@SP
A=M
M=D
// SP++
@SP
M=M+1
```

Implementation:

Supplies the specified constant.

# Implementing `push/pop static i`




Syntax: `push/pop static i`

Why do we need a static segment?

- High-level operations on *static* variables are translates into VM operations on entried of the segment *static*.
- Static variables can be used as "global" variables, or to store constant values.

# Implement push/pop static *i*

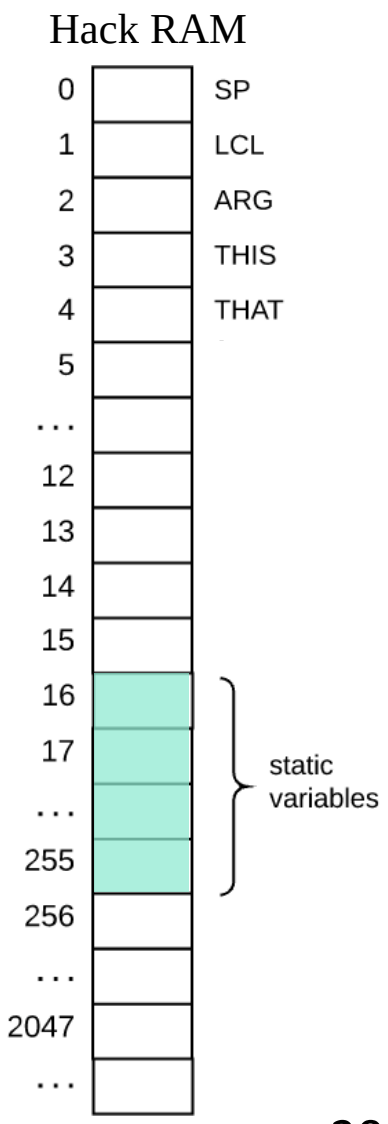
VM code:

```
// File Foo.vm
...
pop static 5
...
pop static 2
...
```

VM translator

Generated assembly code:

```
...
// D = stack.pop (code omitted)
@Foo.5
M=D
...
// D = stack.pop (code omitted)
@Foo.2
M=D
...
```




The challenge:

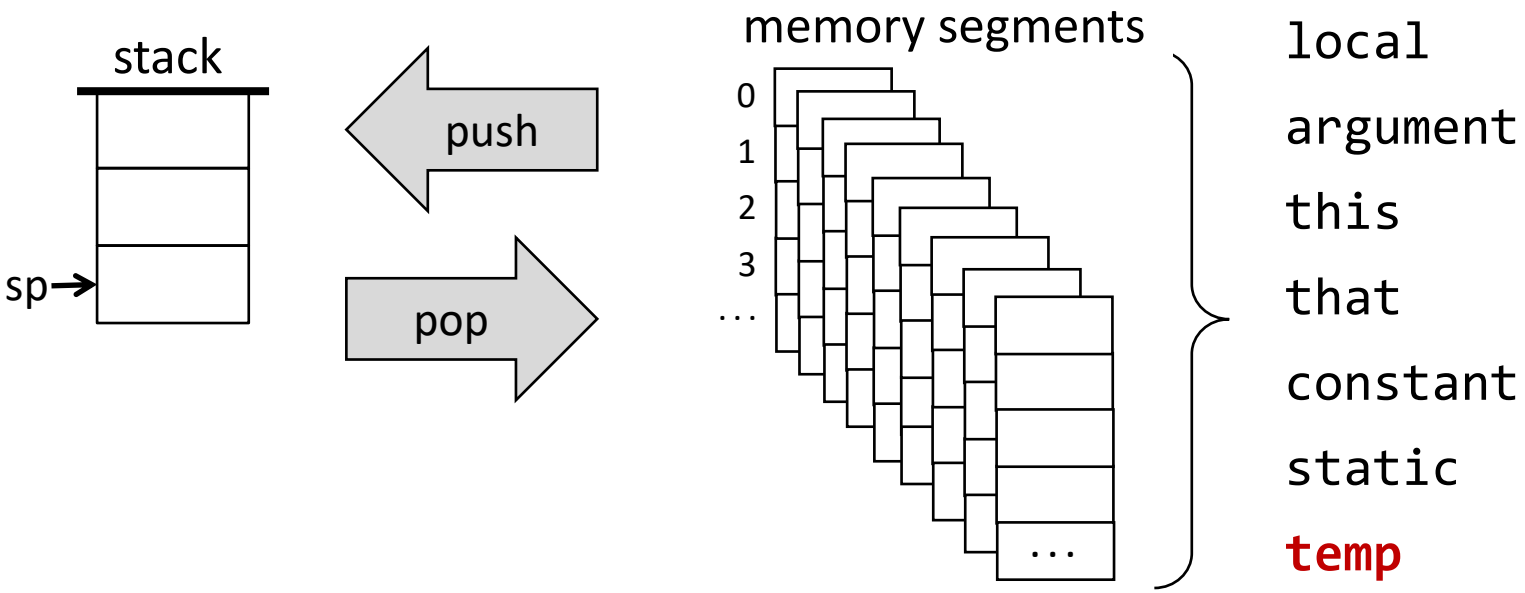
Static variables should be seen by all the methods in a program.

Solution:

Store them in some "**global space**":

- Have the VM translator translate each VM reference static *i* (in file Foo.vm) into an assembly reference Foo.*i*
- Following assembly, the Hack assembler will map these references onto RAM[16], RAM[17], ..., RAM[255]
- Therefore, the entries of the static segment will end up being mapped onto RAM[16], RAM[17], ..., RAM[255], in the order in which they appear in the program.

# Implement `push/pop temp` *i*




Syntax: `push/pop temp` *i*

Why do we need the temp segment?

- So far, all the variable kinds that we discussed came from the source code.
- Sometimes, the **compiler** needs to use some working variables of its own.
- Our VM provides **8** such variables, stored in a segment named *temp*.

# Implement `push/pop temp` *i*

VM code:

`push temp` *i*

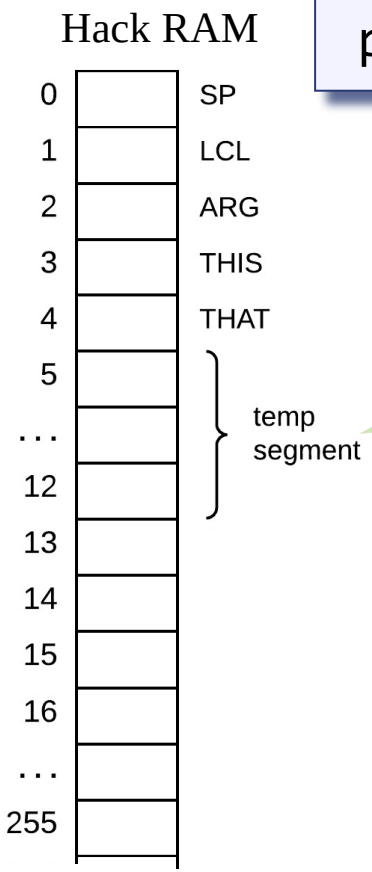
`pop temp` *i*

VM Translator

Assembly psuedo code:

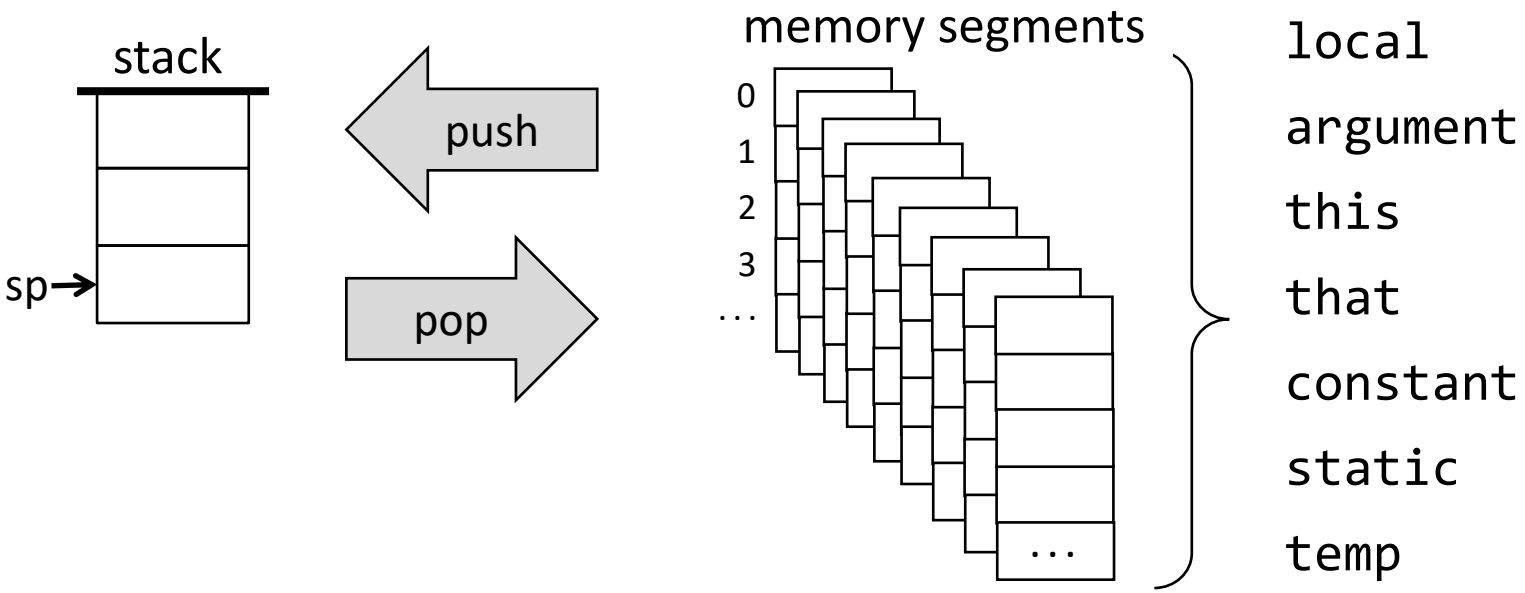
`addr = 5 + i, *SP = *addr, SP++`

`addr = 5 + i, SP--, *addr = *SP`




A fixed, **8-place** memory segment, stored in RAM locations 5 to 12

# Implement `push/pop pointer 0/1`




Syntax: `push/pop pointer 0/1`

Why do we need the *pointer* segment?

- We use it for storing the **base addresses** of the segments **this** and **that**.
- The need for this will become clear when writing the compiler.

# Implement `push/pop pointer 0/1`

VM code:

```
push pointer 0/1
```

```
pop pointer 0/1
```

VM Translator

Assembly psuedo code:

```
*SP = THIS/THAT, SP++
```

```
SP--, THIS/THAT = *SP
```

A fixed, 2-place segment:

- accessing pointer 0 should result in accessing THIS
- accessing pointer 1 should result in accessing THAT

## Implementation:

Supplies THIS or THAT

```
// The base addresses of this and that.
// THIS and THAT: Built-in symbols.
```

# Outlines

- Introduction to virtual machine
- VM abstraction
- VM implementation
  - Stack
  - Memory segment commands
  - Branching commands
  - Function commands
- VM translator

# Branching

- goto *label*
  - jump to execute the command just after *label*
- if-goto *label*
  - *cond* = pop
  - if *cond* jump to execute the command just after *label*
- label *label*
  - label declaration command
- Implementation (VM translation):
  - The assembly language has similar branching commands.

# Outlines

- Introduction to virtual machine
- VM abstraction
- VM implementation
  - Stack
  - Memory segment commands
  - Branching commands
  - Function commands
- VM translator

# Functions in VM language: implementation

```
// Computes 3 +8* 5
0 function main 0
1   push constant 3
2   push constant 8
3   push constant 5
4   call mult 2
5   add
6   return
```

caller

```
// Computes the product of two given arguments
0 function mult 2
1   push constant 0
2   pop local 0
3   push constant 1
4   pop local 1
5 label LOOP
6   push local 1
7   push argument 1
    //... computes the product into local 0
19 label END
20   push local 0
21   return
```

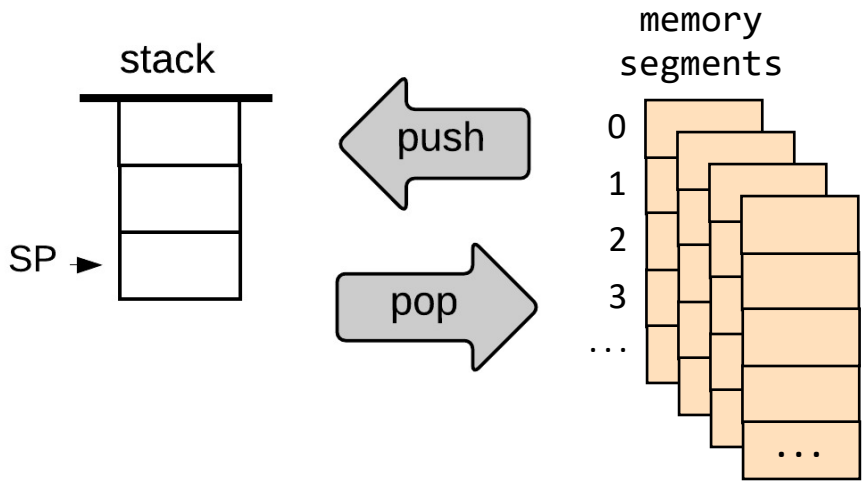
callee

## Implementation

We can write low-level code to

- Handle the VM command call,
- Handle the VM command function,
- Handle the VM command return.

# The function's state



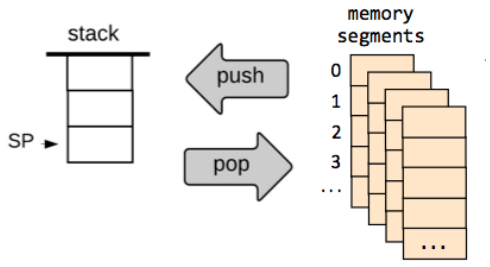

<u>During run-time:</u>

- Each function uses a **working stack** + **memory segments**
- The working stack and some of the segments should be:
  - **Created** when the function starts running,
  - **Maintained** as long as the function is executing,
  - **Recycled** when the function returns.

# The function's state

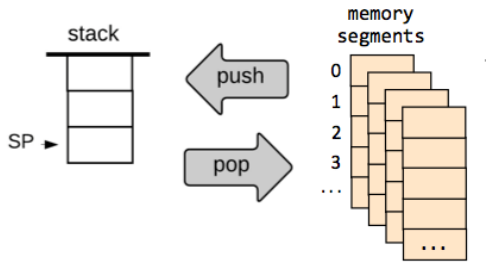
```
function main 0
   push constant 3
   push constant 8
   push constant 5
   call mult 2
   add
   return
```

caller




```
function mult 2
   push constant 0
   pop local 0
   ...
label LOOP
   push local 1
   //... computes the product
label END
   push local 0
   return
```

callee

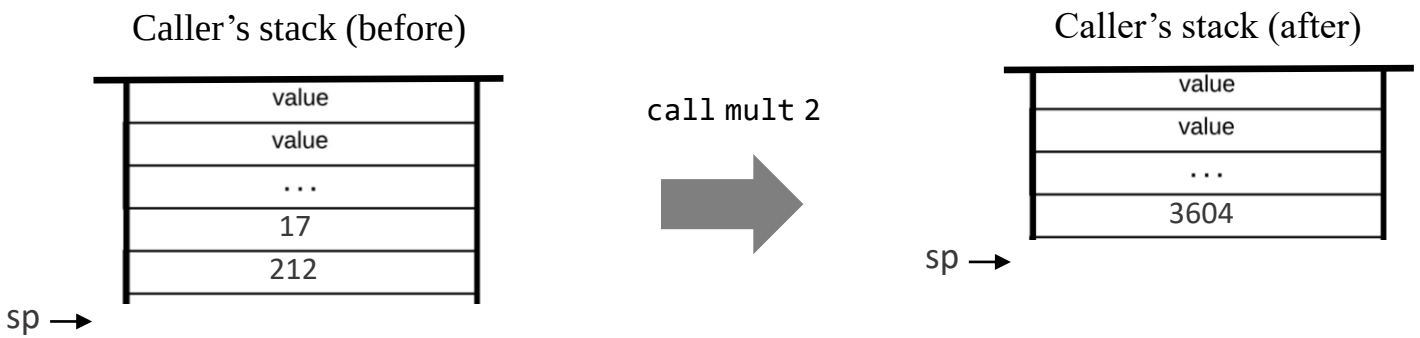



## Challenge:

- Maintain the states of all the functions up the calling chain.
- Can be done by using a single ***global*** *stack*.

# Function call and return: abstraction

Example: computing mult(17,212)

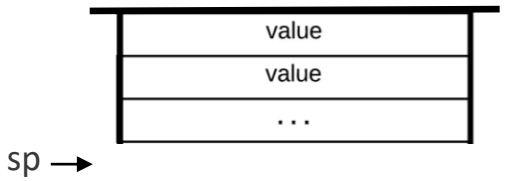



Net effect:

The function's arguments were replaced by the function's return value

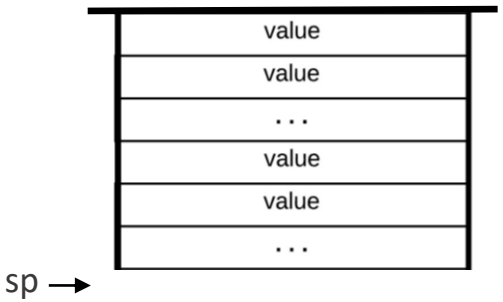
# Function call and return: implementation

A function is running, and doing something



# Function call and return: implementation

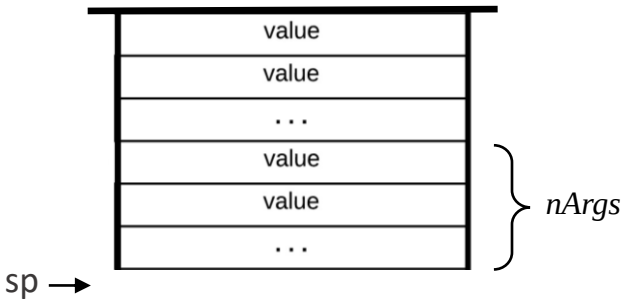
The function prepares
to call another function:



# Function call and return: implementation

The function says:

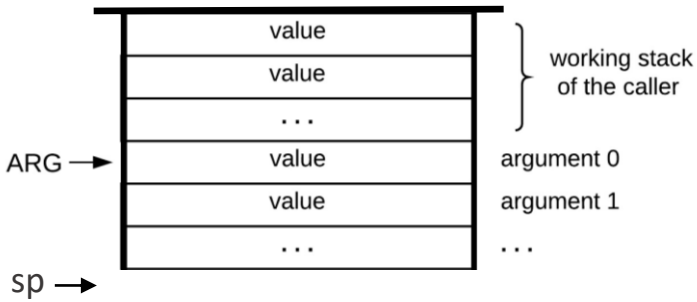
call *foo nArgs*



# Function call and return: implementation

The function says:

call *foo nArgs*



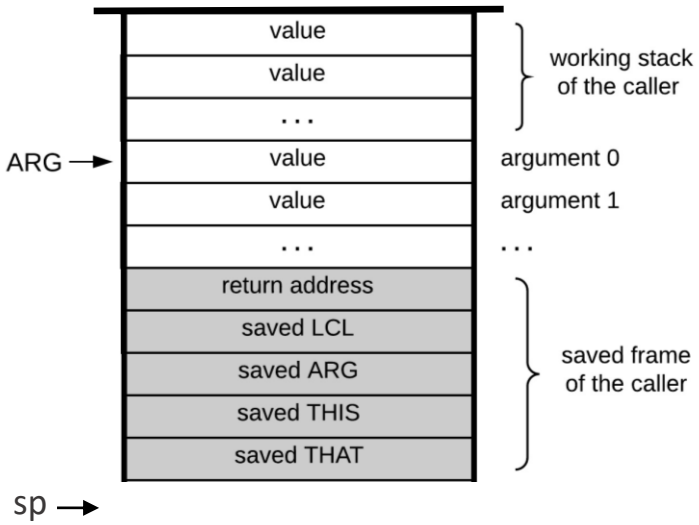

VM implementation (handling call):

1. Set ARG

# Function call and return: implementation

The function says:

call *foo nArgs*



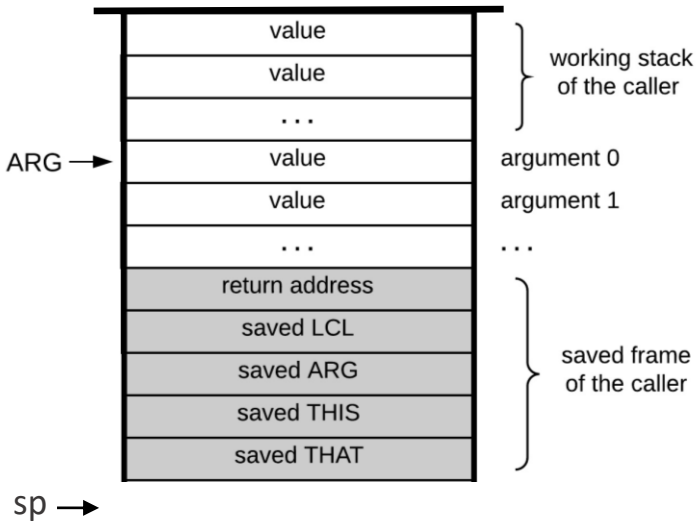

VM implementation (handling call):

1. Set ARG
2. Save the caller's frame

# Function call and return: implementation

The called function is entered:

function *foo nVars*



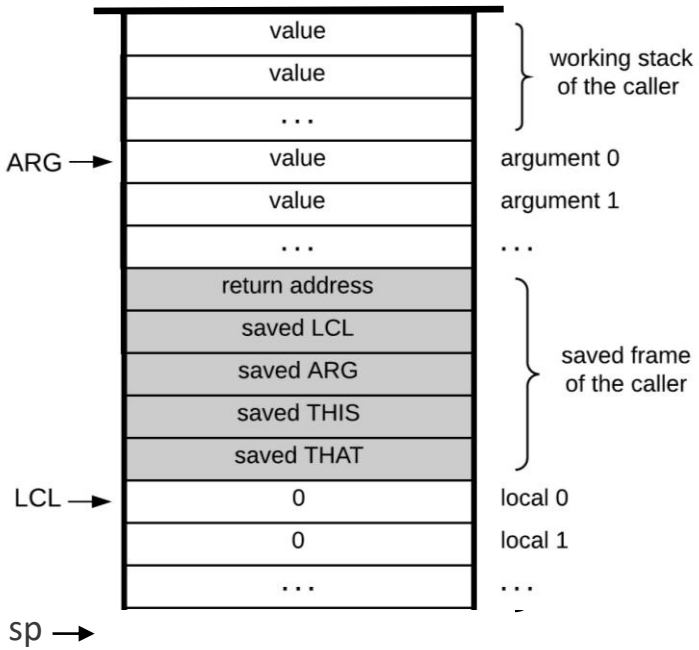

VM implementation (handling call):

1. Set ARG
2. Save the caller's frame
3. Jump to execute *foo*

# Function call and return: implementation

The called function is entered:

function *foo nVars*




VM implementation (handling call):

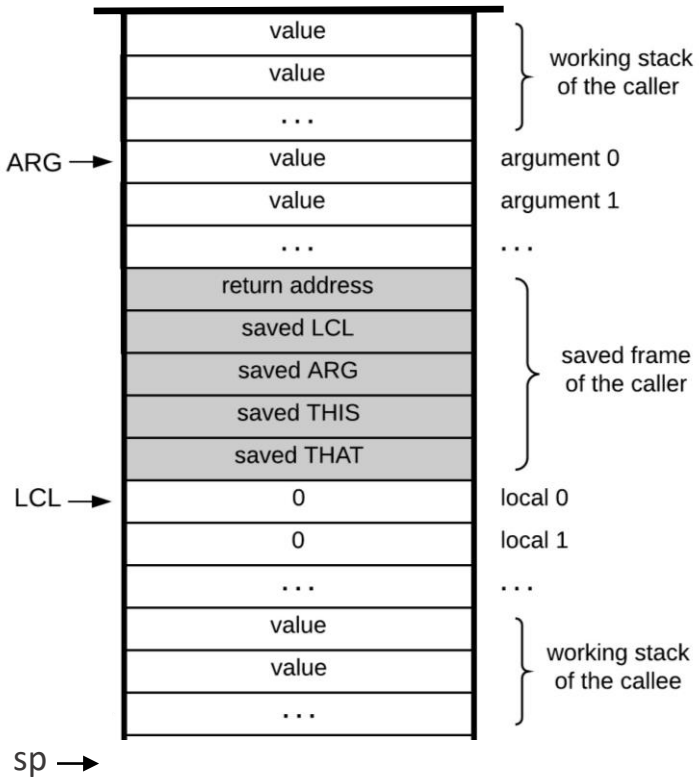
1. Set ARG
2. Save the caller's frame
3. Jump to execute *foo*

VM implementation (handling function):

Set up the local segment of the called function

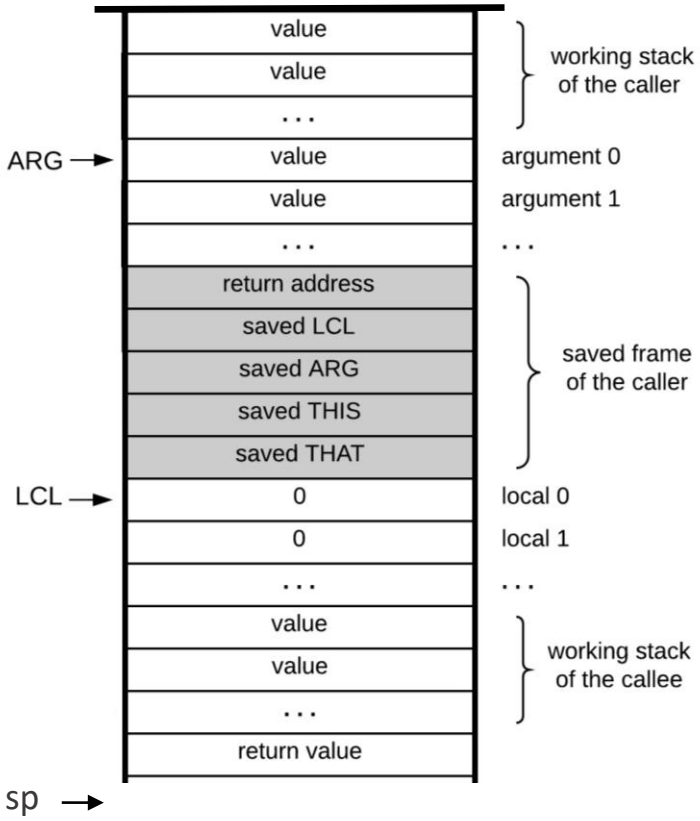
# Function call and return: implementation

The called function is running,
doing something



# Function call and return: implementation

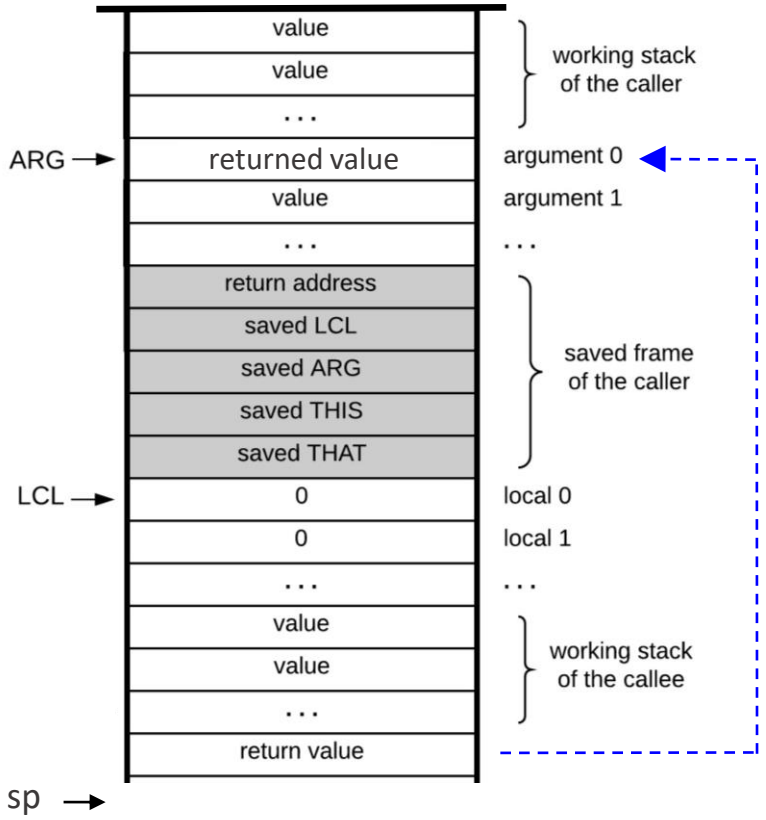
The called function prepares to return:
it pushes a *return value,* and says *return.*



# Function call and return: implementation

The called function says:

return




VM implementation (handling call):

1. Set ARG
2. Save the caller's frame
3. Jump to execute *foo*

VM implementation (handling function):

Set up the local segment of the called function

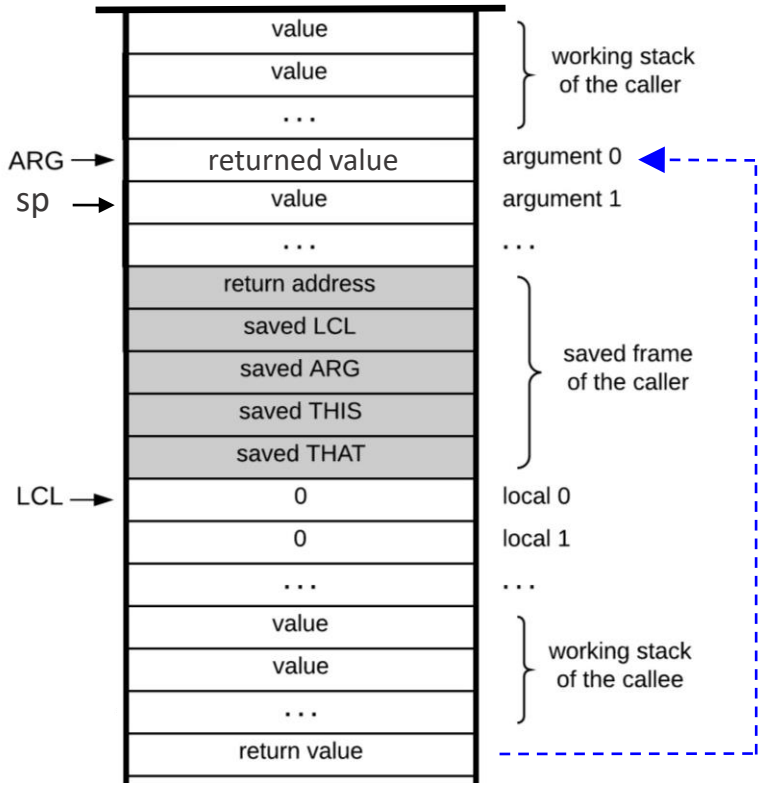
VM implementation (handling return):

1. Copy return value onto argument 0.

# Function call and return: implementation

The called function says:

return




VM implementation (handling call):

1. Set ARG
2. Save the caller's frame
3. Jump to execute *foo*

VM implementation (handling function):

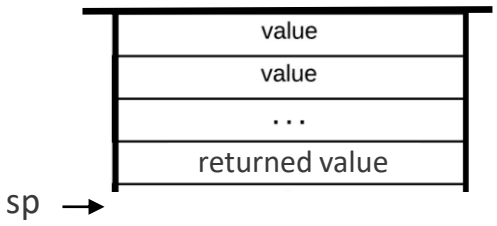
Set up the local segment of the called function

VM implementation (handling return):

1. Copy return value onto argument 0.
2. Set SP for the caller.

# Function call and return: implementation

The caller
resumes its execution




VM implementation (handling call):

1. Set ARG
2. Save the caller's frame
3. Jump to execute *foo*

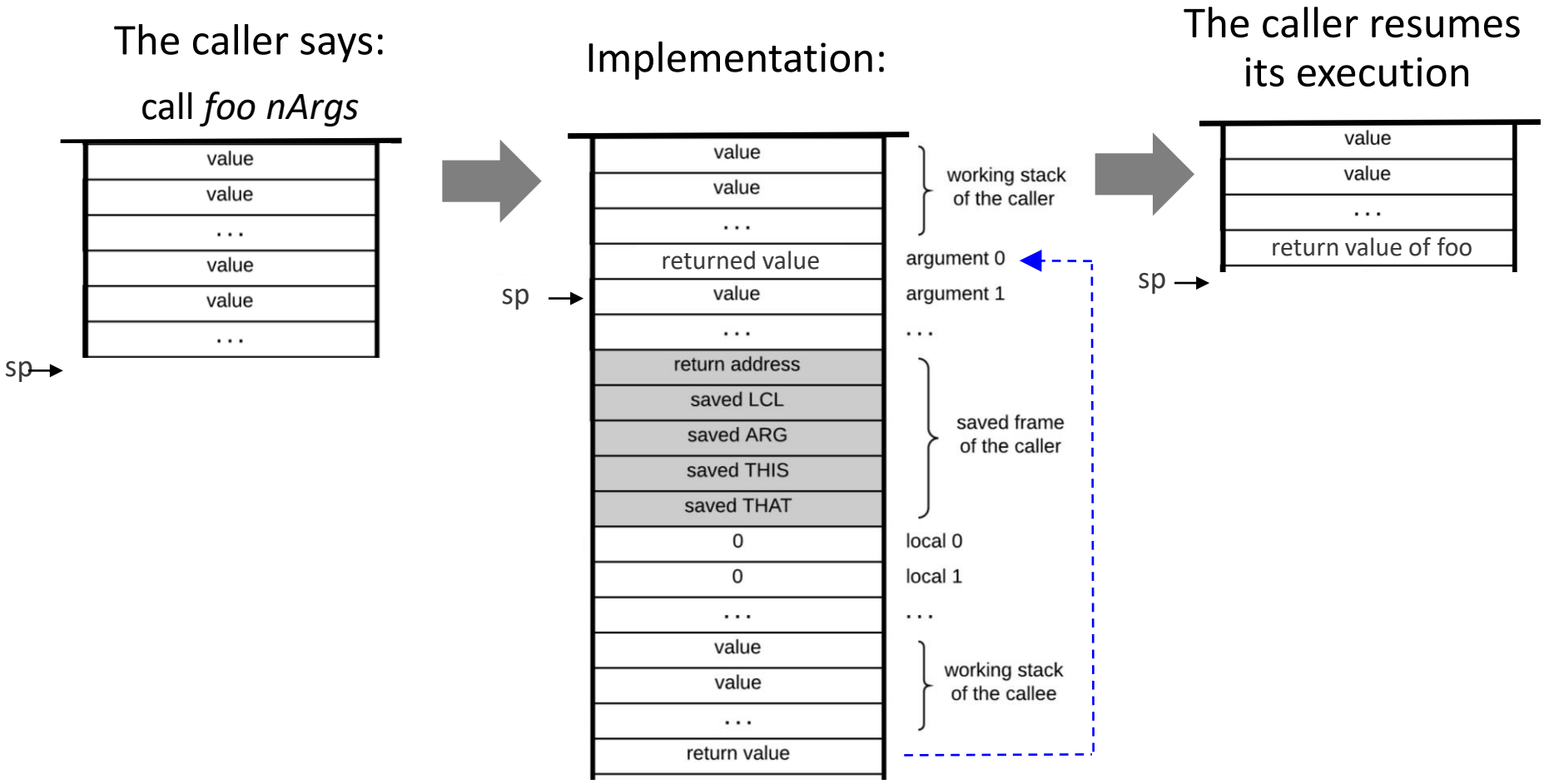
VM implementation (handling function):

Set up the local segment
of the called function

VM implementation (handling return):

1. Copy return value onto argument 0.
2. Set SP for the caller.
3. Restore segment pointers of the caller.
4. Jump to the return address within the caller's code. (note that the stack space below sp is recycled)

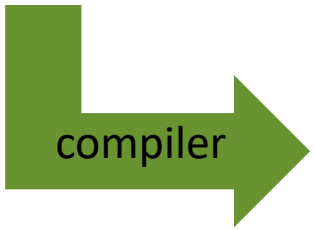
# Recap: function call and return



# Example: `factorial`

High-level program

```
// Tests the factorial function
int main() {
   return factorial(3);
}

// Returns n!
int factorial(int n) {
   if (n==1)
      return 1;
   else
      return n * factorial(n-1);
}
```




Pseudo VM code

```
function main
   push 3
   call factorial
   return

function factorial(n)
   push n
   push 1
   eq
   if-goto BASECASE

   push n
   push n
   push 1
   sub
   call factorial
   call mult
   return

label BASECASE
   push 1
   return

function mult(a,b)
 // Code omitted
```

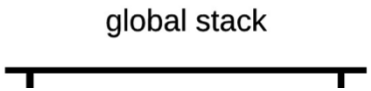
VM program

```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE

   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return

label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```

# Run-time example

VM program

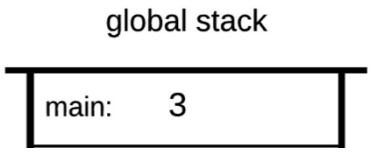
```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



# Run-time example

VM program

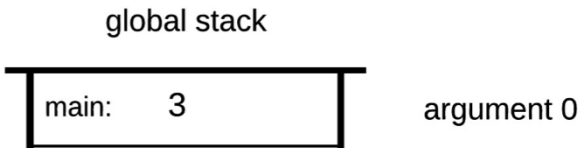
```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



# Run-time example

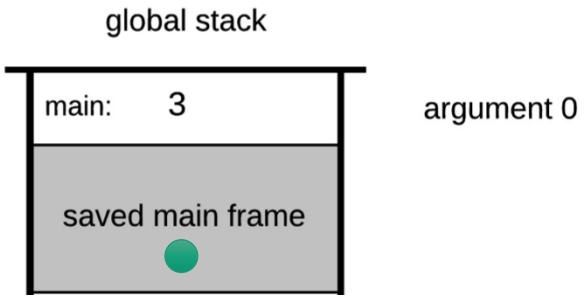
VM program

```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



# Run-time example

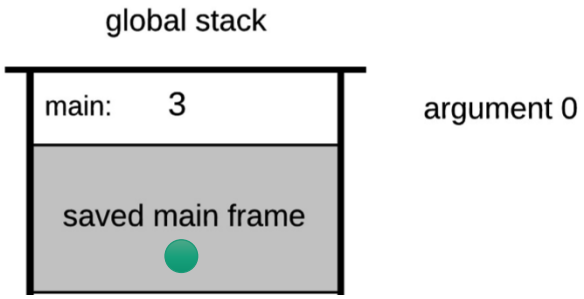
```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



# Run-time example

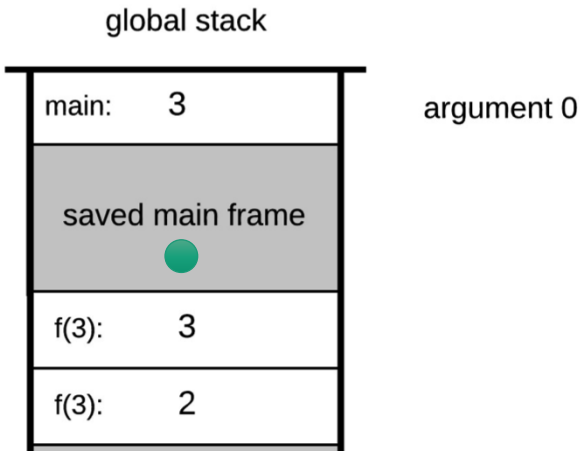
```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```

impact on the global stack not shown



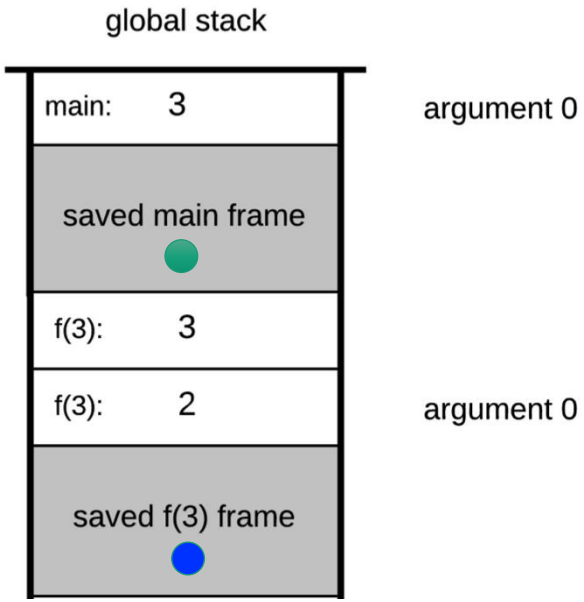
# Run-time example

```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



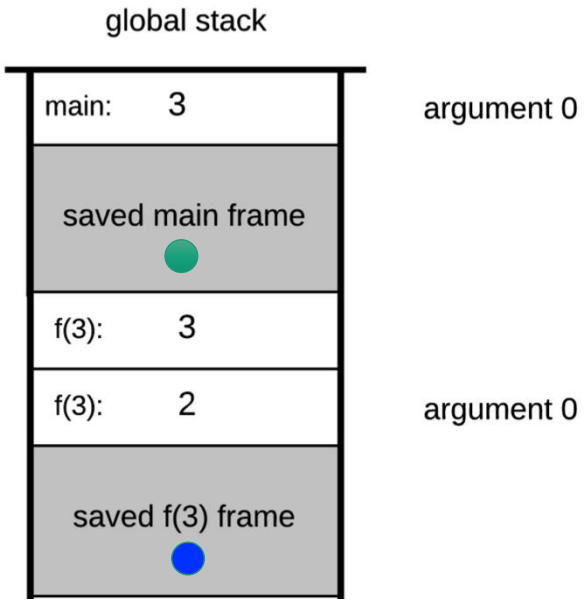
# Run-time example

```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



# Run-time example

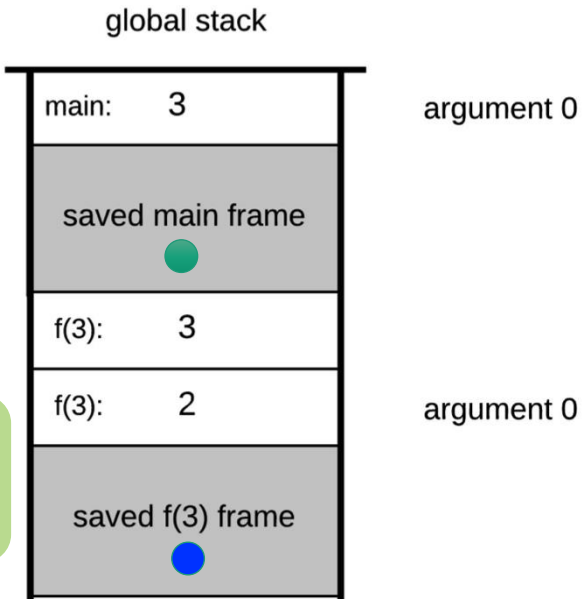
```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



# Run-time example

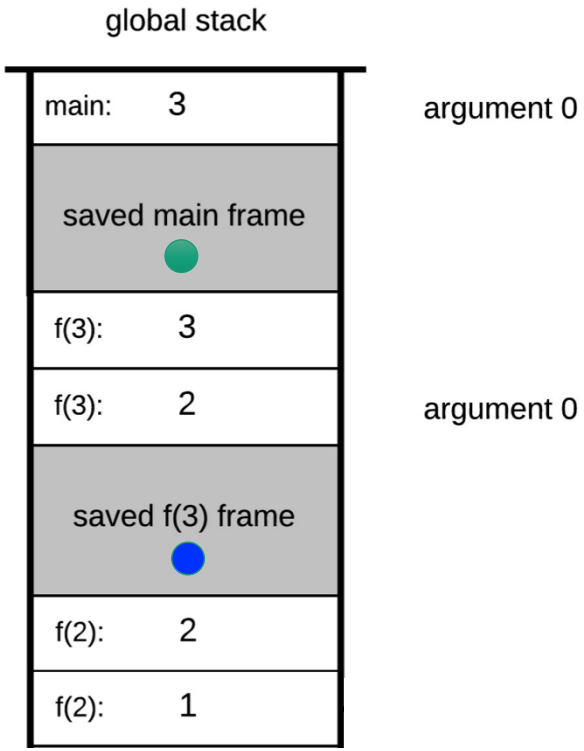
```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```

impact on the global stack not shown



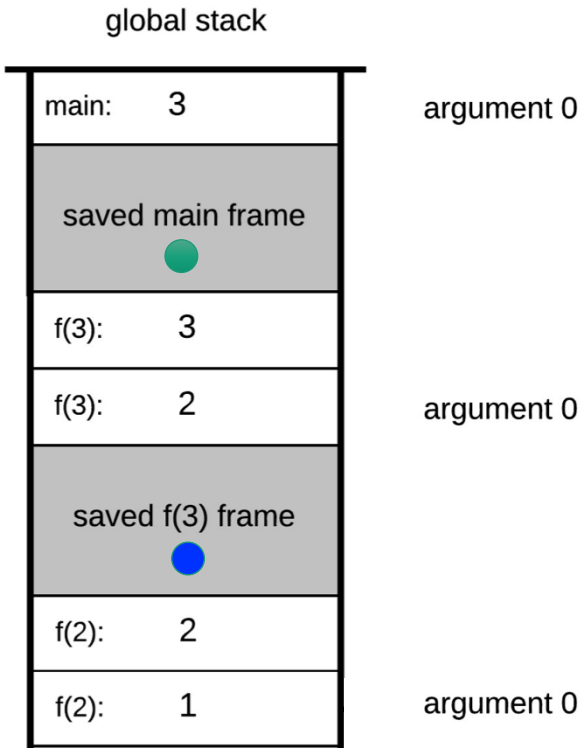
# Run-time example

```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



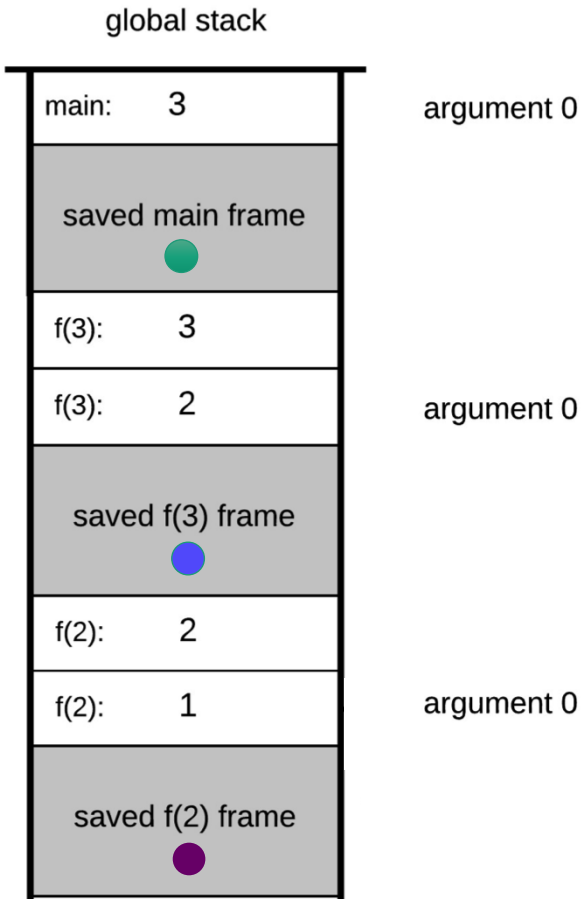
# Run-time example

```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



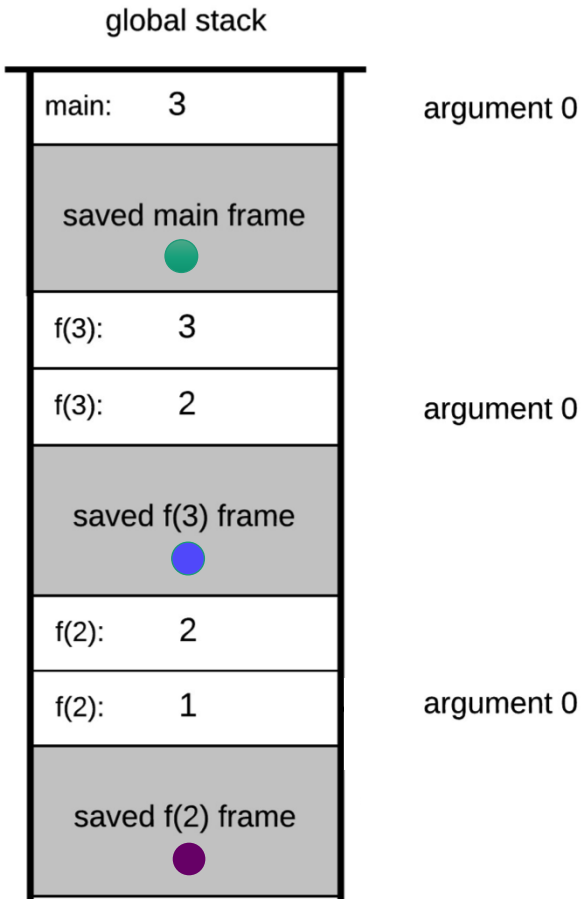
# Run-time example

```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



# Run-time example

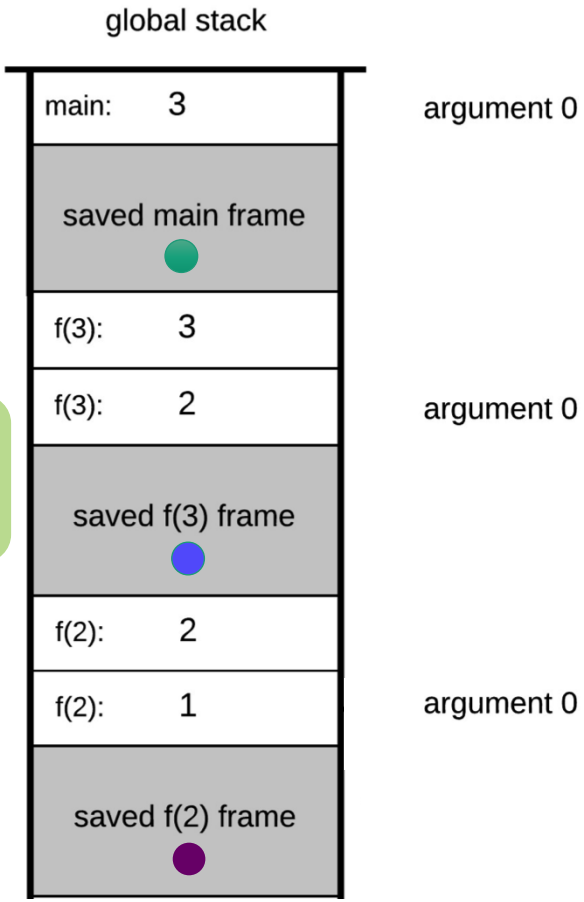
```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



# Run-time example

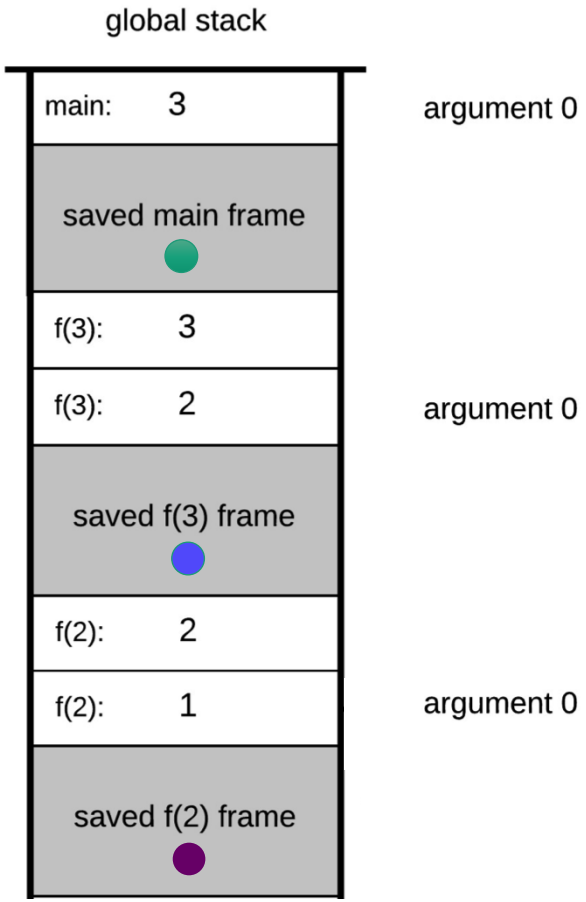
```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```

impact on the global stack not shown



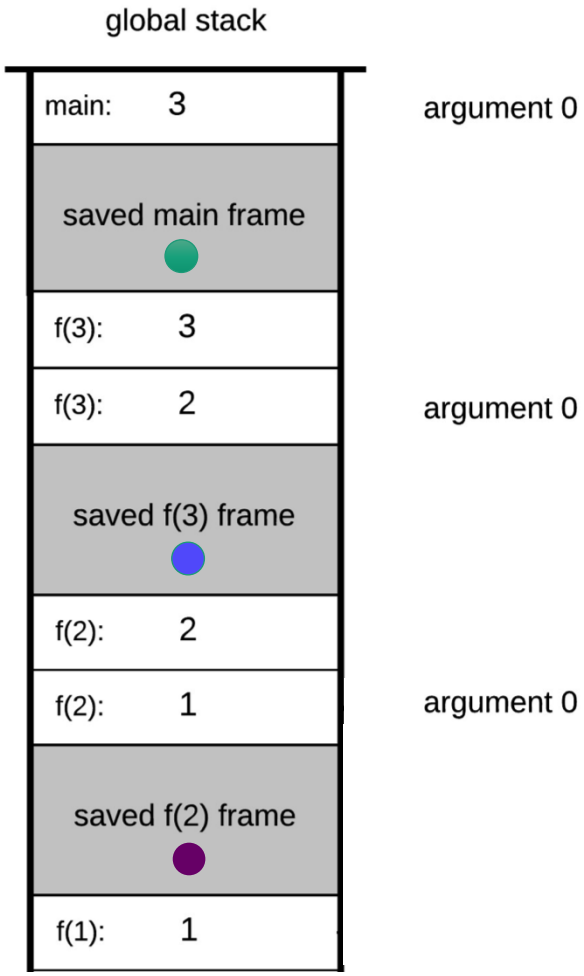
# Run-time example

```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



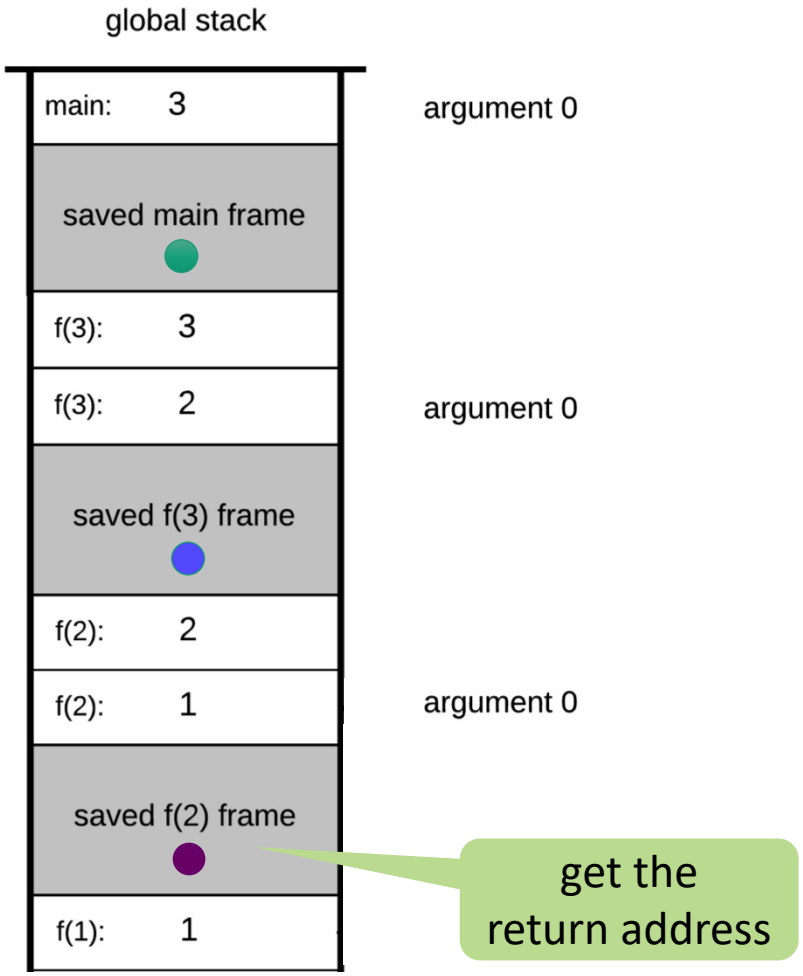
# Run-time example

```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



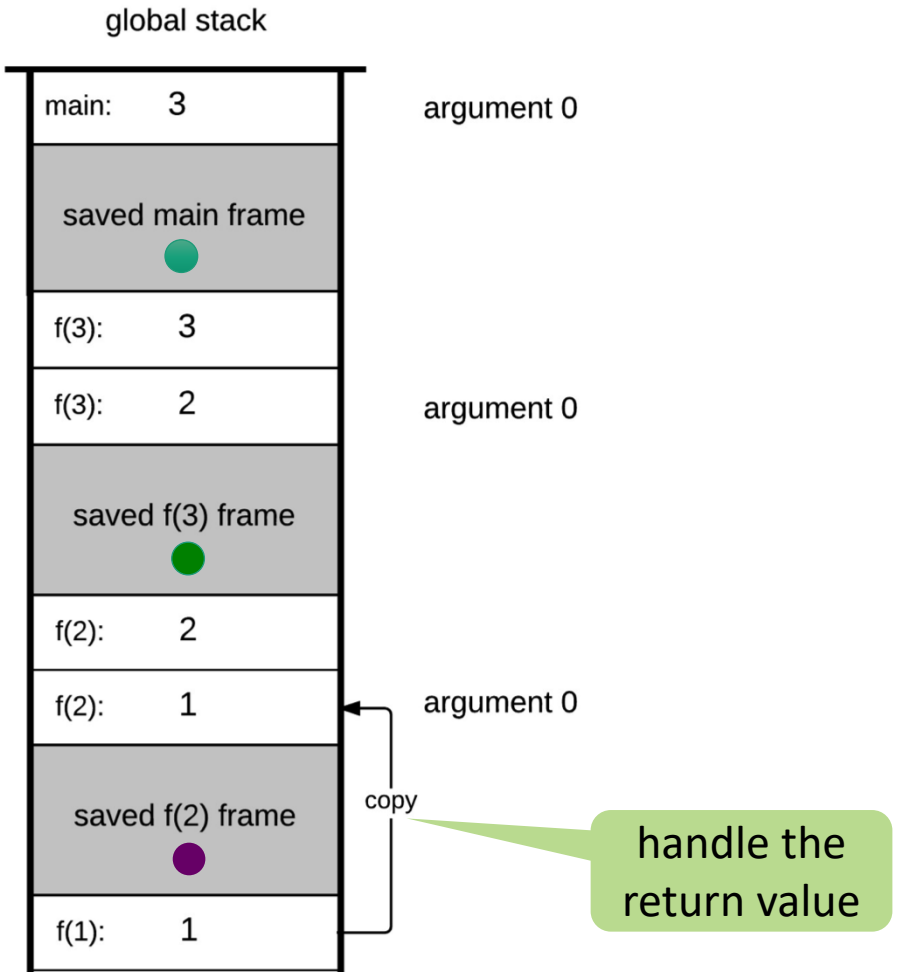
# Run-time example

```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



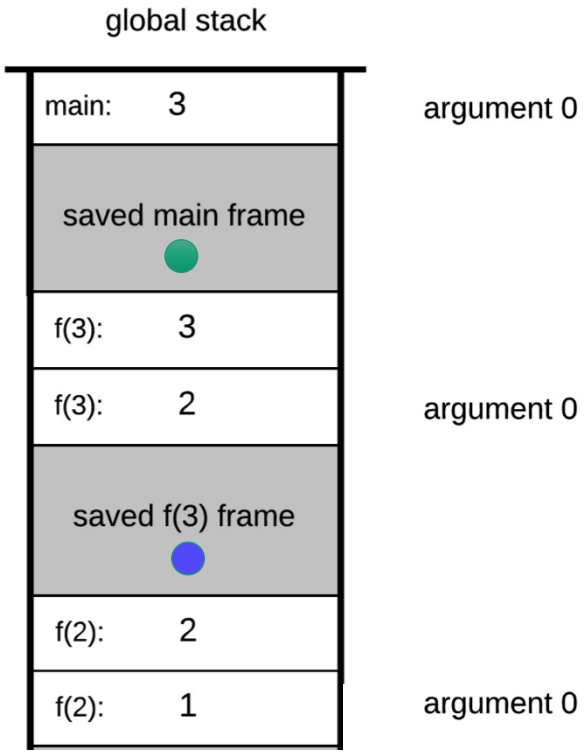
# Run-time example

```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



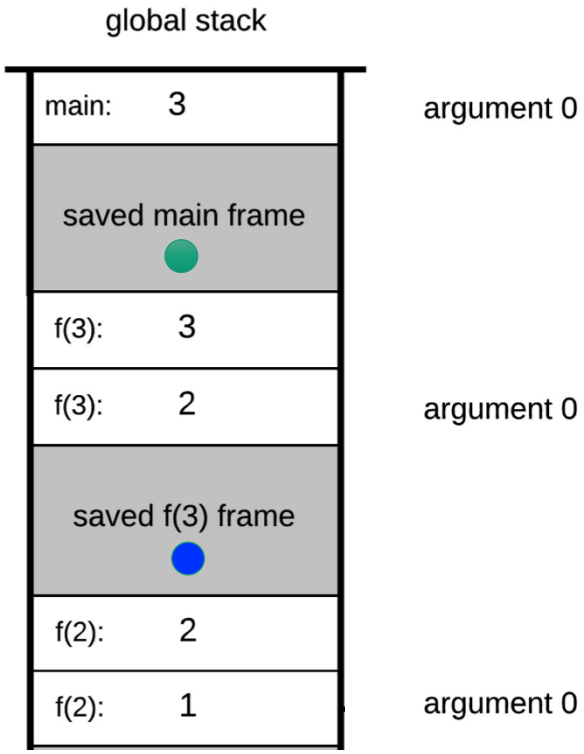
# Run-time example

```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



# Run-time example

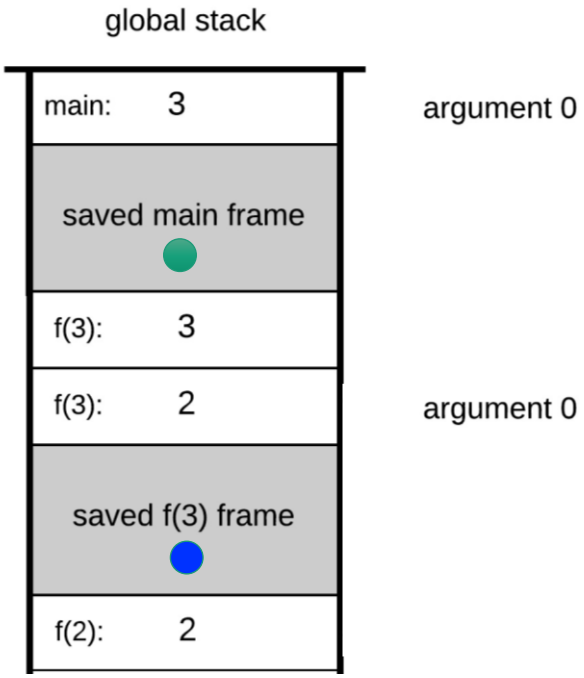
```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```




impact on the global stack not shown (except for end result)

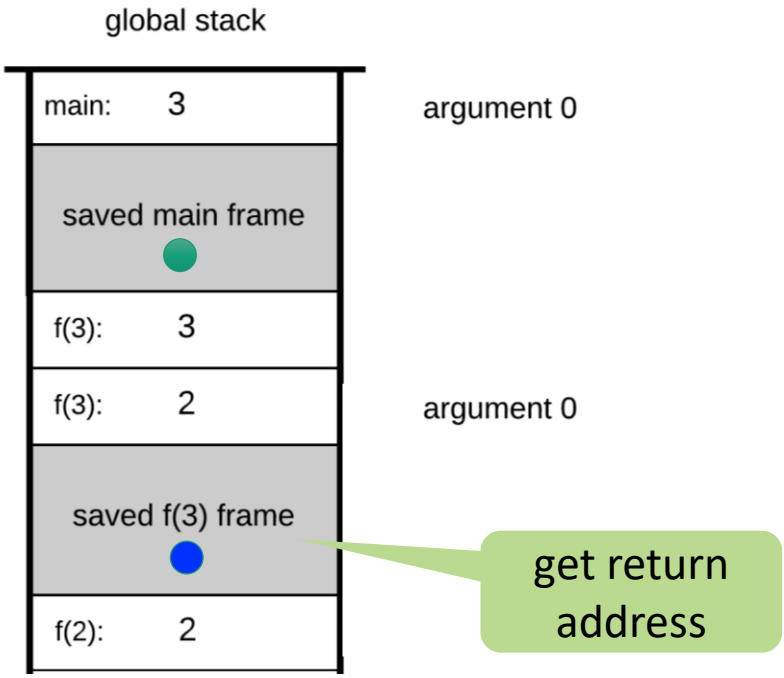
# Run-time example

```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



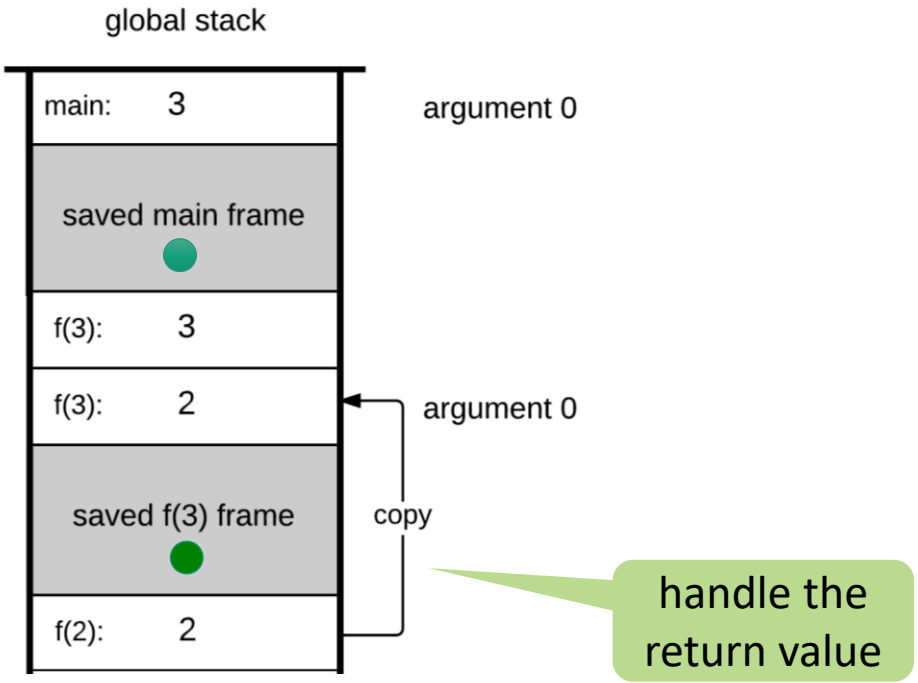
# Run-time example

```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



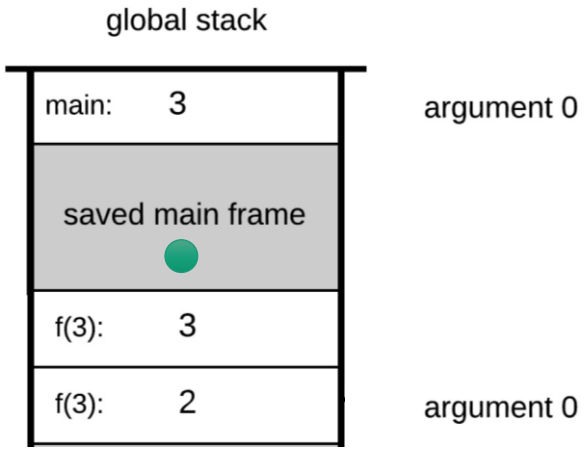
# Run-time example

```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



# Run-time example

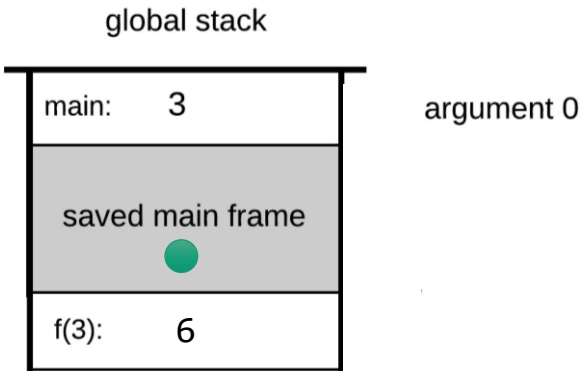
```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```




impact on the global stack not shown (except for end result)

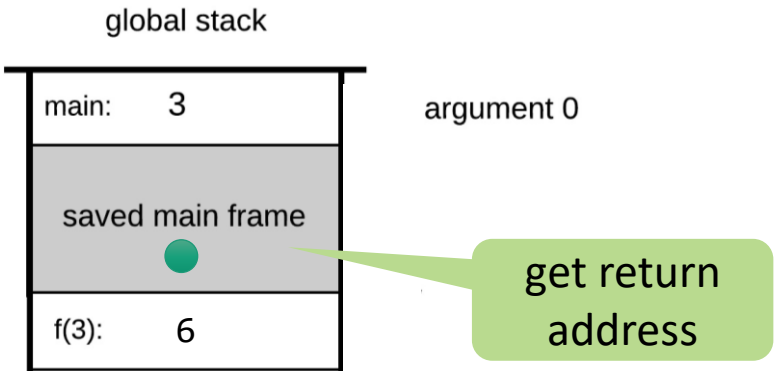
# Run-time example

```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



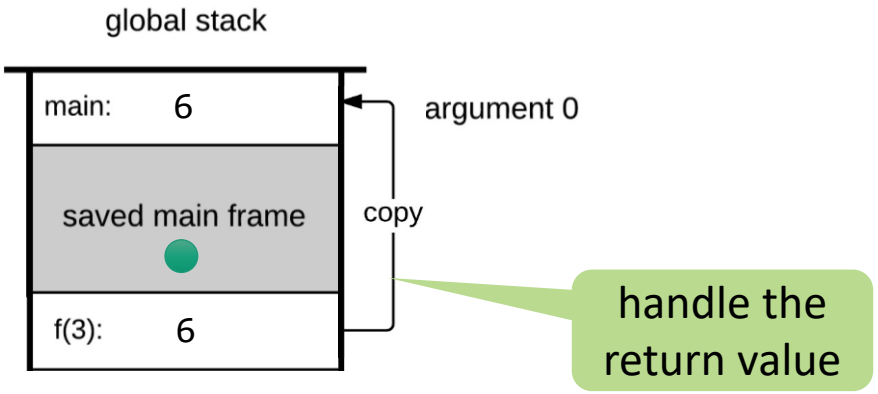
# Run-time example

```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



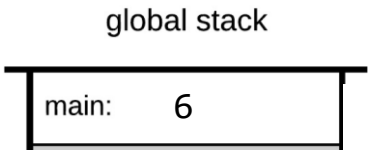
# Run-time example

```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



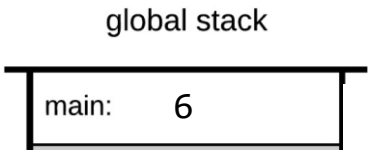
# Run-time example

```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



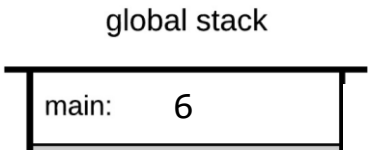
# Run-time example

```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```



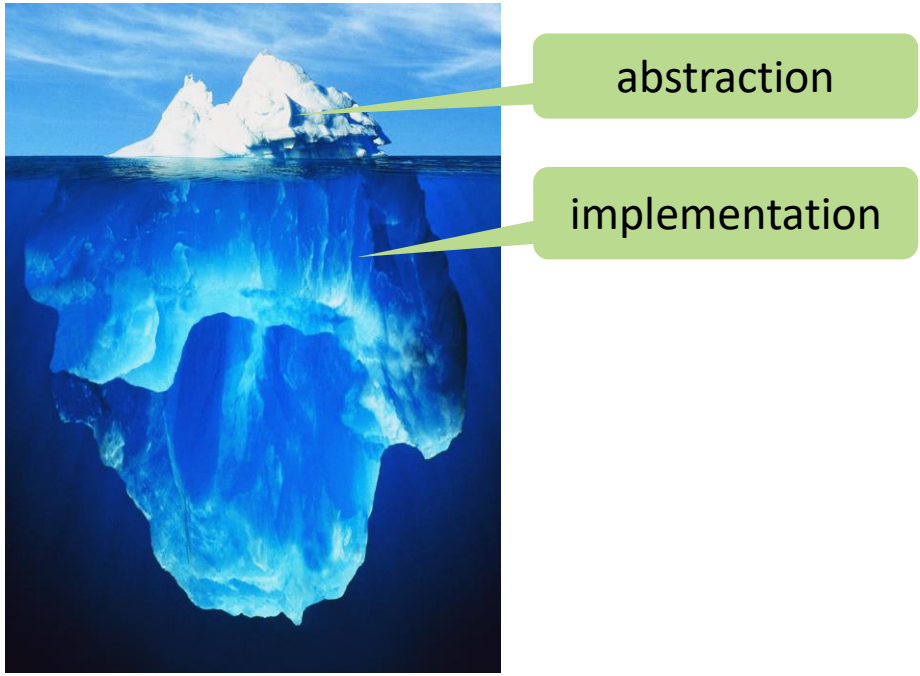
# Recap

```
function main 0
   push constant 3
   call factorial 1
   return

function factorial 1
   push argument 0
   push constant 1
   eq
   if-goto BASECASE
   push argument 0
   push argument 0
   push constant 1
   sub
   call factorial 1
   call mult 2
   return
label BASECASE
   push constant 1
   return

function mult 2
   // Code omitted
```




The caller (`main` function) wanted to compute 3!

- it pushed 3, called `factorial`, and got 6
- from the caller's view, nothing exciting happenned...



# Detailed implementation of function

VM code (arbitrary example)

caller

```
function Foo.main 4
  ...
  // computes –(19 * (local 3))
  push constant 19
  push local 3
  call Bar.mult 2
  neg
  ...
```

callee

```
function Bar.mult 2
  // Computes the product of
     the first two
  // arguments and puts the
     result in local 1
  ...
  push local 1   // return value
  return
```

We focus on VM function commands:

- call *functionName nArgs*
- function *functionName nVars*
- return

# Contract: the caller's view

VM code (arbitrary example)

caller

```
function Foo.main 4
  ...
  // computes –(19 * (local 3))
  push constant 19
  push local 3
  call Bar.mult 2
  neg
  ...

function Bar.mult 2
  // Computes the product of
     the first two
  // arguments and puts the
     result in local 1
  ...
  push local 1   // return value
  return
```

- Before calling another function, push as many **arguments** as the function expects to get.
- Next, **invoke** the function using

  call *functionName nArgs*
- After the called **function returns**,
  - the **argument** values being pushed before the call disappear from the stack, and a *return value* (that always exists) appears at the top of the stack;
  - all my **memory segments** are exactly the same as they were before the call (except that temp is undefined and some values of my static segment may have changed).

# Contract: the caller's view

VM code (arbitrary example)

caller

```
function Foo.main 4
  ...
  // computes –(19 * (local 3))
  push constant 19
  push local 3
  call Bar.mult 2
  neg
  ...

function Bar.mult 2
  // Computes the product of
     the first two
  // arguments and puts the
     result in local 1
  ...
  push local 1   // return value
  return
```

- Before calling another function, push as many **arguments** as the function expects to get.
- Next, **invoke** the function using

  call *functionName nArgs*

- After the called **function returns**,
  - the **argument** values being pushed before the call disappear from the stack, and a *return value* (that always exists) appears at the top of the stack;
  - all my **memory segments** are exactly the same as they were before the call (except that temp is undefined and some values of my static segment may have changed).

blue: must be handled by the VM implementation

# Contract: the callee's view

VM code (arbitrary example)

```
function Foo.main 4
  ...
  // computes –(19 * (local 3))
  push constant 19
  push local 3
  call Bar.mult 2
  neg
  ...

function Bar.mult 2
  // Computes the product of
     the first two
  // arguments and puts the
     result in local 1
  ...
  push local 1   // return value
  return
```

callee

- Before start executing, my **argument** segment has been initialized with the argument values passed by the caller,
- My **local** variables segment has been allocated and initialized to zeros,
- My **static** segment has been set to the static segment of the VM file to which I belong,

  (memory segments this, that, pointer, and temp are undefined upon entry)
- My **stack** is empty,
- Before **returning**, I must push a value onto the stack.

# Contract: the callee's view

VM code (arbitrary example)

```
function Foo.main 4
  ...
  // computes –(19 * (local 3))
  push constant 19
  push local 3
  call Bar.mult 2
  neg
  ...

function Bar.mult 2
  // Computes the product of
     the first two
  // arguments and puts the
     result in local 1
  ...
  push local 1   // return value
  return
```

callee

- Before start executing, my argument segment has been initialized with the argument values passed by the caller
- My local variables segment has been allocated and initialized to zeros
- My static segment has been set to the static segment of the VM file to which I belong

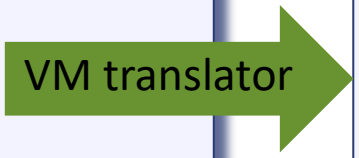
  (memory segments this, that, pointer, and temp are undefined upon entry)
- My stack is empty
- Before returning, I must push a value onto the stack.

blue: must be handled by the VM implementation

# The VM implementation view

VM code

```
function Foo.main 4
  ...
  // computes –(19 * (local 3))
  push constant 19
  push local 3
  call Bar.mult 2
  neg
  ...

function Bar.mult 2
  // Computes the product of
     the first two
  // arguments and puts the
     result in local 1
  ...
  push local 1   // return value
  return
```




Generated assembly code

```
(Foo.main)          // created and plugged by the translator
    // assembly code that handles the initialization of the
    // function's execution
    ...
    // assembly code that handles push constant 19
    // assembly code that handles push local 3
    // assembly code that saves the caller's state on the stack,
    // sets up for the function call, and then:
    goto Bar.mult     // (in assembly)
(Foo$ret.1)         // created and plugged by the translator
    // assembly code that handles neg
    ...
(Bar.mult)          // created and plugged by the translator
    // assembly code that handles the initialization of the
    // function's execution
    ...
    // assembly code that handles push local 1
    // Assembly code that gets the return address (which happens
    // to be Foo$ret.1) off the stack, copies the return value to
    // the caller, reinstates the caller's state, and then:
    goto Foo$ret.1    // (in assembly)
```

psuedocode!

# Outlines

- Introduction to virtual machine
- VM abstraction
- VM implementation
- VM translator

# Implementation

## Proposed design:

- Parser: parses each VM command into its lexical elements,
- CodeWriter: writes the assembly code that implements the parsed command,
- Main: drives the process (VMTranslator).

## Main (VMTranslator)

- Input: *fileName*.vm,
- Output: *fileName*.asm.

## Main logic:

- Construct a Parser to handle the input file,
- Construct a CodeWriter to handle the output file,
- March through the input file, parsing each line and generating code from it.

# Parser

- Handle the parsing of a single .vm file,
- Read a VM command, parse the command into its lexical components, and provide convenient access to these components,
- Ignore all white space and comments.

| **Routine** | **Arguments** | **Returns** | **Function** |
|---|---|---|---|
| Constructor | Input file / stream | — | Opens the input file/stream and gets ready to parse it. |
| `hasMoreCommands` | — | Boolean | Are there more commands in the input? |
| `advance` | — | — | Reads the next command from the input and makes it the *current command*. Should be called only if `hasMoreCommands()` is true. Initially there is no current command. |

# Parser

- Handle the parsing of a single .vm file,
- Read a VM command, parse the command into its lexical components, and provide convenient access to these components,
- Ignore all white space and comments.

| Routine | Arguments | Returns | Function |
|---|---|---|---|
| `commandType` | — | `C_ARITHMETIC`, `C_PUSH`, `C_POP`, `C_LABEL`, `C_GOTO`, `C_IF`, `C_FUNCTION`, `C_RETURN`, `C_CALL` | Returns a constant representing the type of the current command. `C_ARITHMETIC` is returned for all the arithmetic/logical commands. |
| `arg1` | — | string | Returns the first argument of the current command. In the case of `C_ARITHMETIC`, the command itself (`add`, `sub`, etc.) is returned. Should not be called if the current command is `C_RETURN`. |
| `arg2` | — | int | Returns the second argument of the current command. Should be called only if the current command is `C_PUSH`, `C_POP`, `C_FUNCTION`, or `C_CALL`. |

# CodeWriter

Generates assembly code from the parsed VM command:

| **Routine** | **Arguments** | **Returns** | **Function** |
|---|---|---|---|
| Constructor | Output file / stream | — | Opens the output file / stream and gets ready to write into it. |
| `writeArithmetic` | command (string) | — | Writes to the output file the assembly code that implements the given arithmetic command. |
| `WritePushPop` | command (`C_PUSH` or `C_POP`), `segment` (string), `index` (int) | — | Writes to the output file the assembly code that implements the given command, where command is either `C_PUSH` or `C_POP`. |
| Close | — | — | Closes the output file. |

# Booting

## VM program convention

- One file in any **VM program** is expected to be named Main.vm;
- One **VM function** in this file is expected to be named main.

## VM implementation conventions

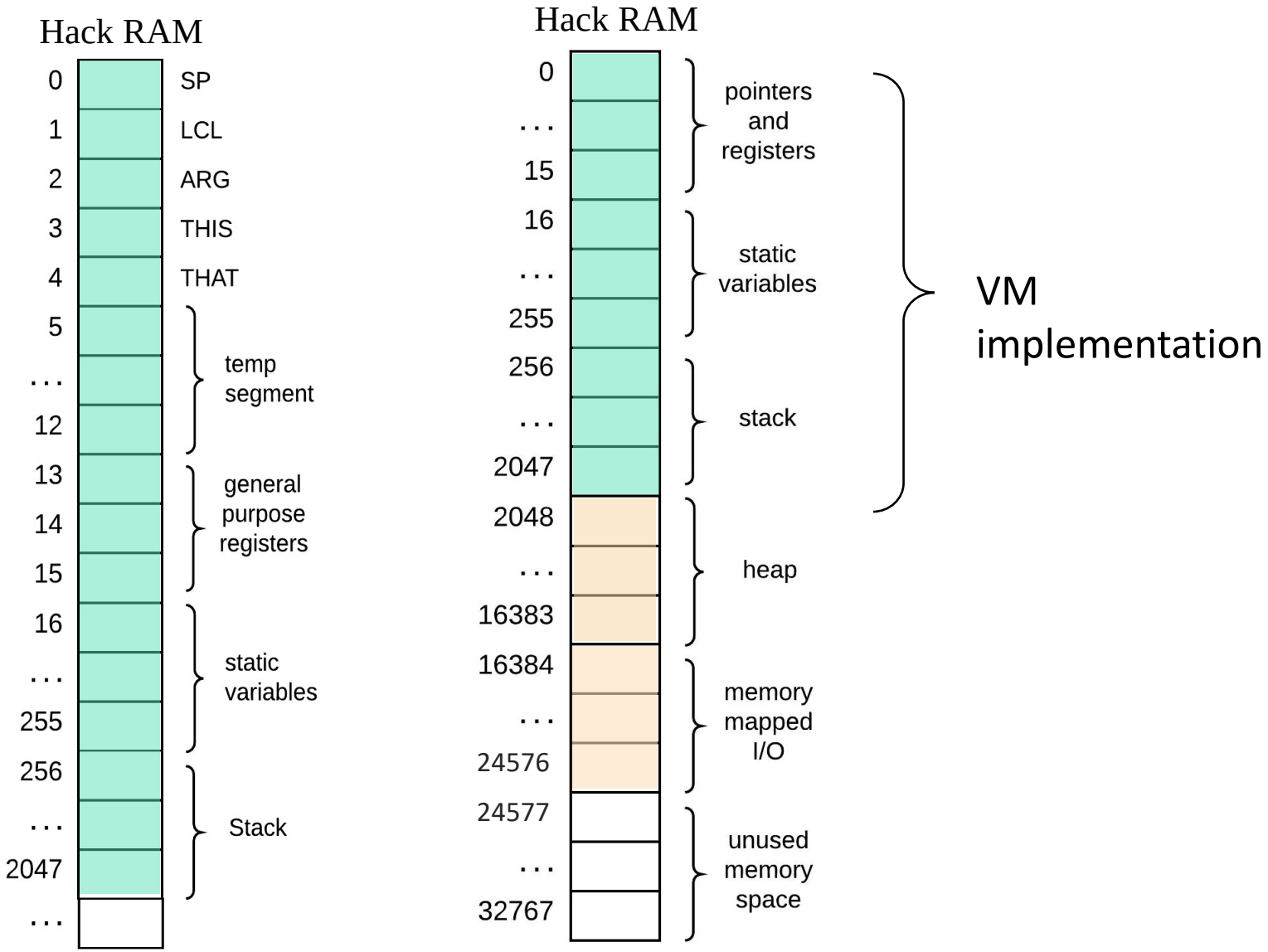
- The stack starts in address 256 in the host RAM,
- When the VM implementation starts running, or is reset, it starts executing an argument-less OS function named **Sys.init**,
- **Sys.init** is designed to call **Main.main**, and then enter an infinite loop.

## These conventions are realized by the following code:

```
// Bootstrap code (should be
   written in assembly)
SP = 256
call Sys.init
```

In the Hack platform, this code should be put in the ROM, starting at address 0

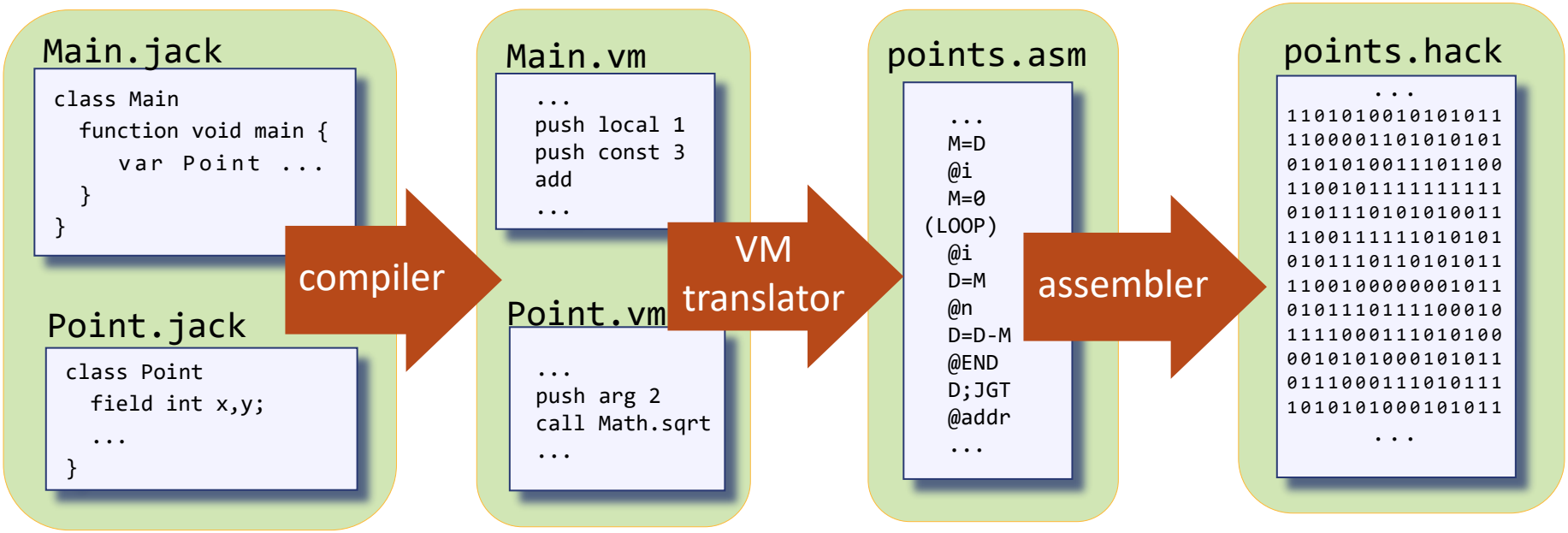
# Standard mapping of the VM on the Hack platform



# Special symbols in translated VM programs

| *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 addresses within the host RAM of the virtual segments `local`, `argument`, `this`, and `that` of the currently running VM function. |
| `R13`–`R15` | These predefined symbols can be used for any purpose. |
| `Xxx.`*i* symbols | Each static variable *i* in file `Xxx.vm` is translated into the assembly symbol `Xxx.`*j*., where *j* is incremented each time a new static variable is encountered in the file `Xxx.vm`. In the subsequent assembly process, these symbolic variables will be allocated to the RAM by the Hack assembler. |
| *functionName* `$` *label* | Let `foo` be a function within a VM file `Xxx`. Each `label bar` command within `foo` should generate and insert into the assembly code stream a symbol `Xxx.foo$bar`.<br>When translating `goto bar` and `if-goto bar` commands (within `foo`) into assembly, the full label specification `Xxx.foo$bar` must be used instead of `bar`. |
| *functionName* | Each `function foo` command within a VM file `Xxx` should generate and insert into the assembly code stream a symbol `Xxx.foo` that labels the entry point to the function's code. In the subsequent assembly process, the assembler will translate this symbol into the physical memory address where the function code starts. |
| *functionName* `$ret.`*i* | Let `foo` be a function within a VM file `Xxx`.<br>Within `foo`, each function `call` command should generate and insert into the assembly code stream a symbol `Xxx.foo$ret.`*i*, where *i* is a running integer (one such symbol should be generated for each `call` command within `foo`).<br>This symbol serves as the return address to the calling function. In the subsequent assembly process, the assembler will translate this symbol into the physical memory address of the command immediately after the function call command. |

# Big picture


Main.jack
class Main
function void main {
var Point ...
}
}
Point.jack
class Point
field int x,y;
...
}
compiler
Main.vm
...
push local 1
push const 3
add
...
Point.vm
...
push arg 2
call Math.sqrt
...
VM translator
points.asm
...
M=D
@i
M=0
(LOOP)
@i
D=M
@n
D=D-M
@END
D;JGT
@addr
...
assembler
points.hack
...
1101010010101011
1100001101010101
0101010011101100
1100101111111111
0101110101010011
1100111111010101
0101110110101011
1100100000001011
0101110111100010
1111000111010100
0010101000101011
0111000111010111
1010101000101011
...
load
points.hack
(4,6)
5
Hack

# Summary

- VM bridges the high-level programming language and the machine code.
- VM is implemented using stack
  - Arithmetic/logic operation
  - memeory segment
  - branching
  - function
- VM translator: VM code to assembly code
  - Stack
  - memory segment
  - Branching
  - function

# Acknowlegement


- This set of lecture notes are based on the lecture notes provided by Noam Nisam / Shimon Schocken.
- You may find more information on: www.nand2tetris.org.