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UK | CHINA | MALAYSIA

Virtual Machine

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Outlines

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

Hello World

Jack program

```
// First example in Programming 101
class Main {
    function void main() {
        do Output.printString("Hello World!");
        do Output.println(); // New line.
        return;
    }
}
```

abstraction

Issues:

- Program execution
- Writing on the screen
- Handling class, function ...
- Handling do, while, ...
- function call and return
- Operating system
- ...

Q: How can high-level programmers ignore all these issues?

A: They treat the high-level language as an ***abstraction***.



Hello World

Jack program

```
// First example in Programming 101
class Main {
    function void main() {
        do Output.printString("Hello World!");
        do Output.println(); // New line.
        return;
    }
}
```

abstraction

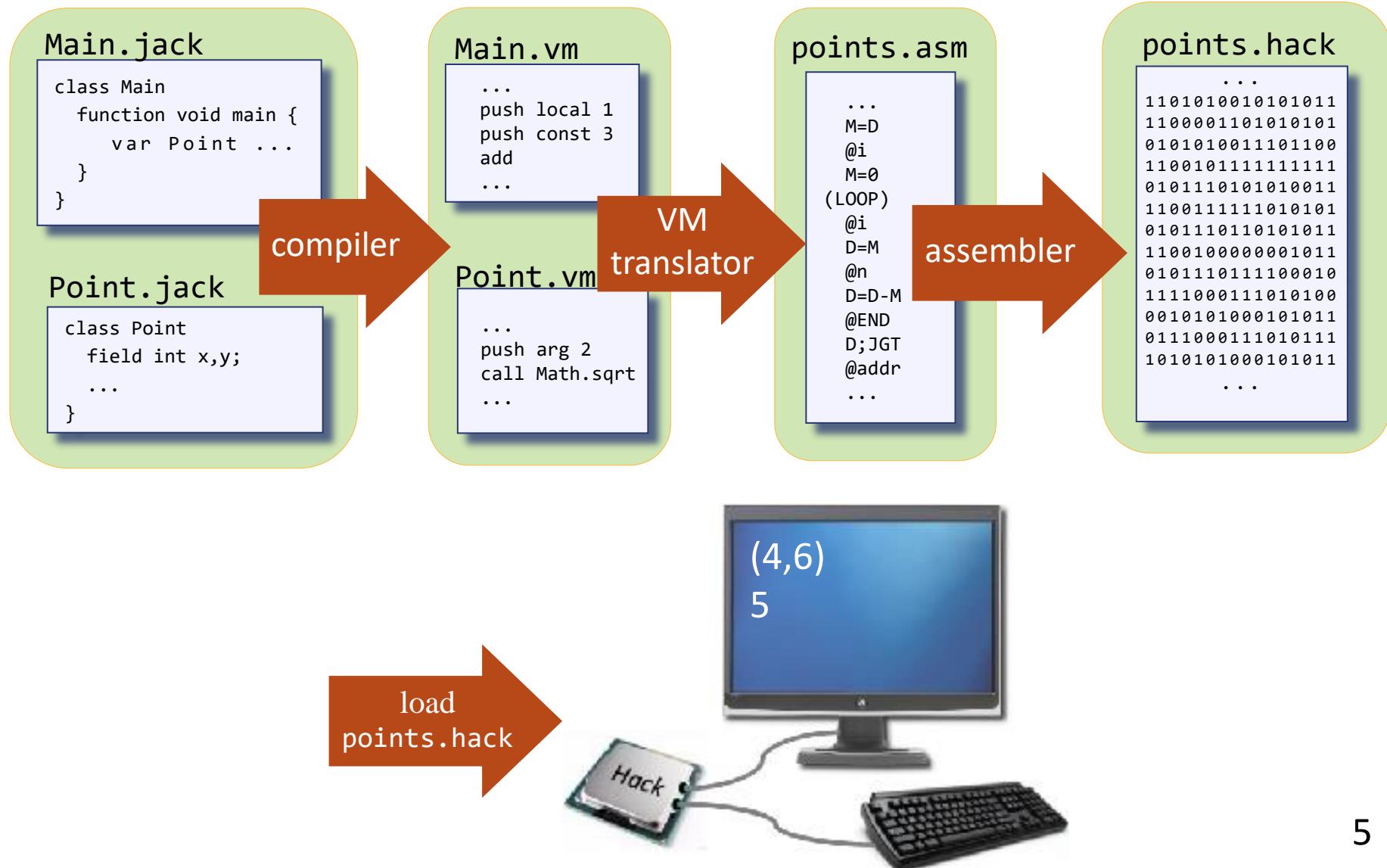
Issues:

- Program execution
- Writing on the screen
- Handling class, function ...
- Handling do, while, ...
- function call and return
- Operating system
- ...

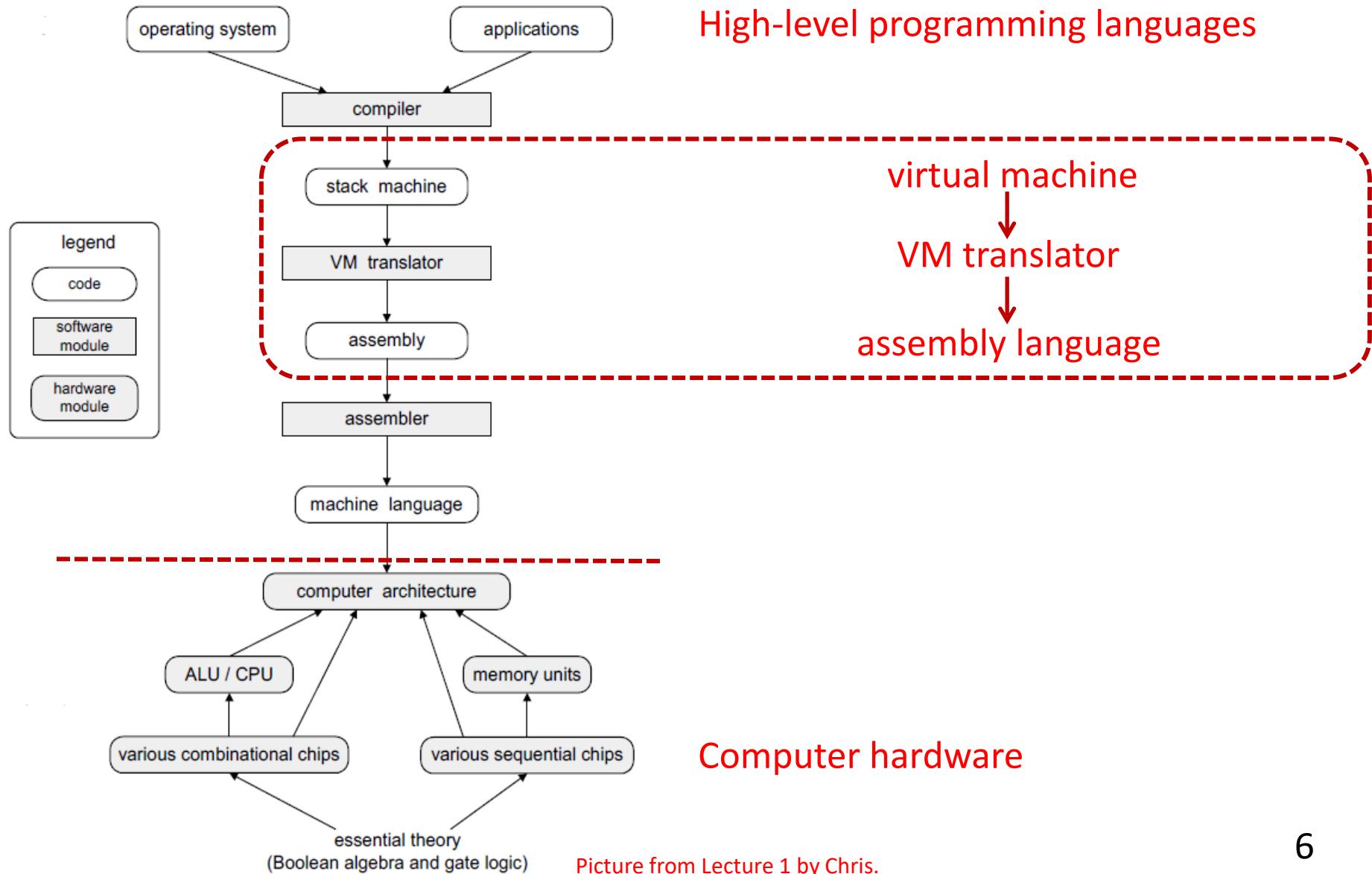
- Q: What makes the abstraction work?
- A:
 - Operating system,
 - Compiler,
 - Virtual machine,
 - Assembler.



From high-level to low-level



Overview of computer system



What is virtual machine?

- “*The VM is an abstract computer that does not exist for real, but can rather be realized on other computer platforms.*” Nisan & Schocken.
- Keywords: abstract computer.
 - Not a real computer, a virtual computer.
 - A universal computer, can run on many kinds of real computers.

Examples of virtual machine

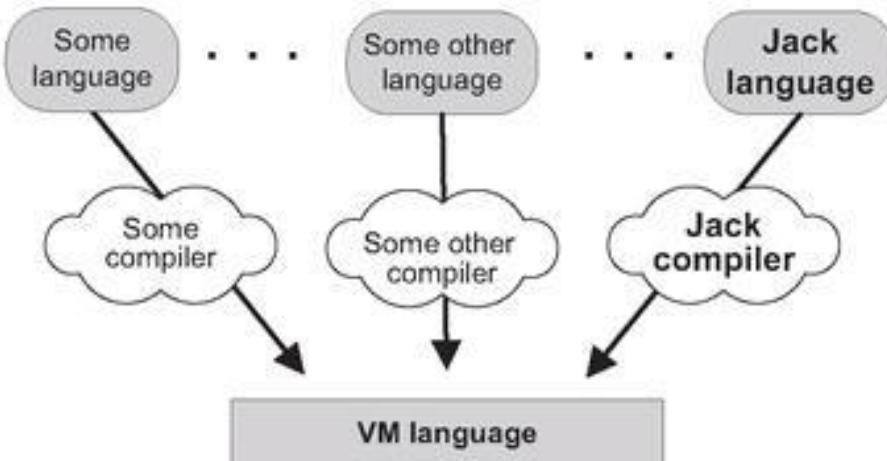
- Java:
 - Java virtual machine (JVM), main component of Java architecture, part of Java Running Environment.
- .NET infrastructure
 - CLR (Common Language Runtime).

Why we need virtual machine?

- **Code transportability**
 - Many high-level languages can work on the same platform: virtual machine.
 - VM may be implemented with relative ease on multiple target platforms.
 - As a result, VM-based software can run on many processors and operating systems without modifying source code.

Virtual machine paradigm

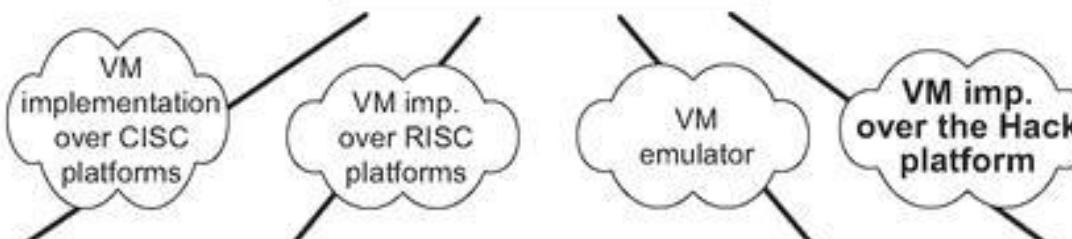
M high-level languages



Many high-level languages

Compiler

One virtual
machine language



VM translator

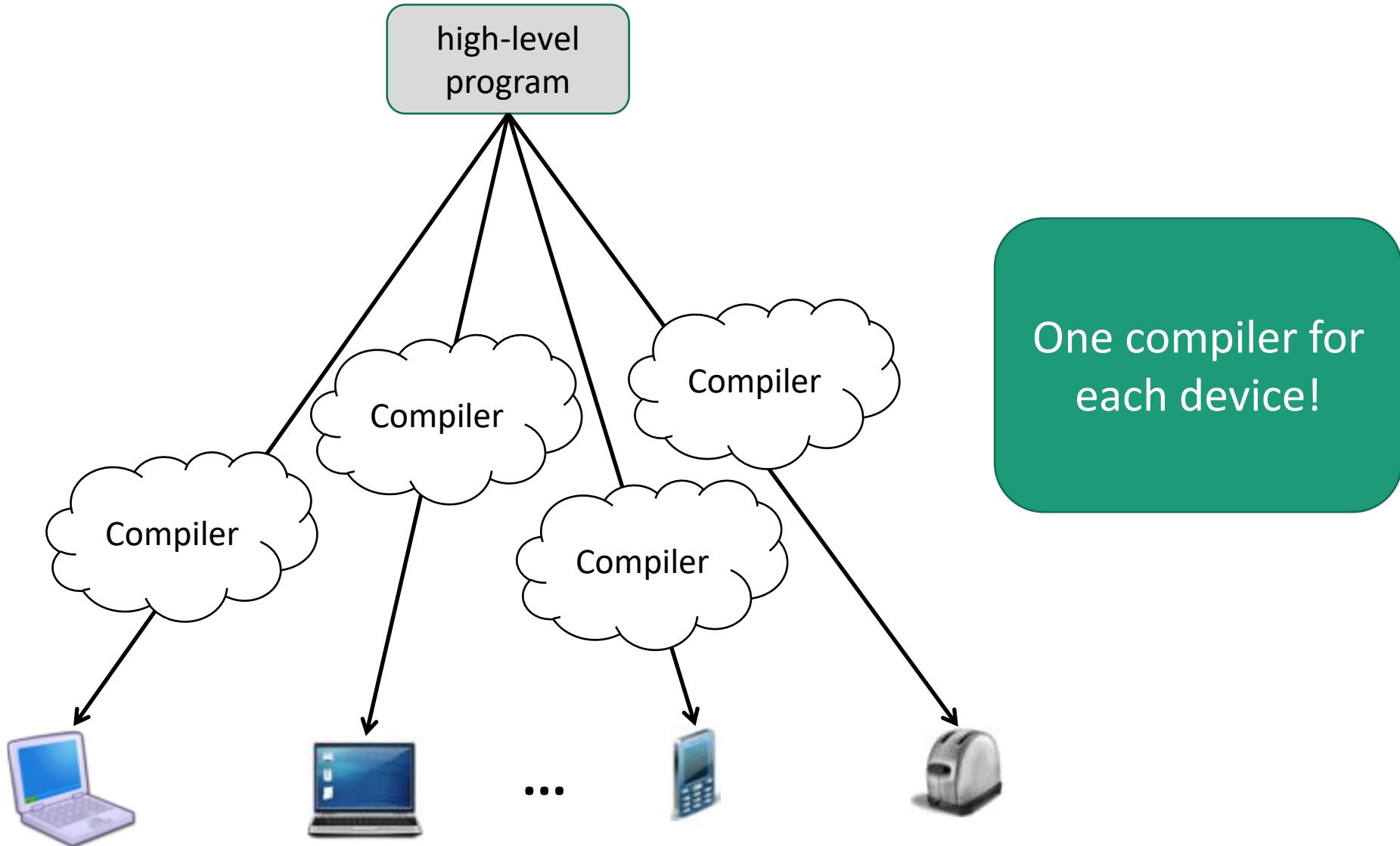
N machine
languages



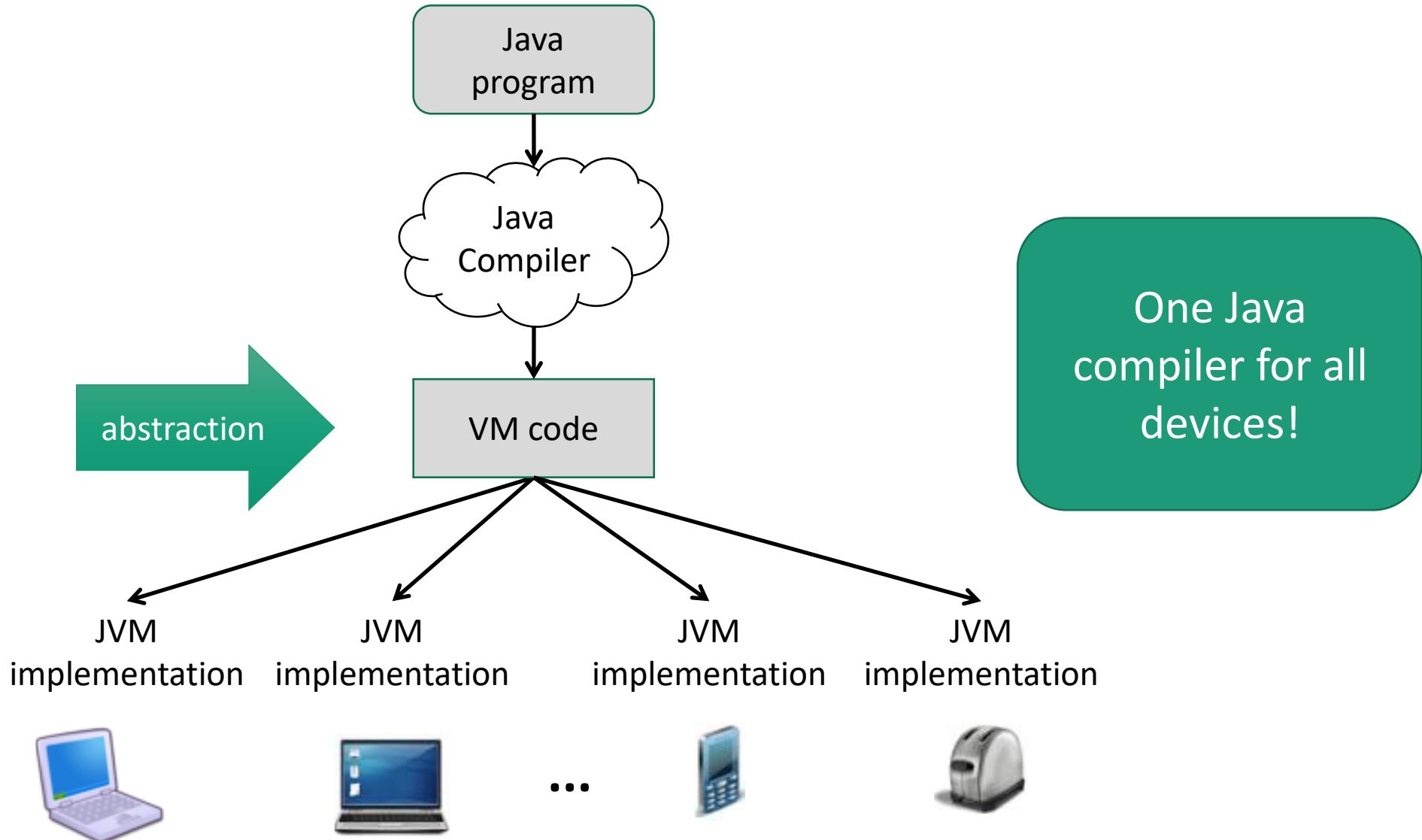
Machine language

Many computer
hardwares

Program compilation: 1-tier



Program compilation: 2-tier

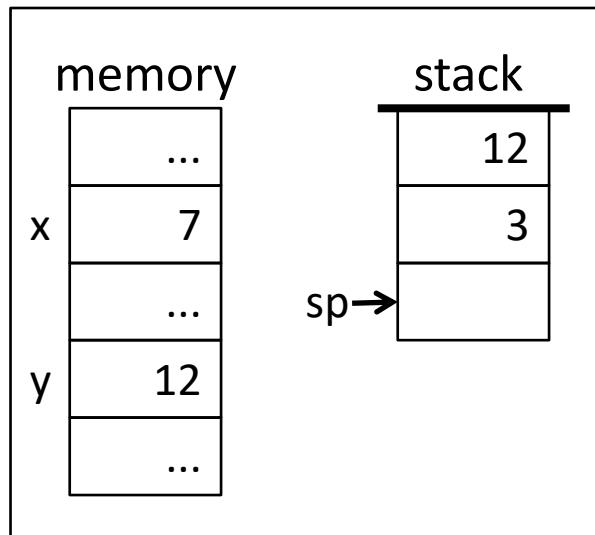


Stack machine model

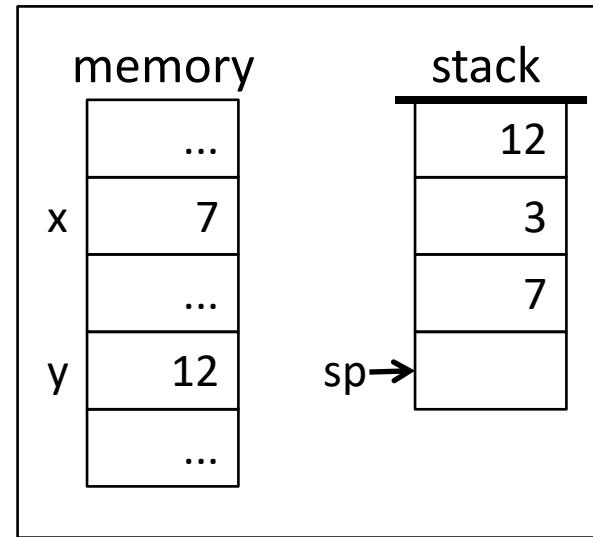
- Question: where will the operands and the results of the VM operations reside?
- Answer: put them on a stack data structure.
- Stack:
 - push: add an element at the stack's **top**.
 - pop: remove the **top** element.



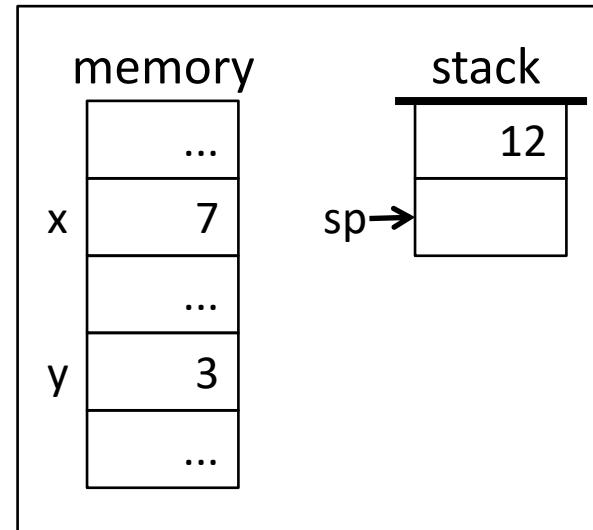
Stack



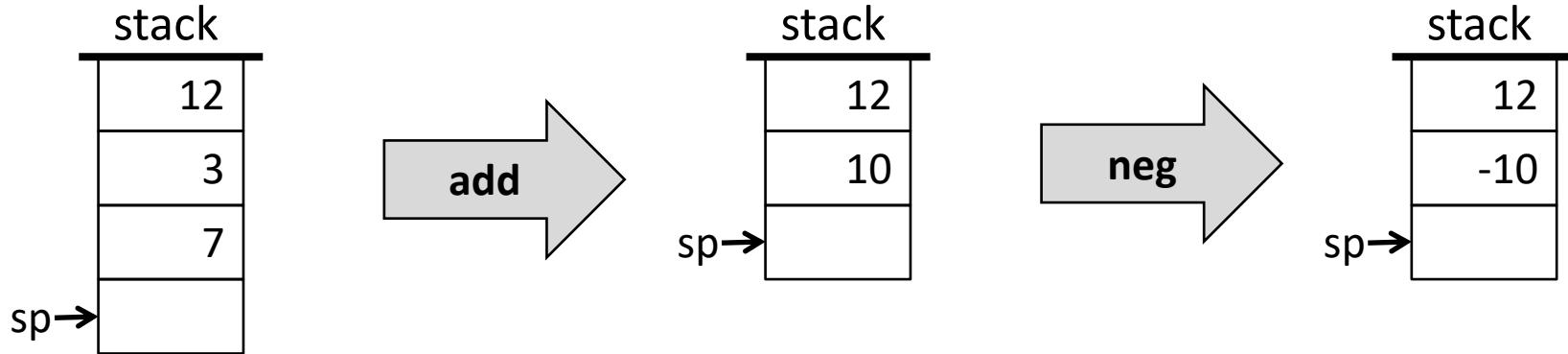
push x



pop y

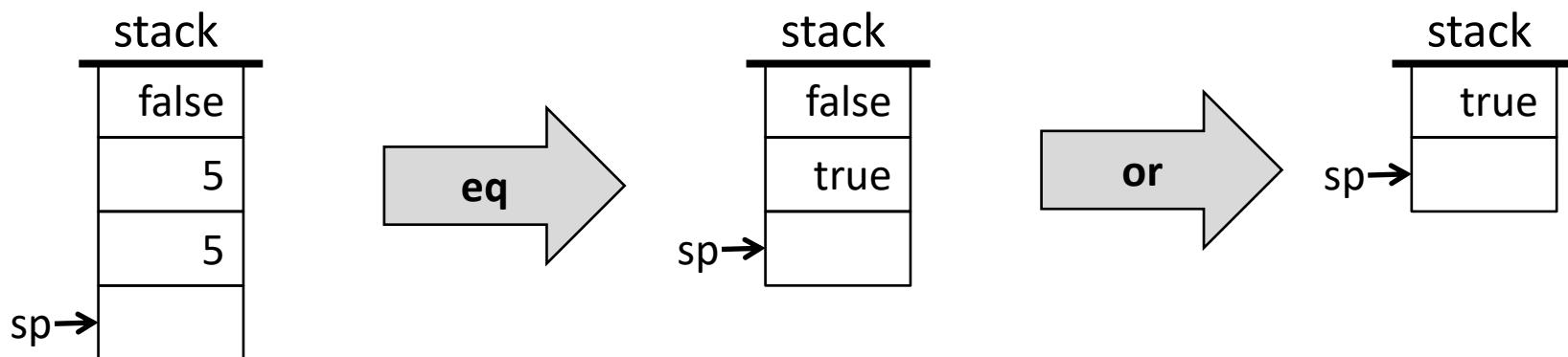


Stack arithmetic

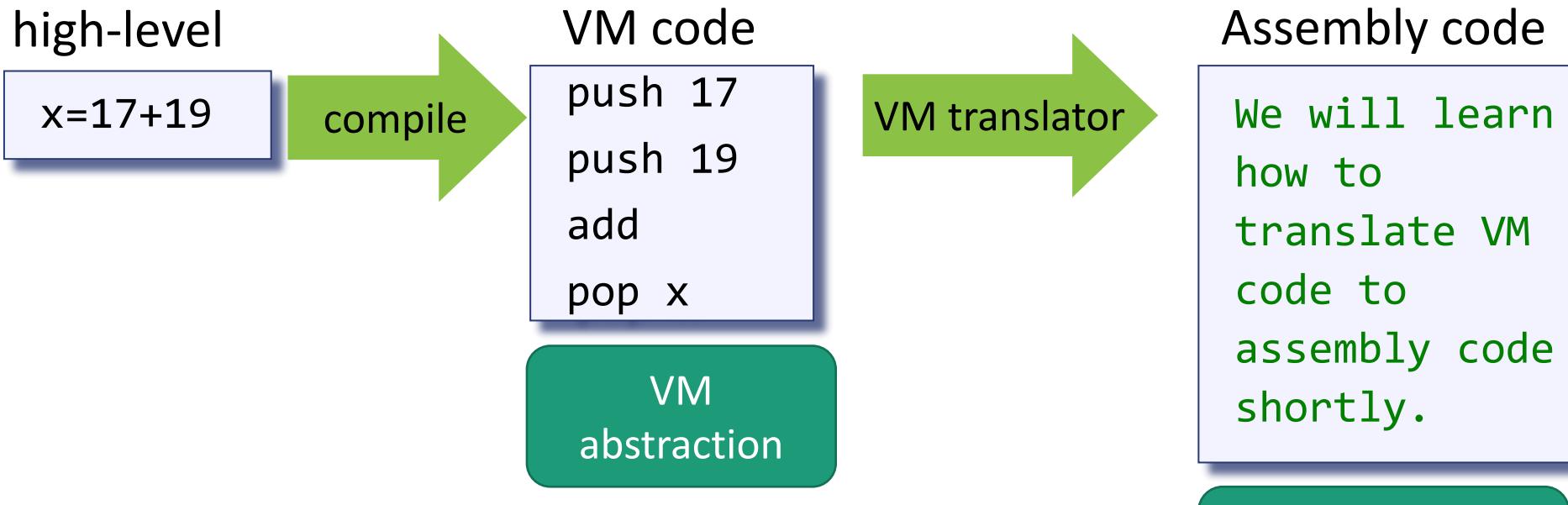


Applying a function f on the stack:

- **Pop** the argument(s) from the stack
- Compute f on the arguments
- **Push** the result onto the stack.



Virtual machine (big picture)



Abstraction / implementation

- The high-level language is an abstraction;
- It can be implemented by a stack machine.
- The stack machine is also an abstraction;
- It can be implemented by assembly code.

Outlines

- Introduction to virtual machine
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 - Arithmetic / logical commands
 - Memory segment commands
 - Branching commands
 - Function commands
- VM implementation
- VM translator

Arithmetic commands

VM code

```
// d=(2-x) +
// (y+9)
```

push 2

push x

sub

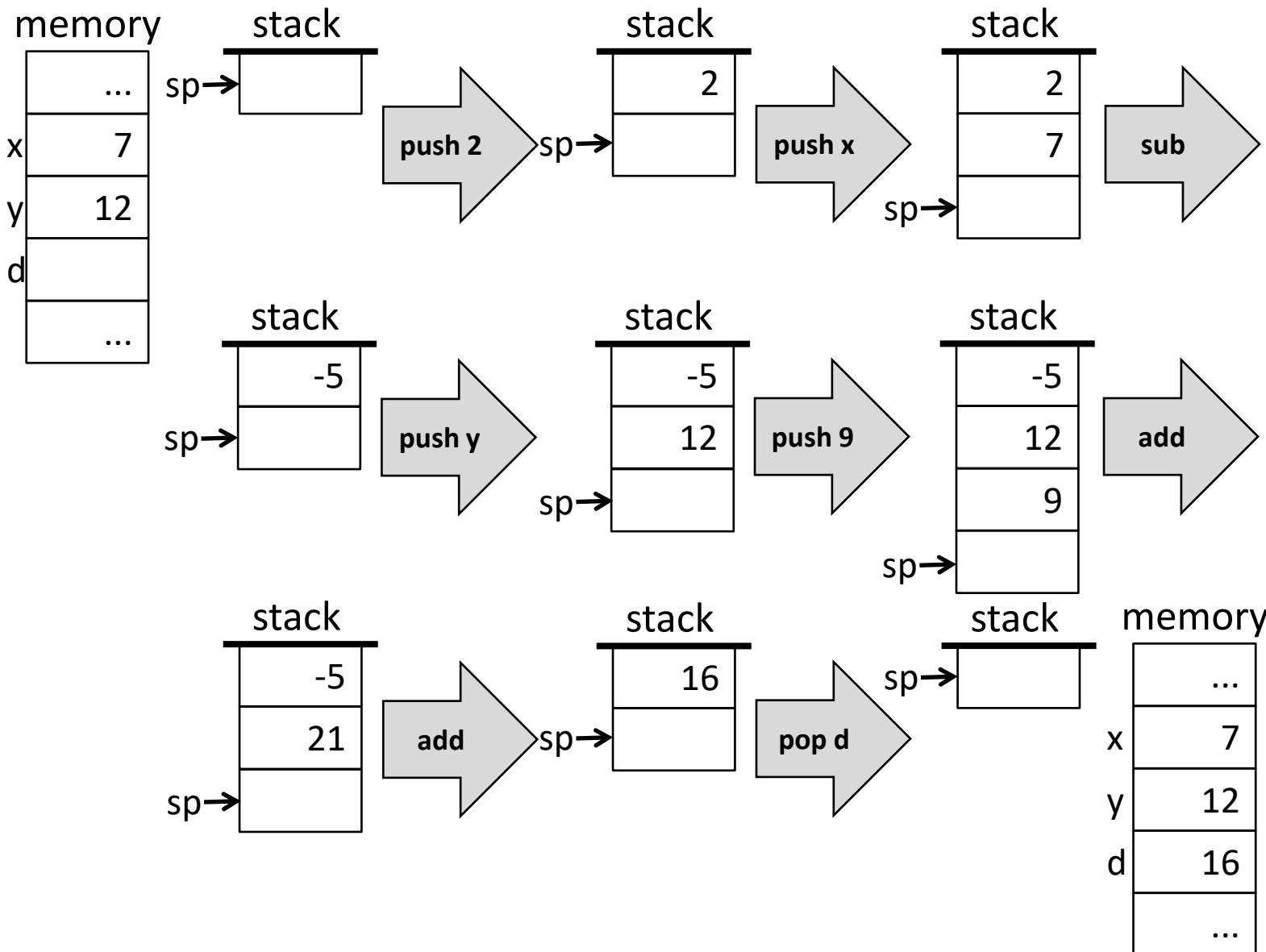
push y

push 9

add

add

pop d



Quiz: arithmetic commands

VM code

// d=(x-5) -

// (y-6)

push x

push 5

sub

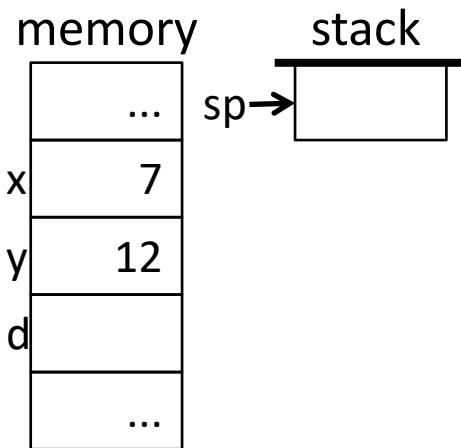
push y

push 6

sub

sub

pop d



Complete the stack operation as last example
and write down each key step.

Answer: arithmetic commands

VM code

// d=(x-5) -

// (y-6)

push x

push 5

sub

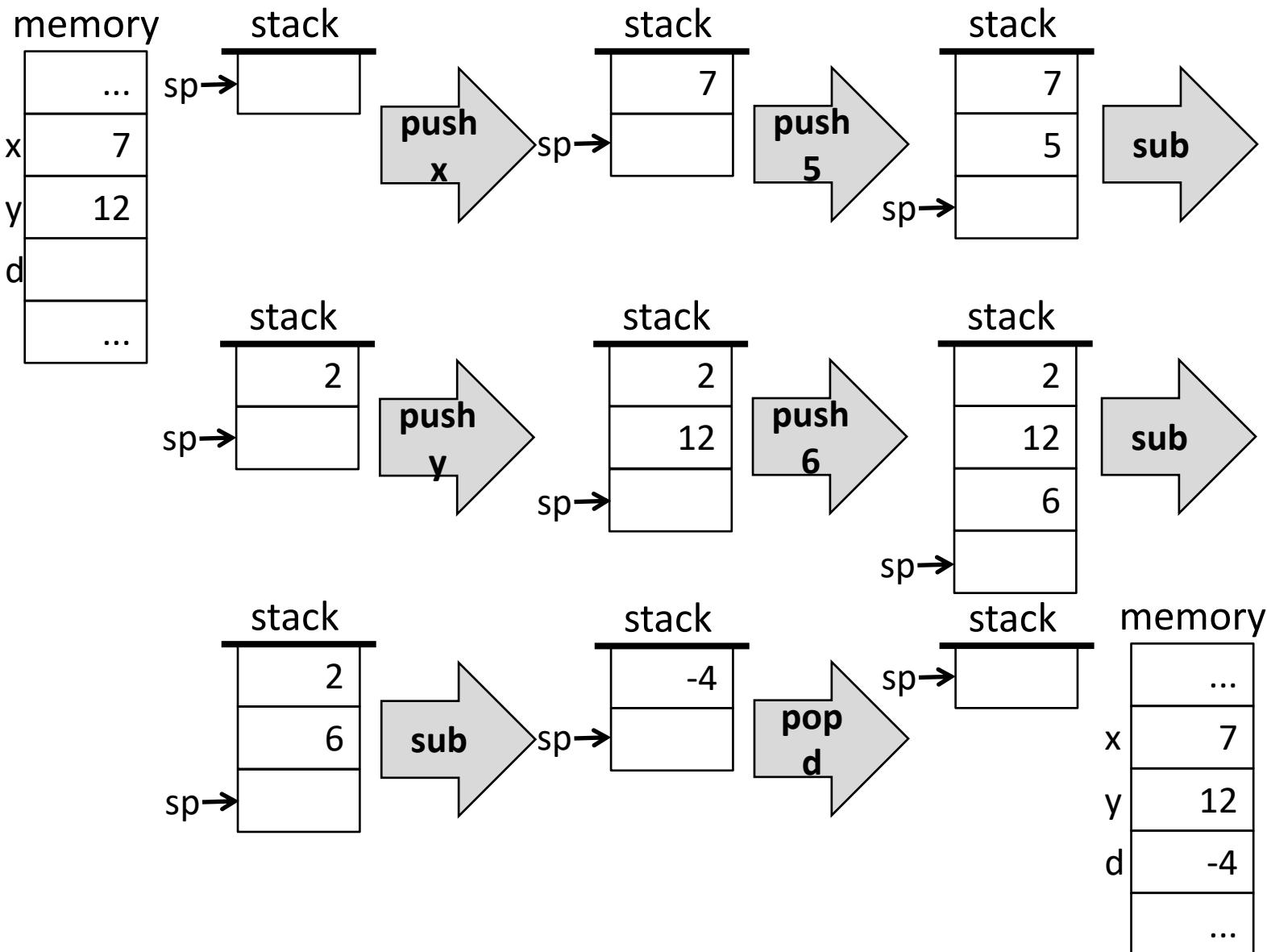
push y

push 6

sub

sub

pop d



Logical commands

VM code

// (x<7)

// or

// (y==8)

push x

push 7

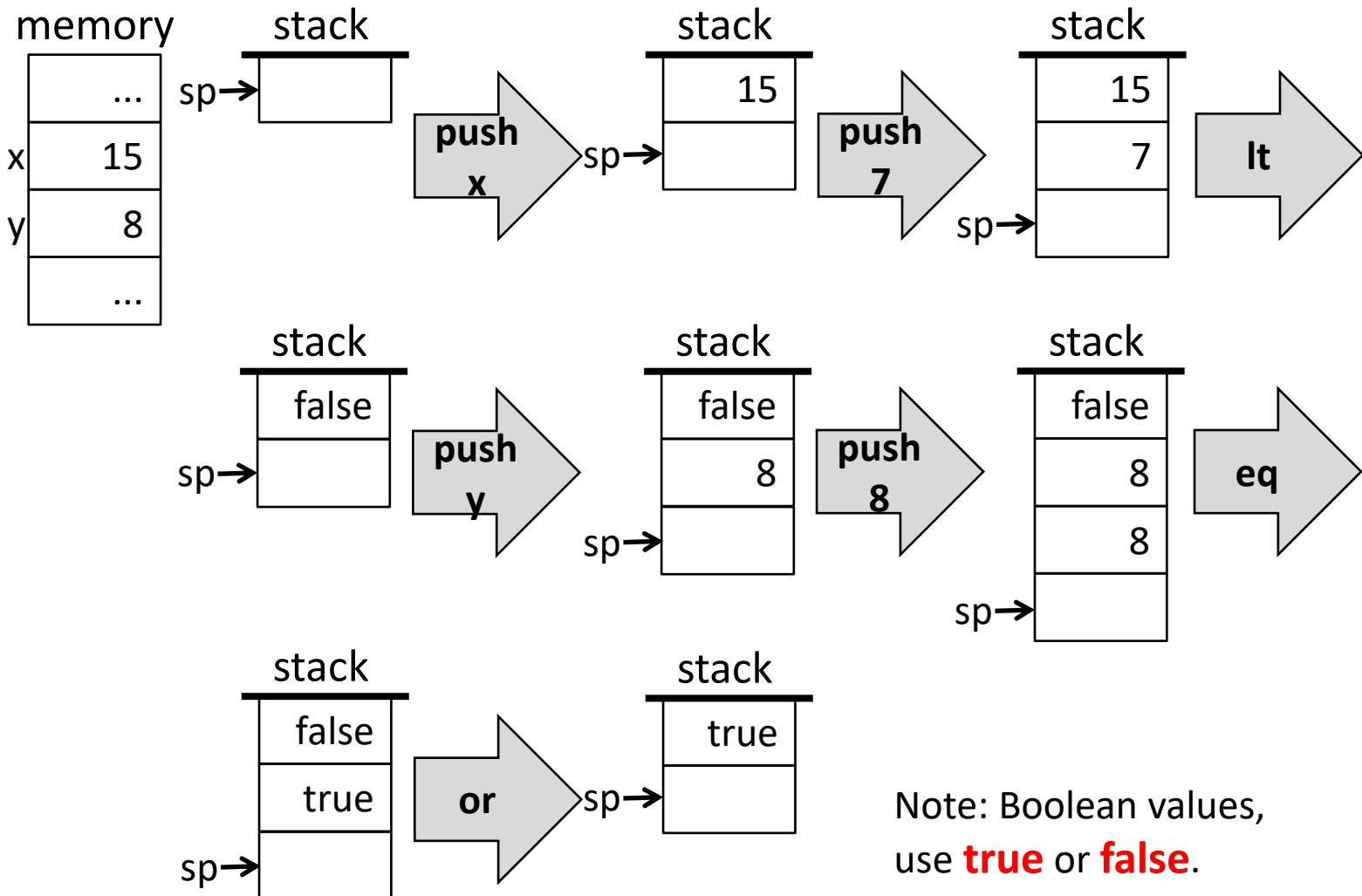
lt

push y

push 8

eq

or



Note: Boolean values,
use **true** or **false**.
Do not use 1 or 0.

Quiz: logical commands

VM code

// (x>7)

// and

// (y>7)

push x

push 7

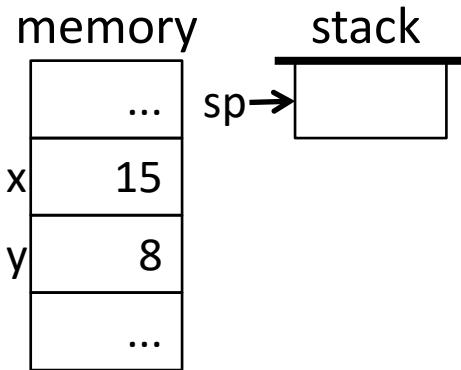
gt

push y

push 7

gt

and



Complete the stack operation as last example
and write down each key step.

Answer: logical commands

VM code

// (x>7)

// and

// (y>7)

push x

push 7

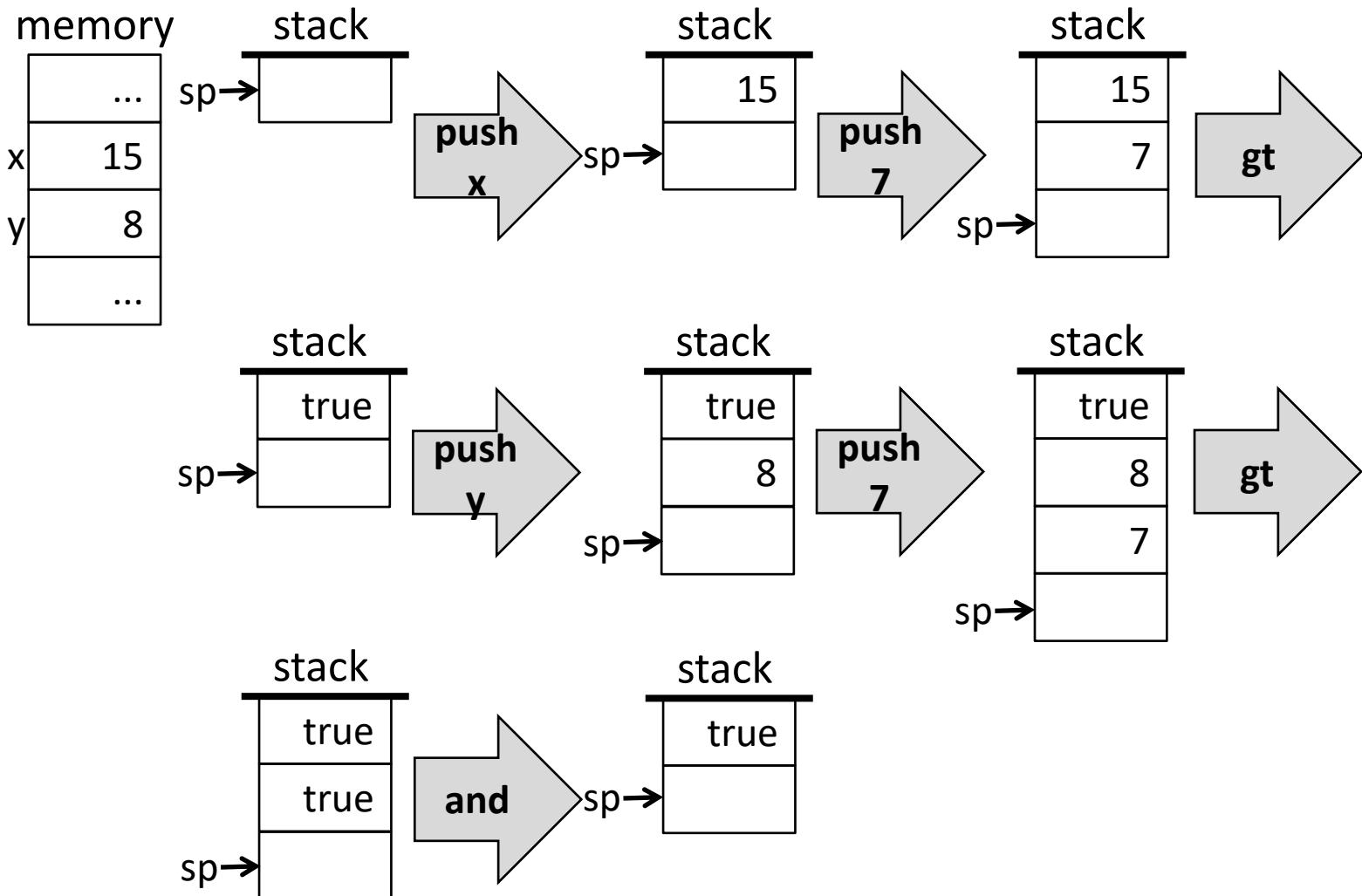
gt

push y

push 7

gt

and



Arithmetic / Logical commands

Command	Return value	Return value
add	$x + y$	integer
sub	$x - y$	integer
neg	$-y$	integer
eq	$x == 0$	boolean
gt	$x > y$	boolean
lt	$x < y$	boolean
and	x and y	boolean
or	x or y	boolean
not	not x	boolean

Observation: Any arithmetic or logical expression can be expressed and evaluated by applying some sequence of the above operations on a stack.

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Variable kinds and memory segments

Source code (Jack)

```
class Foo {  
    static int s1, s2;  
    function int bar (int x, int y) {  
        var int a, b, c;  
        let c = s1 + y;  
        ...  
    }  
}
```

compile

Compiled VM code

```
...  
...  
...  
...  
push s1  
push y  
add  
pop c  
static 0  
argument 1  
local 2  
...
```

Following compilation, all the symbolic references are replaced with references to virtual memory segments.

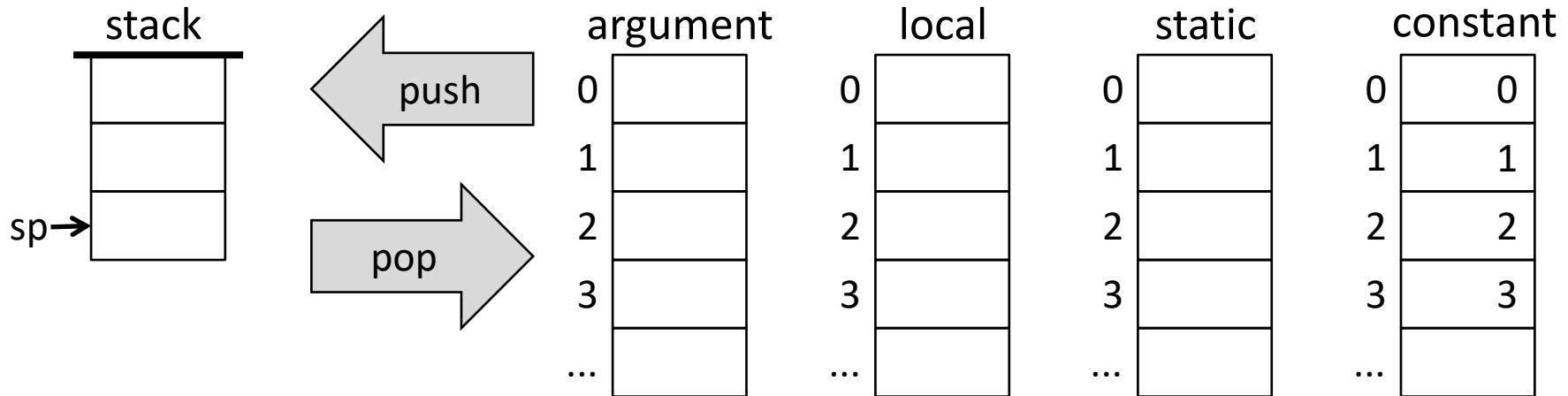
Variable kinds

- Argument variables
 - Local variables
 - Static variables
- (More kinds later)

Virtual memory segments:

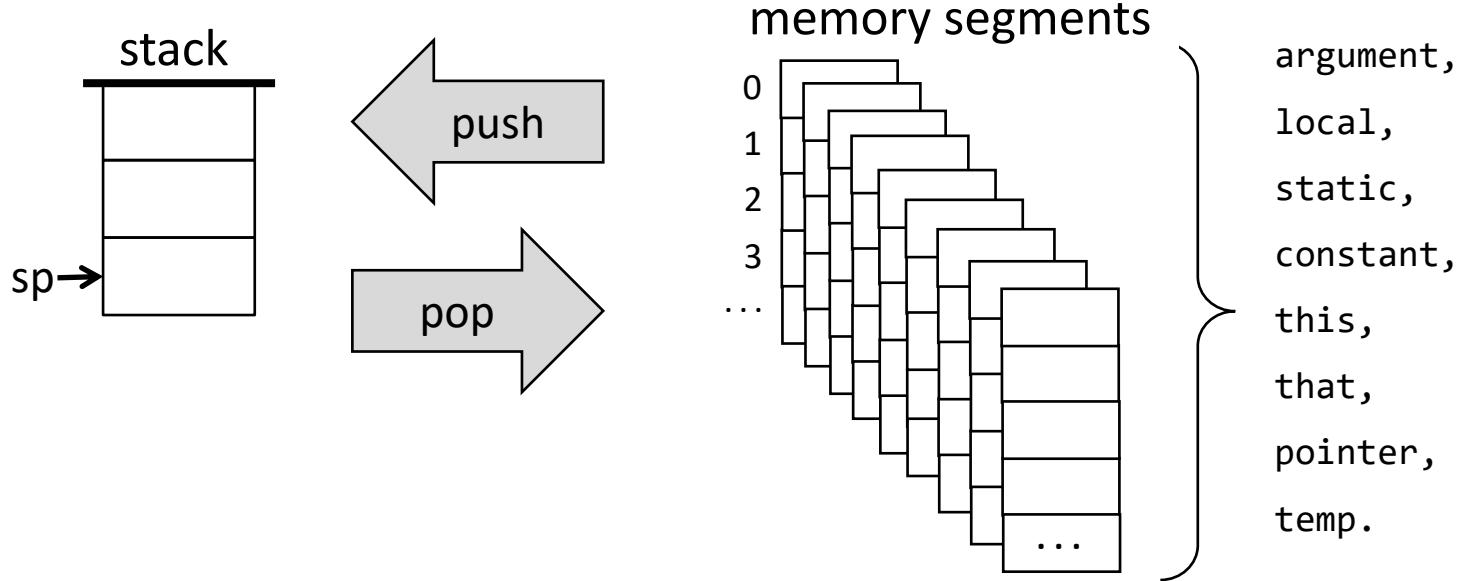
	argument	local	static	
0	x	0	a	0
1	y	1	b	1
2		2	c	2
3		3		3
...	

Memory segments



- Syntax: push / pop segment i
- Examples:
 - push constant 17
 - pop local 2
 - pop static 5
 - push argument 3

Memory segments



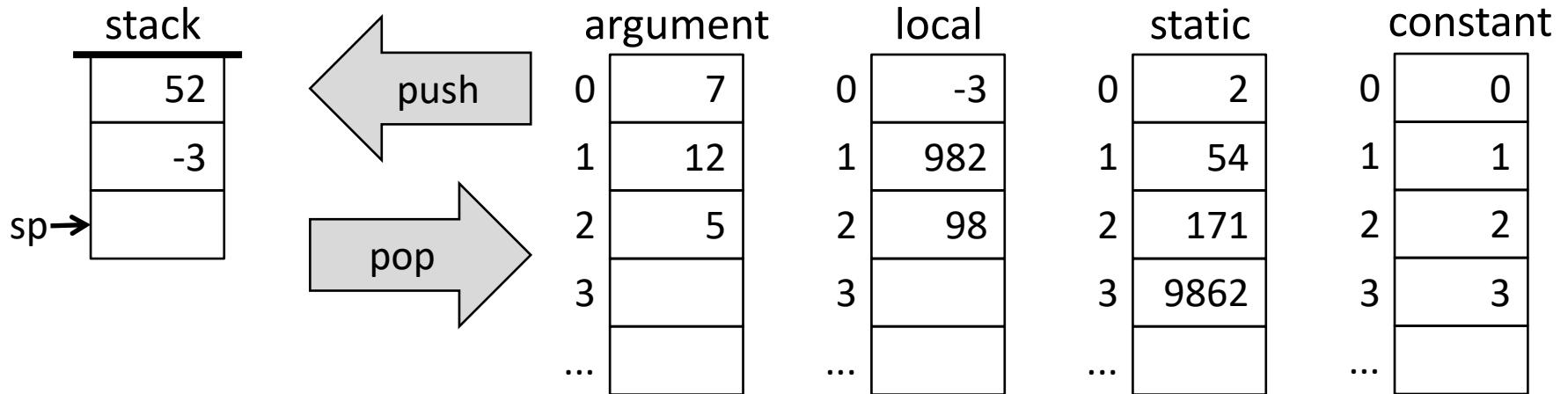
Syntax: *push segment i*

where *segment* is: argument, local, static, **constant**,
this, that, pointer, or temp
and *i* is a non-negative integer.

Syntax: *pop segment i*

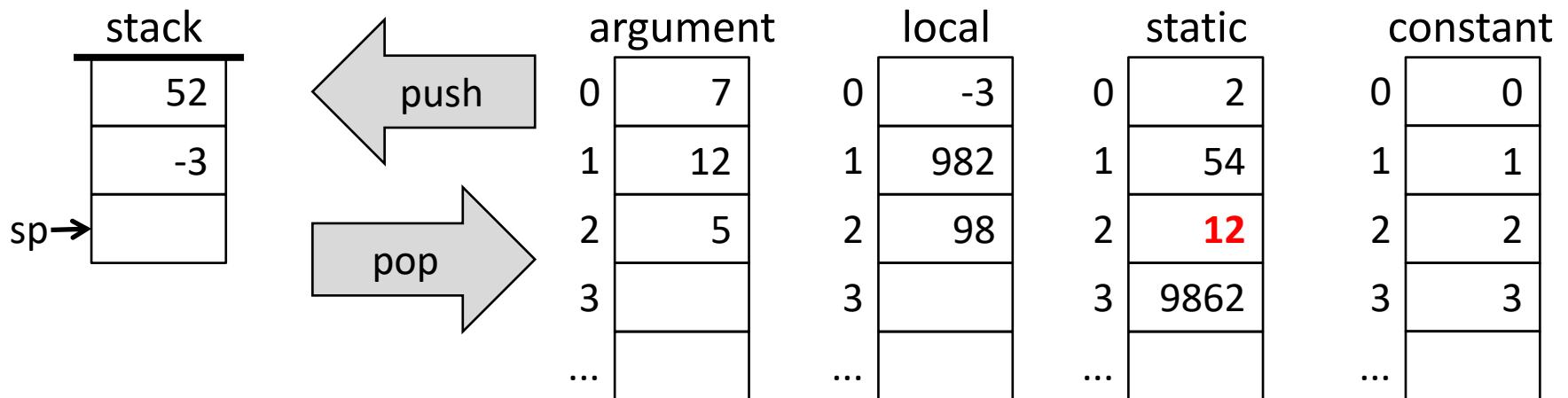
Where *segment* is: argument, local, static,
this, that, pointer, or temp
and *i* is a non-negative integer.

Memory segment commands

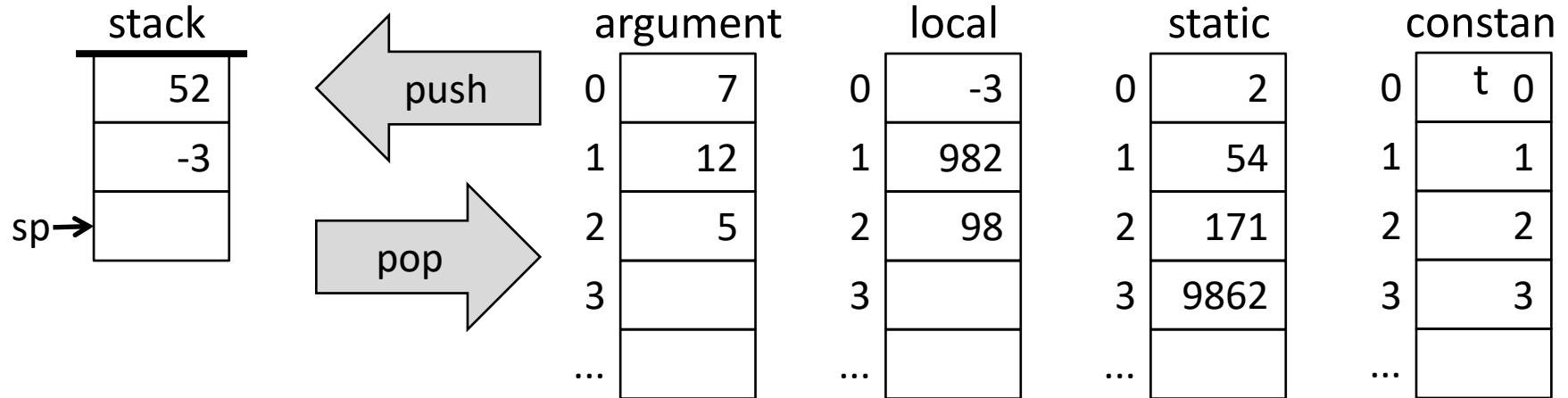


let static 2 = argument 1

push argument 1
pop static 2



Quiz: memory segment commands

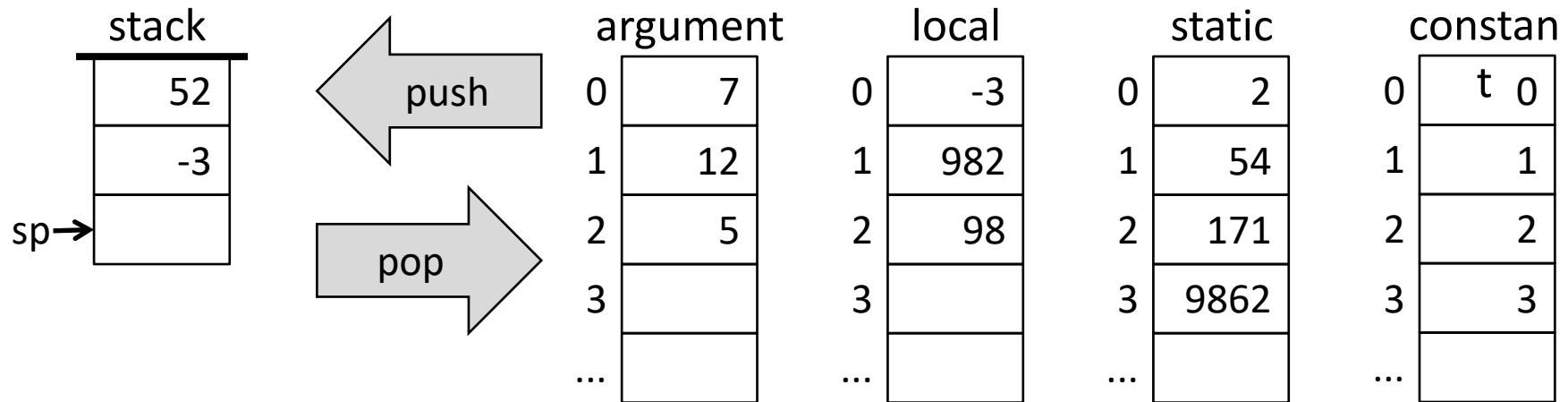


let local 2 = argument 1

How do stack and memory segments change?

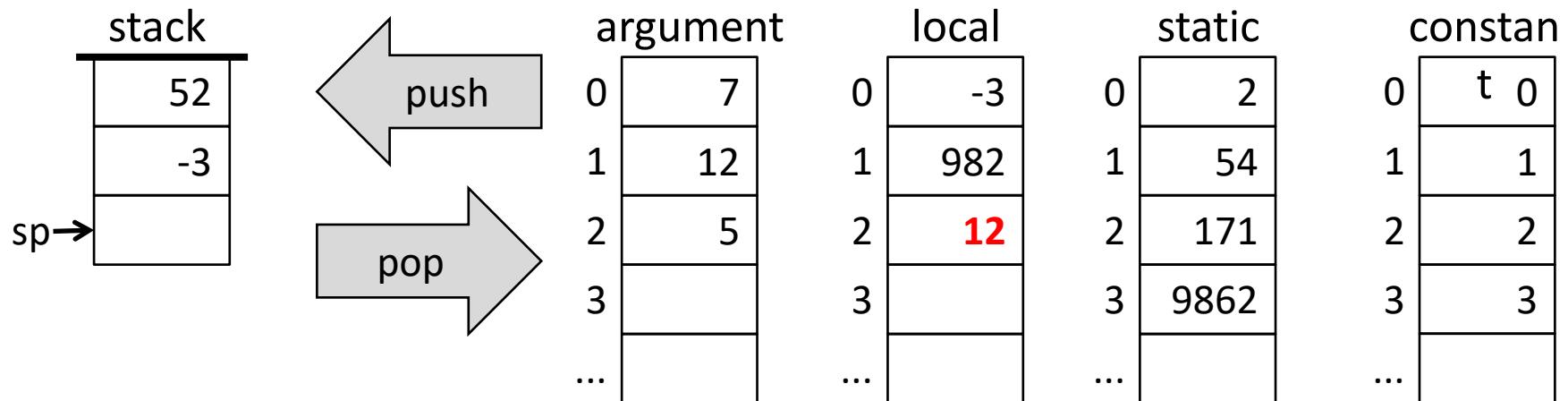
Please write down the key steps for stack operation and memory changes, similarly as last example.

Answer: memory segment commands



let local 2 = argument 1

push argument 1
pop local 2



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Program control

High-level code

```
if !(a==0)
    x=(-b+sqrt(disc(a,b,c)))/(2*a);
else
    x=-c/b;
// code continues
```

compiler

VM code (pseudo)

```
push a
push 0
eq
not
if-goto A_NEQ_ZERO
// We get here if a==0
push c
neg
push b
call div
pop x
goto CONTINUE
label A_NEQ_ZERO
// We get here if !(a==0)
push b
neg
push a
push b
push c
call disc
call sqrt
add
push 2
push a
call mult
call div
pop x
label CONTINUE
// code continues
```

branching

function calls

Program control

VM branching commands:

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

VM function commands:

- `call function`
- `function function`
- `return`

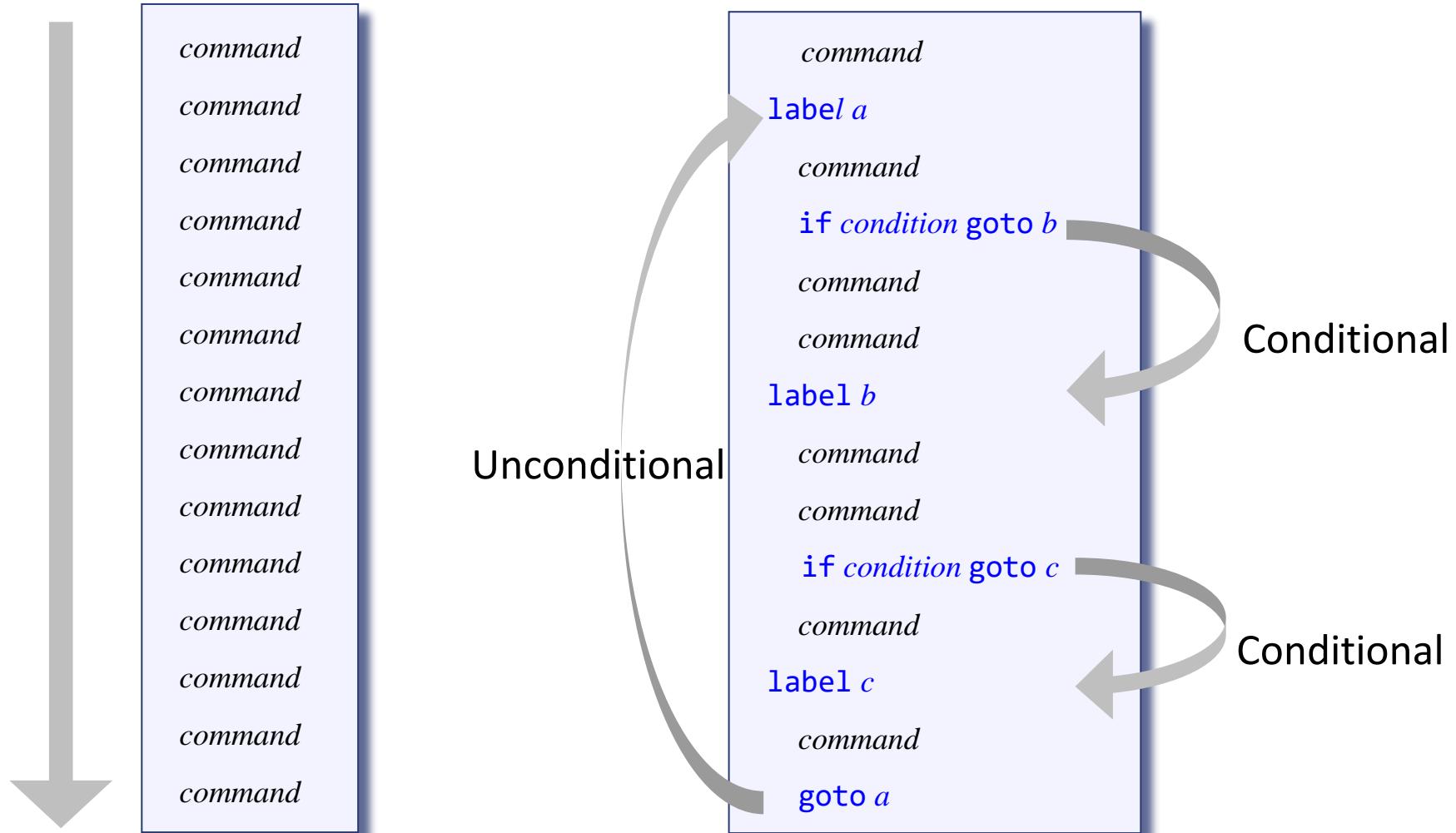
Challenges:

- Understand what the commands do (abstraction),
- Realize the commands on the host platform (implementation).

VM code (pseudo)

```
push a
push 0
eq
not
if-goto A_NEQ_ZERO
// We get here if a==0
push c
neg
push b
call div
pop x
goto CONTINUE
label A_NEQ_ZERO
// We get here if !(a==0)
push b
neg
push a
push b
push c
call disc
call sqrt
add
push 2
push a
call mult
call div
pop x
label CONTINUE
// code continues
```

Branching



Branching

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;
}
```



Pseudo VM code

```
function mult(x,y)
    push 0
    pop sum
    push 1
    pop n
    label WHILE_LOOP
    push n
    push y
    gt
    if-goto ENDLOOP
    push sum
    push x
    add
    pop sum
    push n
    push 1
    add
    pop n
    goto WHILE_LOOP
    label ENDLOOP
    push sum
    return
```

Conditional branching:

if-goto label

VM logic:

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

(**Require pushing the condition to the stack before the if-goto command**)

unconditional
branching

Recap

- *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):
 - Translate each branching command into assembly instructions that effect the specified operation on the host machine.

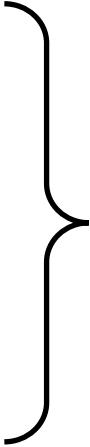
The assembly language has similar branching commands.

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Functions

- High-level programming languages can be extended using:

- Subroutines
 - Functions
 - Procedures
 - Methods
- 
- functions

(different names of the same thing)

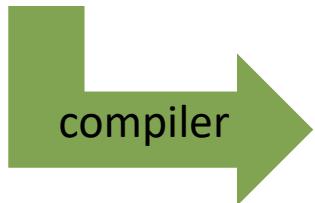
Functions in VM language

High-level program

```
...  
sqrt(x - 17 + x * 5)  
...
```

Pseudo VM

```
...  
push x  
push 17  
sub  
push x  
push 5  
call Math.multiply  
add  
call Math.sqrt  
...
```



The VM language features:

- Primitive operations (fixed): add, sub, ...
- Abstract operations (extensible): multiply, sqrt, ...

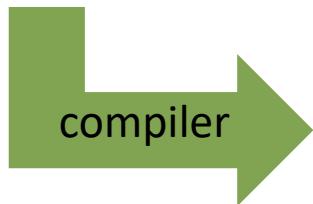
Programming style:

- Applying a primitive operator or calling a function have the same look-and-feel.

Functions in VM language: defining

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;
}
```



Pseudo VM code

```
function mult(x,y)
    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
```

Final VM code

```
function mult 2 // 2 local vars.
    push constant 0 // sum=0
    pop local 0
    push constant 1 // n=1
    pop local 1
    label LOOP
    push local 1 // if !(n>y)
    push argument 1 // goto END
    gt
    if-goto END
    push local 0 // sum+=x
    push argument 0
    add
    pop local 0
    push local 1 // n++
    push constant 1
    add
    pop local 1
    goto LOOP
label END
push local 0 // return sum
return
```

Functions in VM language: executing

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

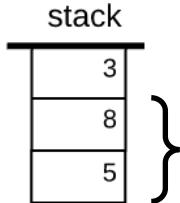
caller

```
// Computes the product of two given arguments
0 function mult 2 // 2 local vars used in this func.
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

main view:

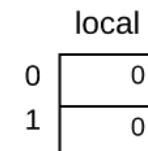
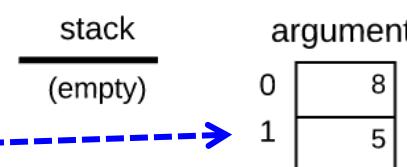
after line 3
is executed:



after line 4
is executed:

mult view:

after line 0
is executed:



Functions in VM language: executing

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

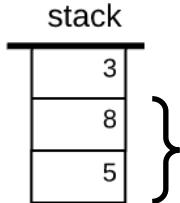
caller

```
// Computes the product of two given arguments
0 function mult 2 // 2 local vars used in this func.
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

main view:

after line 3
is executed:



after line 4
is executed:

return

mult view:

after line 0
is executed:

stack	argument	local
(empty)	0 8 1 5	0 0 1 0

after line 7
is executed:

stack	argument	local
1 5	0 8 1 5	0 0 1 1

after line 20
is executed:

stack	argument	local
40	0 8 1 5	0 40 1 6

Functions in VM language: executing

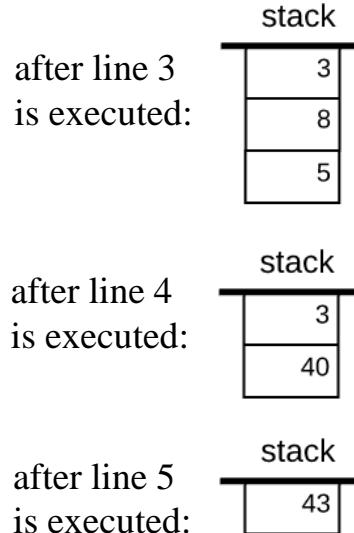
```
// Computes 3 +5 * 8
0 function main 0
1 push constant 3
2 push constant 8
3 push constant 5
4 call mult 2 // 2 args
5 add
6 return
```

caller

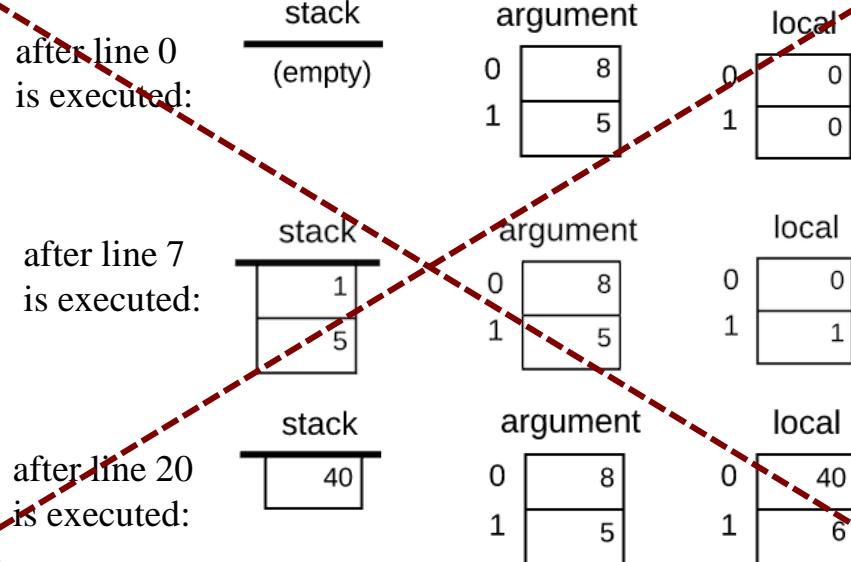
```
// Computes the product of two given arguments
0 function mult 2 // 2 local vars used in this func.
1 push constant 0
2 pop local 0
3 push constant 1
4 pop local 1
5 label LOOP
6 push local 1
7 push argument 1
//... computes the product into local 0
19 label END
20 push local 0
21 return
```

callee

main view:



mult view:



Functions in VM language: implementation

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

caller

```
// Computes the product of two given arguments
0 function mult 2 // 2 local vars used in this func.
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.

Functions in VM language: implementation

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

caller

```
// Computes the product of two given arguments
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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

Handling function call:

- Determine the **return address** within the *caller's* code;
- **Save** the *caller's* return address, stack and memory segments;
- **Pass parameters** from the *caller* to the *callee*;
- **Jump** to execute the *callee*.

Functions in VM language: implementation

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

caller

```
// Computes the product of two given arguments
0 function mult 2 // 2 local vars used in this func.
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

Handling function:

- Initialize the local variables of the *callee*;
- Handle some other simple initializations (later);
- Execute the *callee* function.

Functions in VM language: implementation

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

caller

```
// Computes the product of two given arguments
0 function mult 2 // 2 local vars used in this func.
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



Handling return:

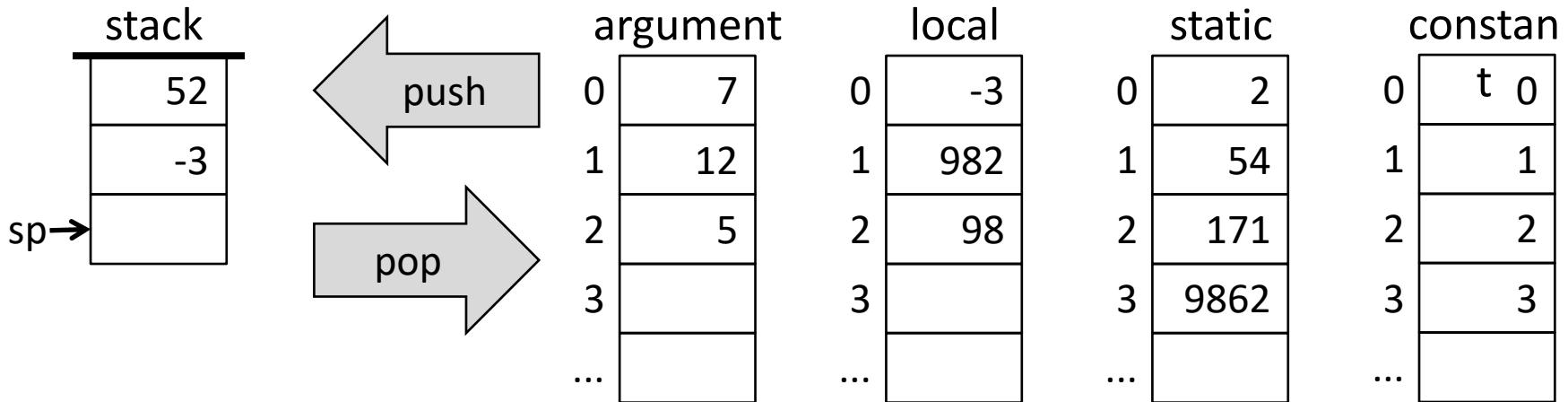
(a function always ends by pushing a return value on the stack)

- **Return** the *return value* to the *caller*;
- **Recycle** the memory resources used by the *callee*;
- **Reinstate** the *caller's* stack and memory segments;
- **Jump** to the return address in the *caller's* code.

Outlines

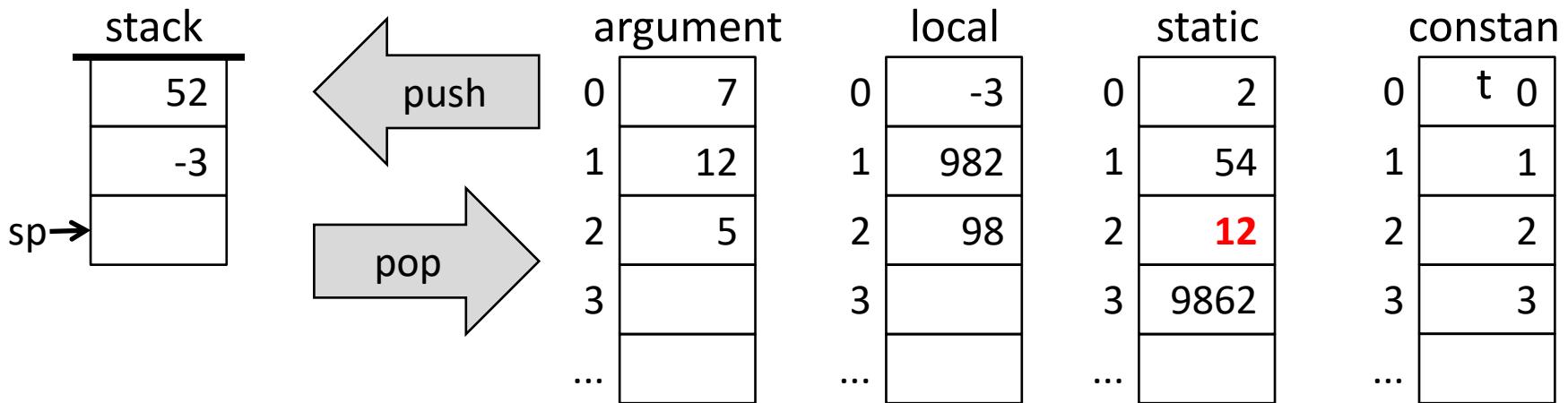
- Introduction to virtual machine
- VM abstraction
- VM implementation
 - Stack
 - Memory segment commands
 - Branching commands
 - Function commands
- VM translator

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

RAM	
0	257
1	1024
2	1765
...	...
256	19
257	23
258	903
...	...
1024	5
1025	12
1026	-3
...	...

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?
```

RAM	
0	257
1	1024
2	1765
...	...
256	19
257	23
258	903
...	...
1024	5
1025	12
1026	-3
...	...

Pointer manipulation - answer

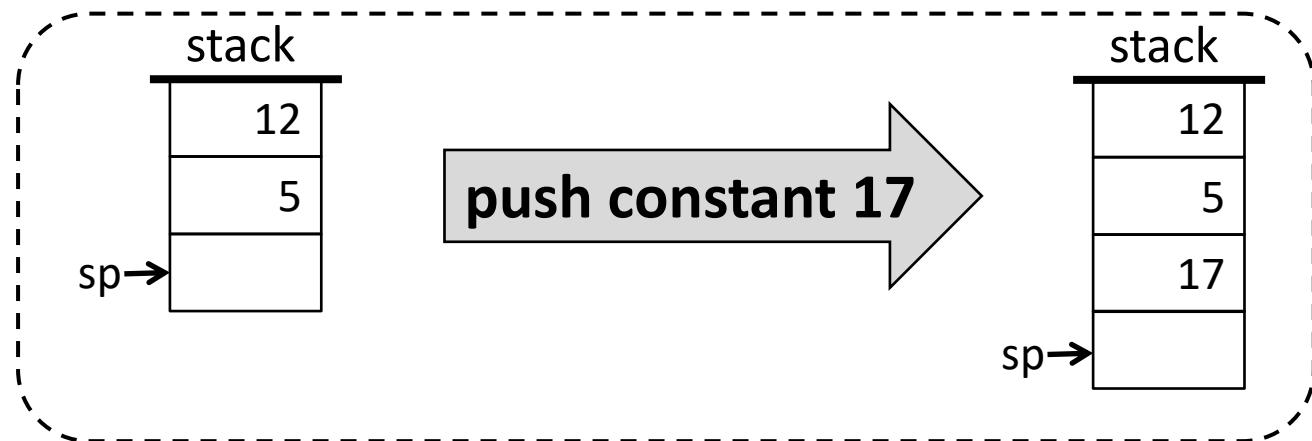
Given the initial memory status shown on the right, find:

```
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
```

RAM	
0	257
1	1024
2	1765
...	...
256	19
257	23
258	903
...	...
1024	5
1025	12
1026	-3
...	...

Stack implementation

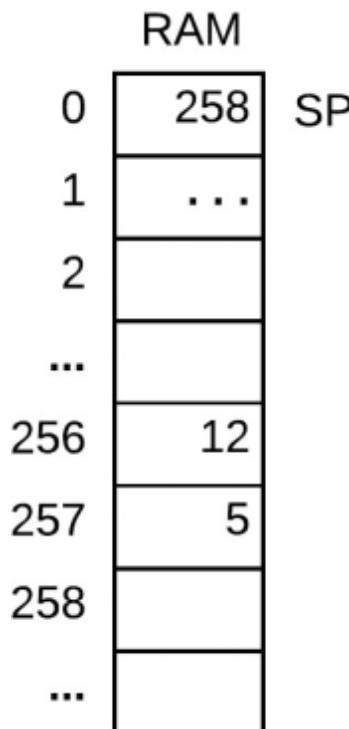
Abstraction:



Implementation:

Assumptions:

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

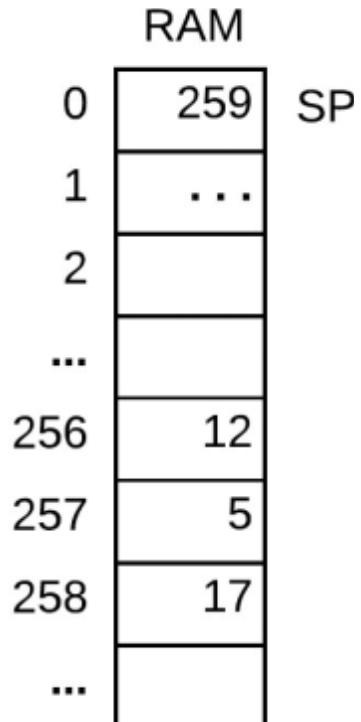


Logic:

```
*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 code:

```
push constant i
```



Assembly psuedo code:

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

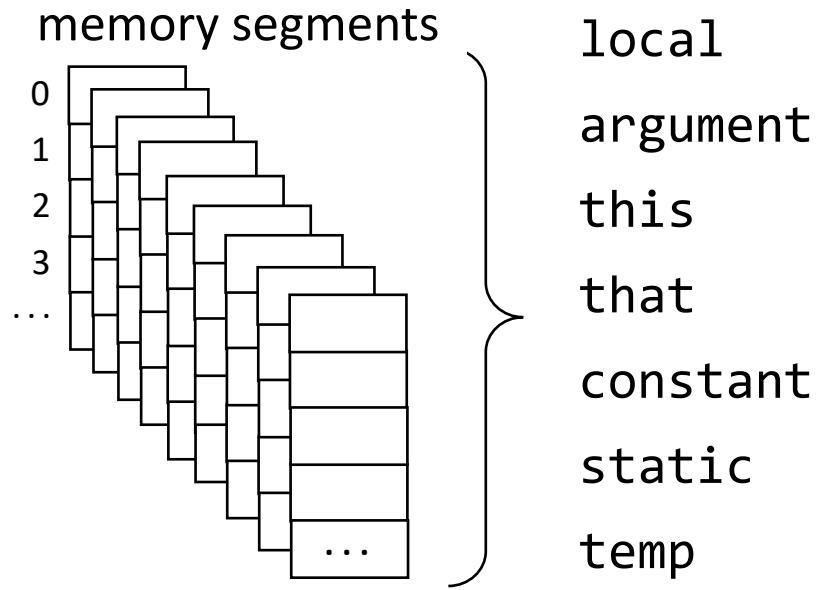
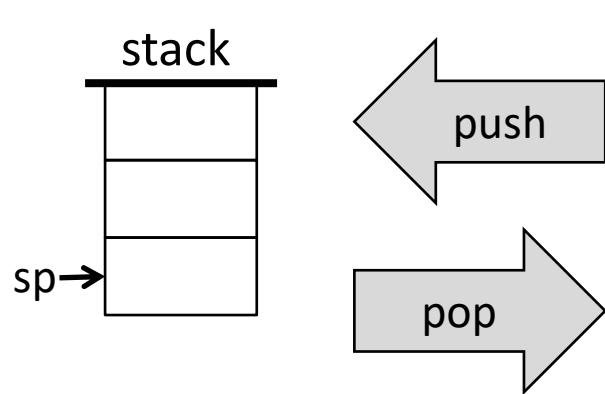
VM Translator

- 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
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 - Function commands
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Memory segments (abstraction)

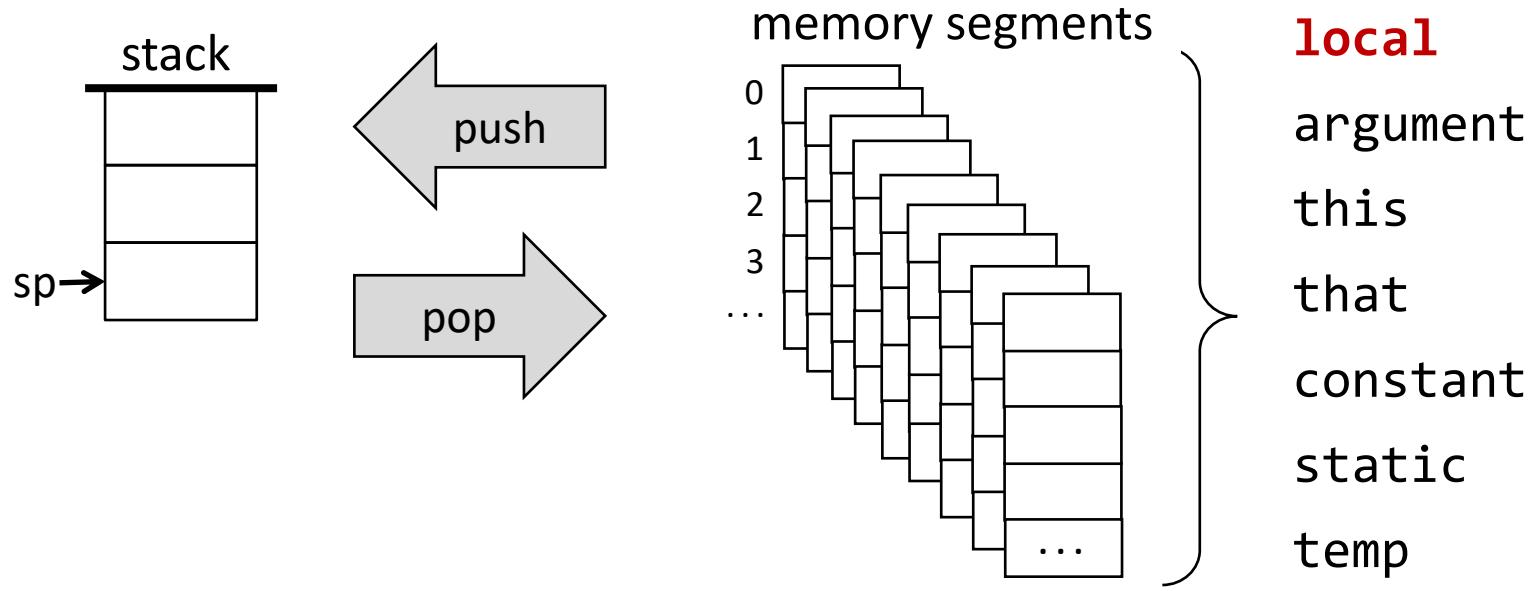


Syntax: push / pop segment i

Examples:

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

Implement push/pop local *i*



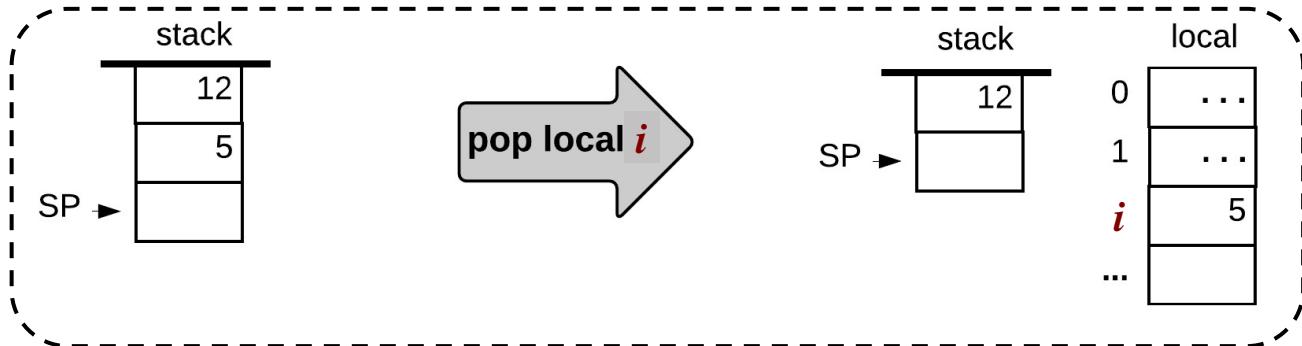
Syntax: push/pop local *i*

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:

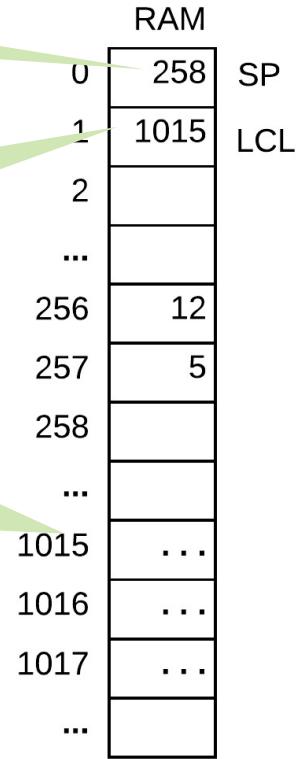


stack pointer

base address of
the local segment

Implementation:

the local segment
is stored some-
where in the RAM

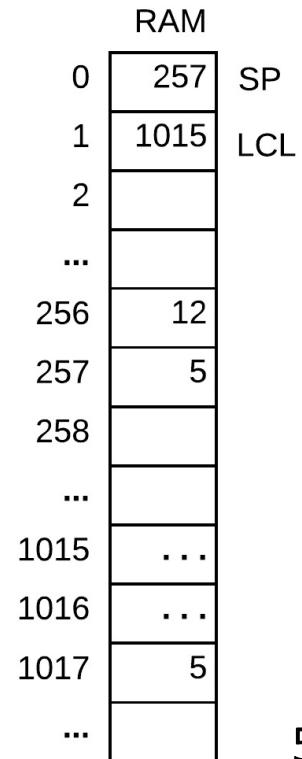


Implementation:

```
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

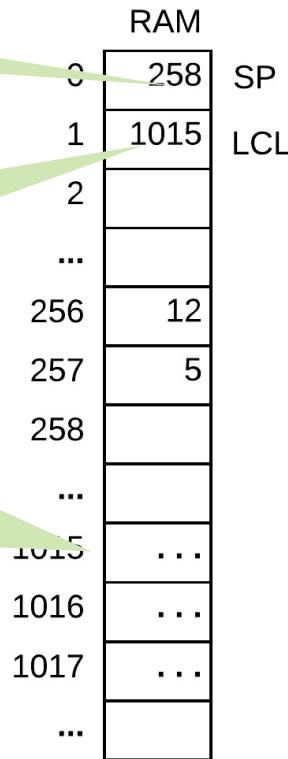
addr = LCL+ *i*, *SP = *addr, SP++

Stack pointer

Base address of
the local segment

Implementation:

The local segment
is stored some-
where in the RAM

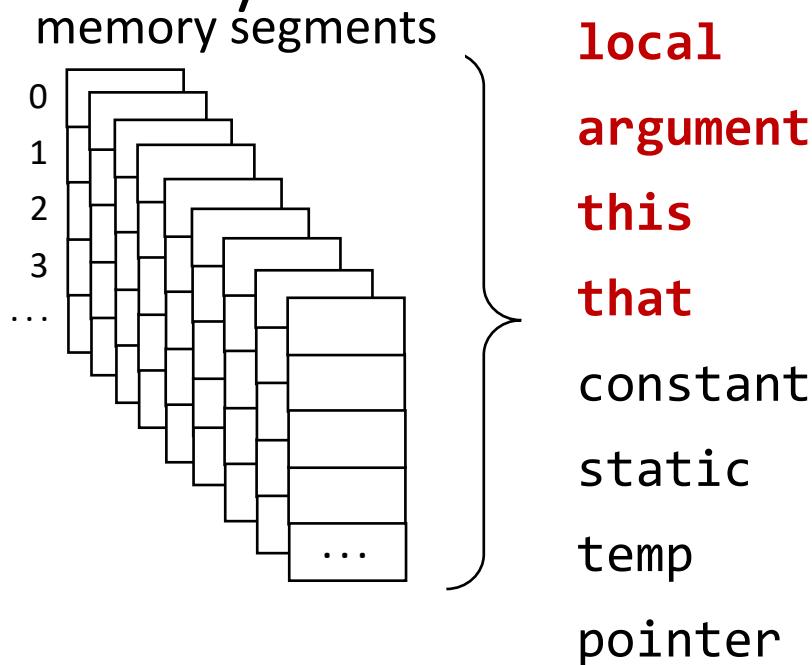
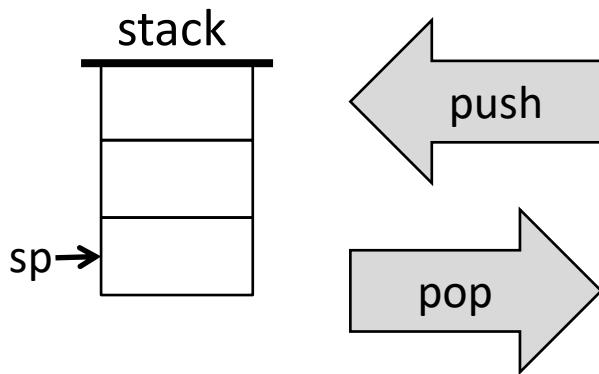


Hack assembly:

```
// 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	<i>local variable</i>	<i>local i</i>
argument	<i>argument</i> in a function call	<i>argument i</i>
this	<i>field variables</i> of the current object	<i>this i</i>
that	<i>array entries</i>	<i>that i</i>

Implement push / pop local / argument /this / that i

VM code:

```
push segment i
```

```
pop segment i
```

VM translator

Assembly pseudo code:

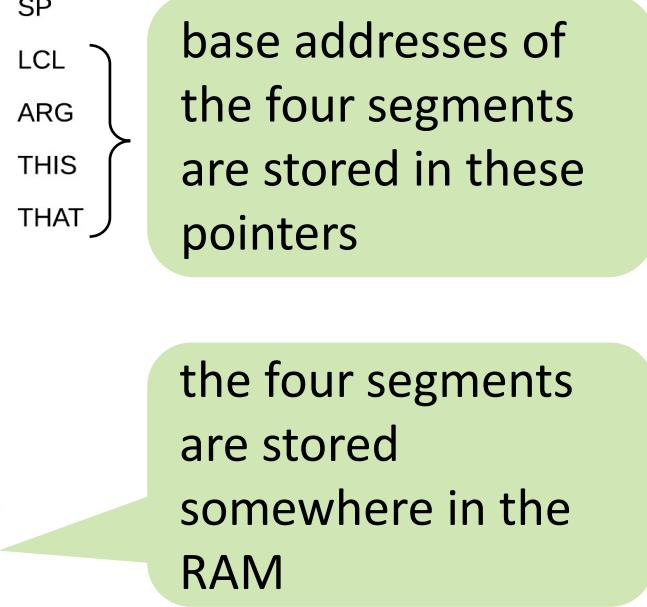
```
addr = segmentPointer + i, *SP = *addr, SP++
```

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

$segment = \{local, argument, this, that\}$

Host RAM

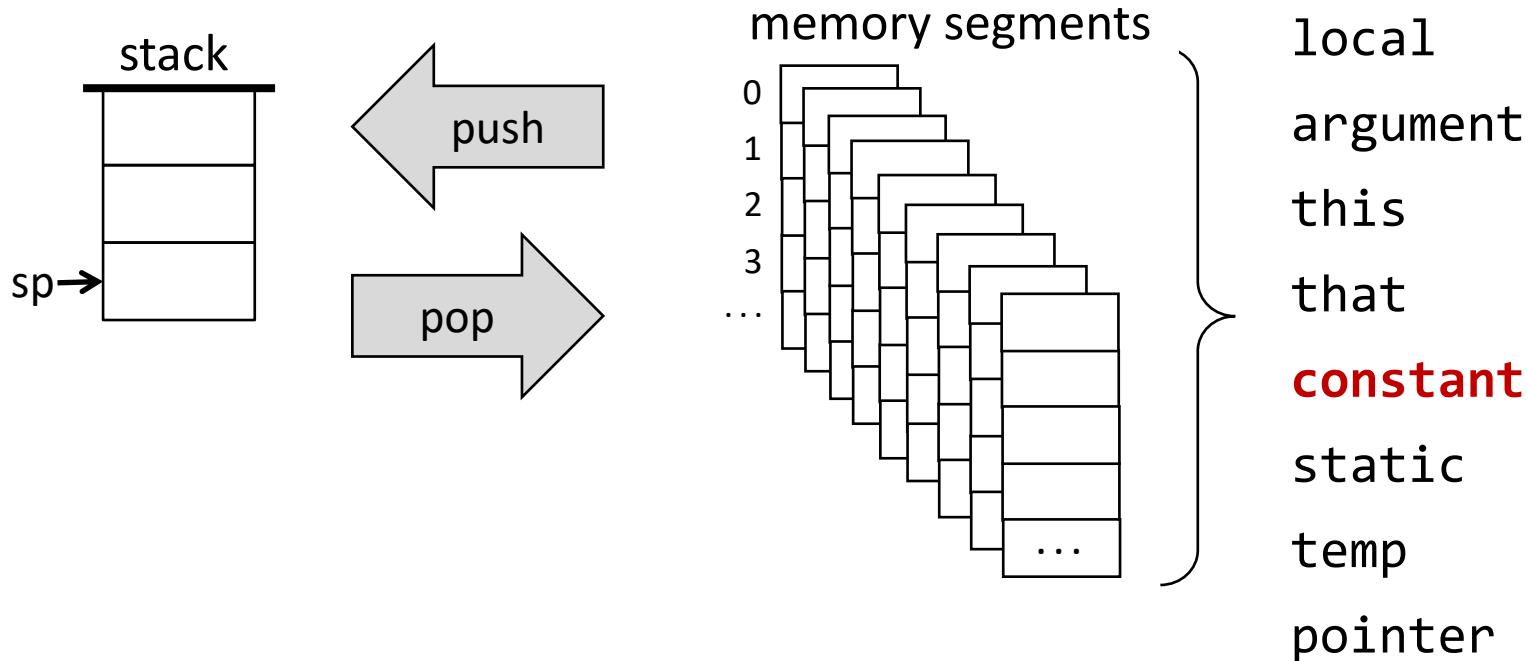
0	SP
1	LCL
2	ARG
3	THIS
4	THAT
5	
...	
12	
13	
14	
15	
...	



- 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*

VM Translator

(no pop constant operation)

Implementation:

Supplies the specified constant.

Assembly psuedo code:

*SP = *i*, SP++

Hack assembly:

// D = *i*

@*i*

D=A

// *SP=D

@SP

A=M

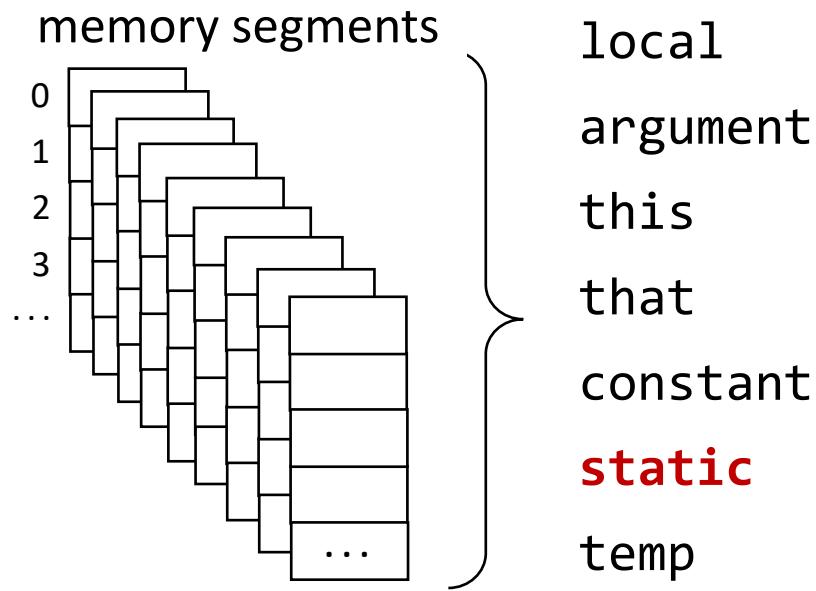
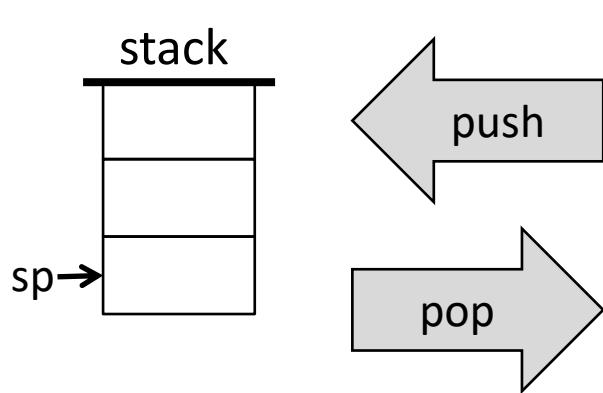
M=D

// SP++

@SP

M=M+1

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 entries 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  
...
```



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**”:

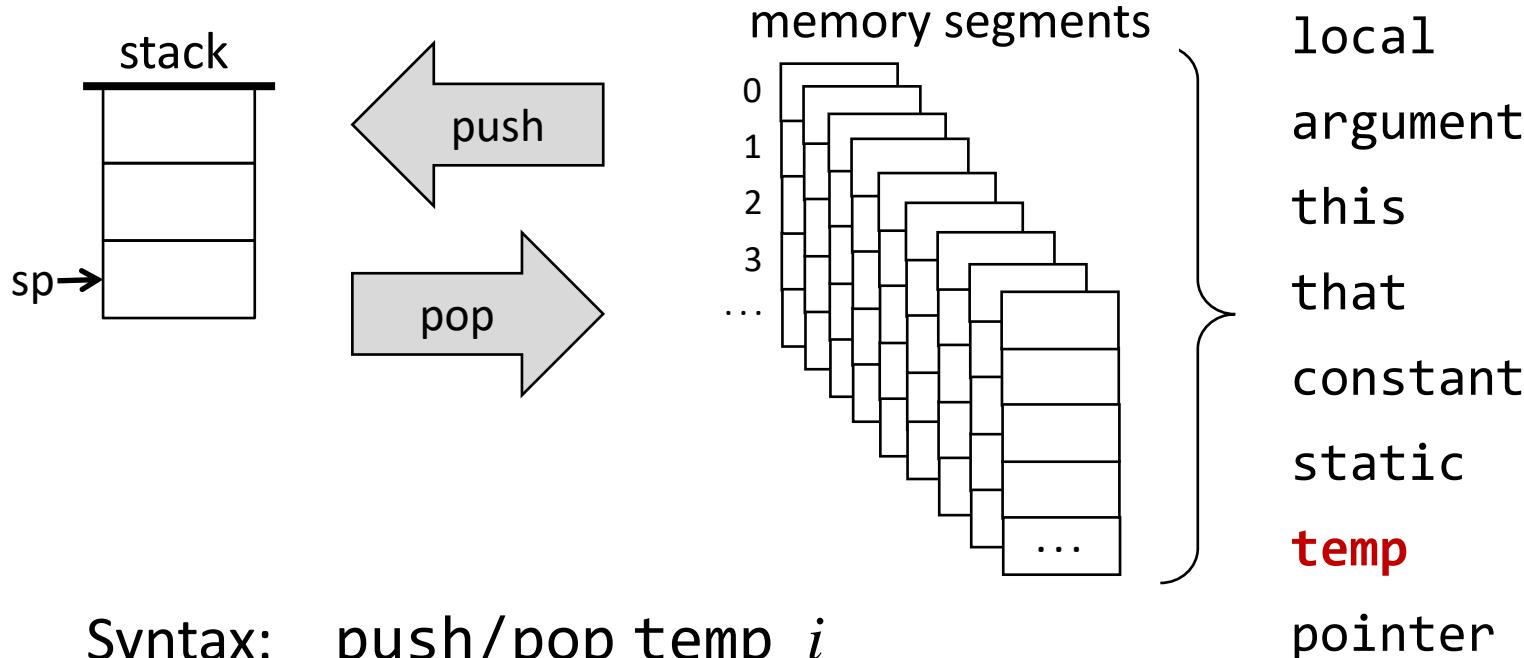
- Have the VM translator translate each VM reference `static i` (in file `Foo.vm`) into an assembly reference `Foo.i`
- Following assembly, the Hack assembler will map these references onto `RAM[16], RAM[17], ..., RAM[255]`
- Therefore, the entries of the `static` segment will end up being mapped onto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

Hack RAM

0	SP
1	LCL
2	ARG
3	THIS
4	THAT
5	
...	
12	
13	
14	
15	
16	
17	
...	
255	
256	
...	
2047	
...	

} static
variables

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*

Assembly psuedo code:

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

VM Translator

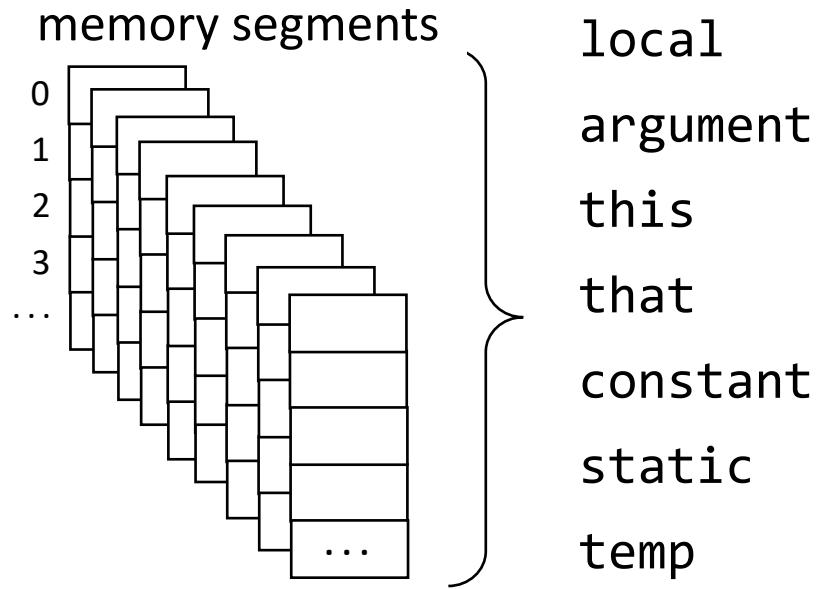
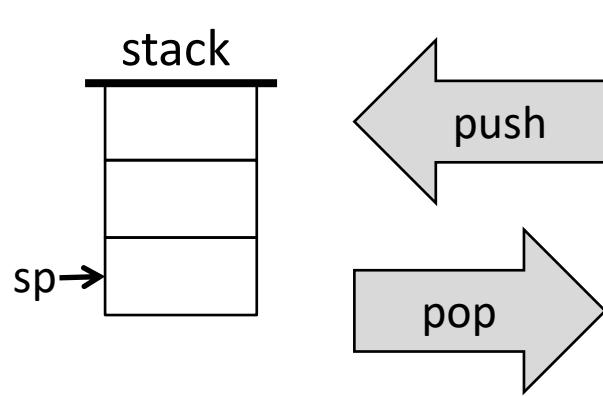
pop temp *i*

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

Hack RAM	
0	SP
1	LCL
2	ARG
3	THIS
4	THAT
5	temp segment
...	
12	
13	
14	
15	
16	
...	
255	

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 **pointer**

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

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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
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Functions in VM language: implementation

```
// Computes 3 +5 * 8
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
```

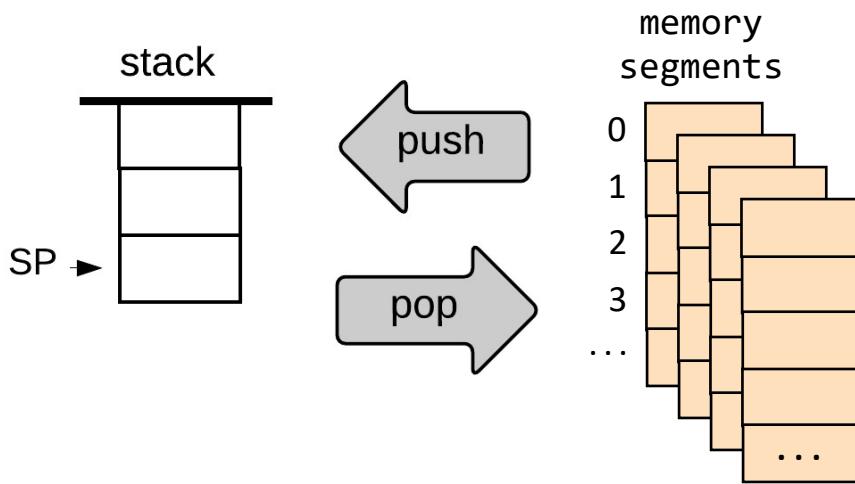
callee

Implementation

We can write low-level code to

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

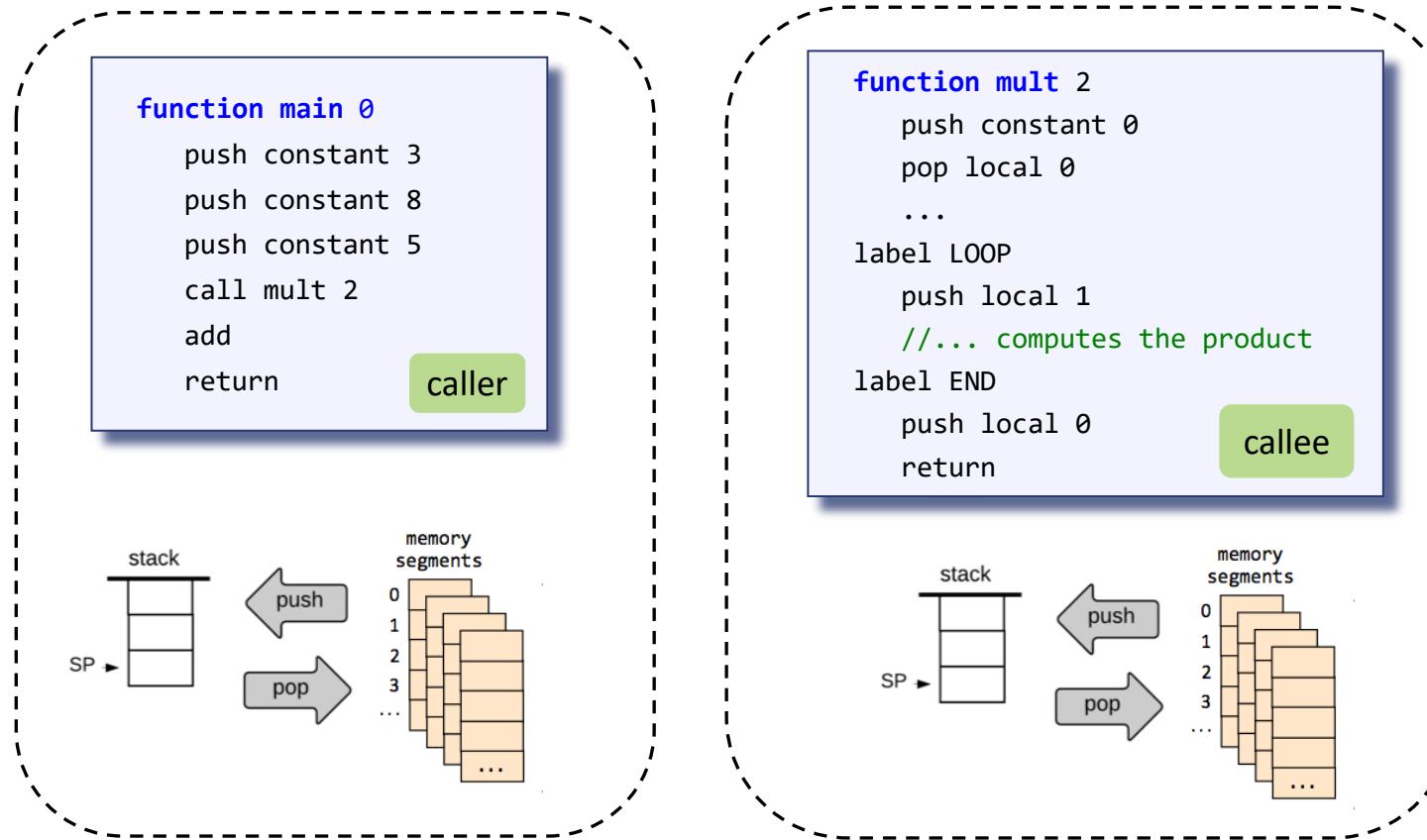
The function's state



During run-time:

- 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

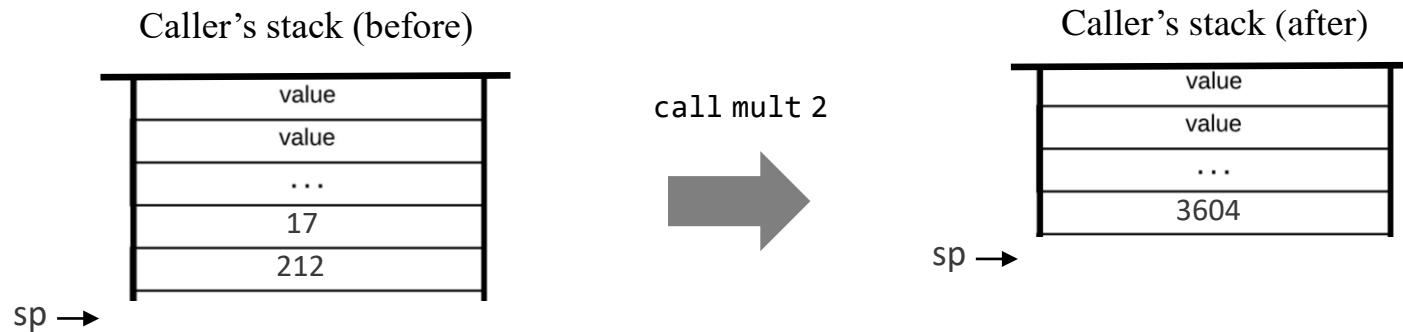


Challenge:

- 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)`

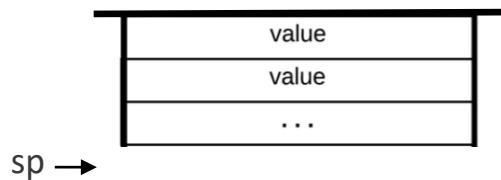


Net effect:

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

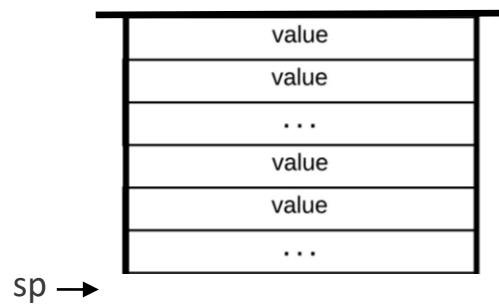
Function call and return: implementation

A function is running, and
doing something



Function call and return: implementation

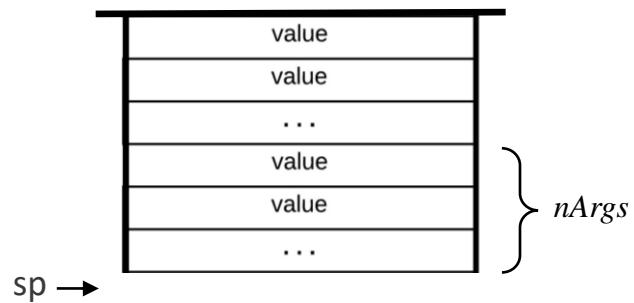
The function prepares
to call another function:



Function call and return: implementation

The function says:

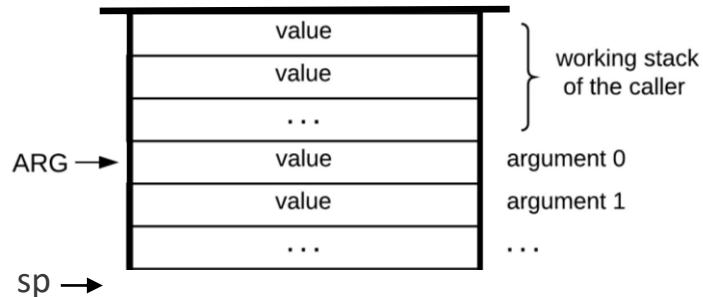
call foo nArgs



Function call and return: implementation

The function says:

call foo nArgs



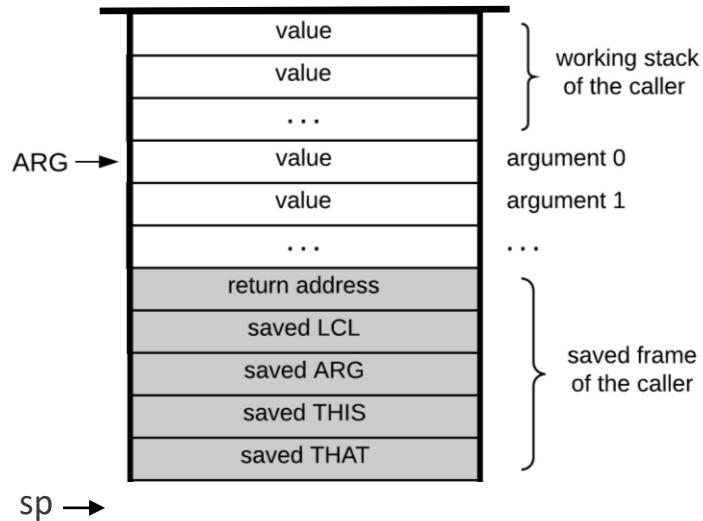
VM implementation (handling call):

1. Set ARG

Function call and return: implementation

The function says:

call foo nArgs



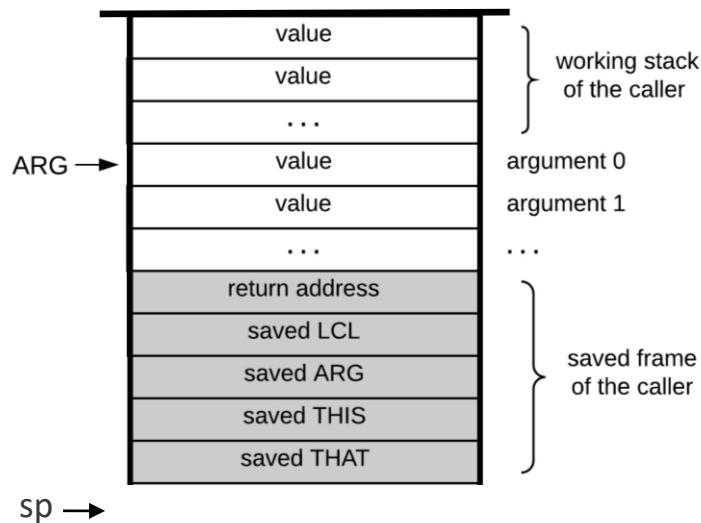
VM implementation (handling call):

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

Function call and return: implementation

The called function is entered:

function *foo nVars*



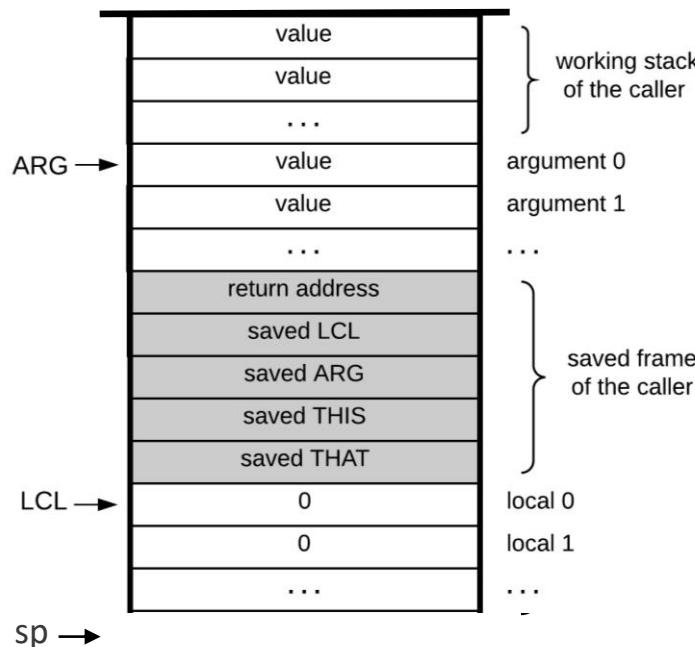
VM implementation (handling call):

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):

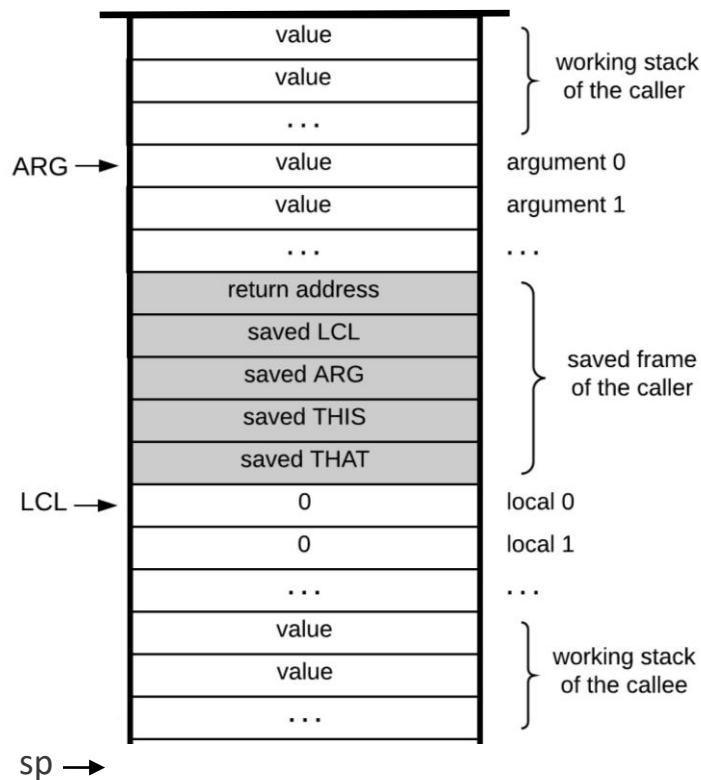
1. Set ARG
2. Save the caller's frame
3. Jump to execute *foo*

VM implementation (handling function):

Set up the local segment
of the called function

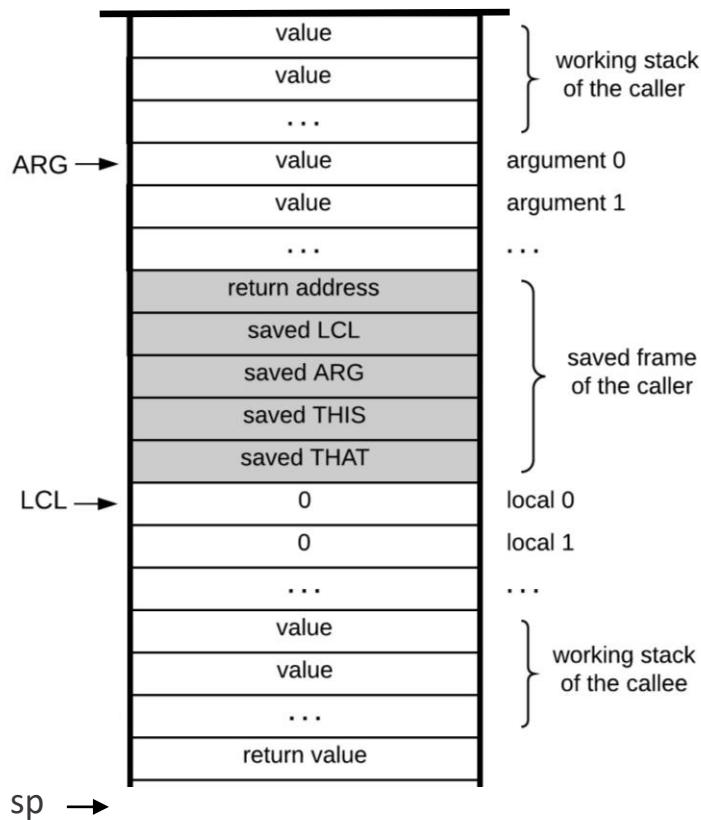
Function call and return: implementation

The called function is running,
doing something



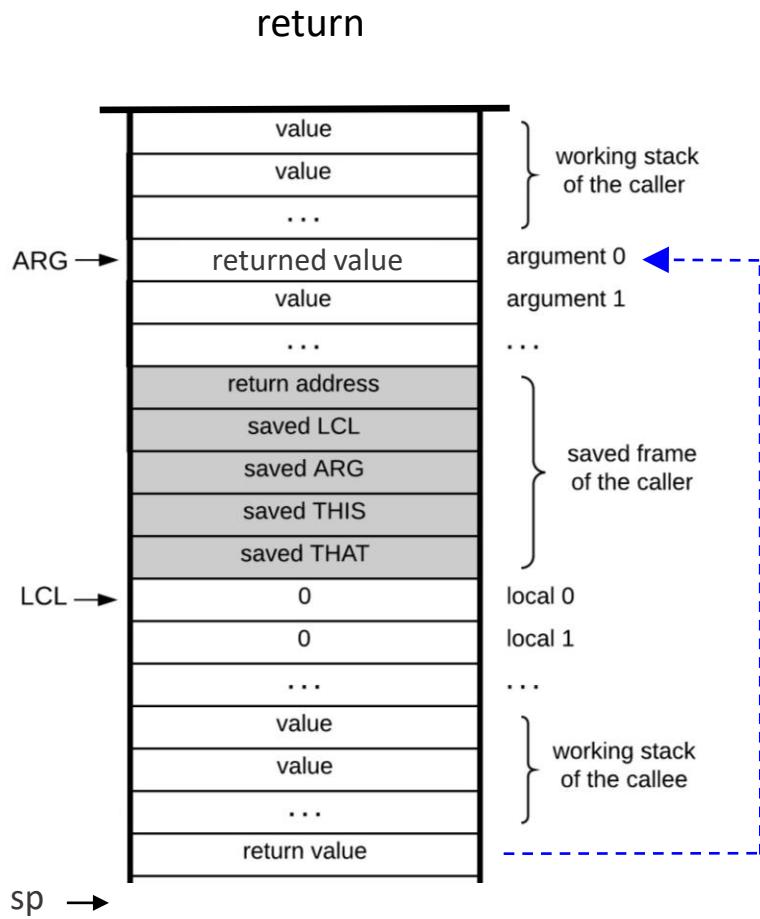
Function call and return: implementation

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



Function call and return: implementation

The called function says:



VM implementation (handling call):

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

VM implementation (handling function):

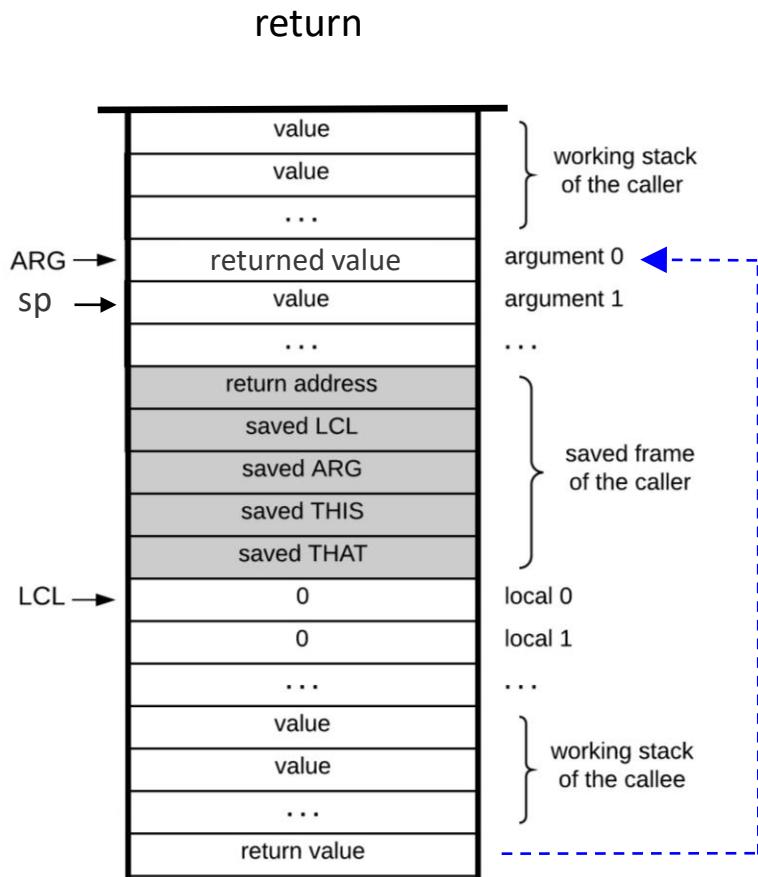
Set up the local segment
of the called function

VM implementation (handling return):

1. Copy return value onto argument 0.

Function call and return: implementation

The called function says:



VM implementation (handling call):

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

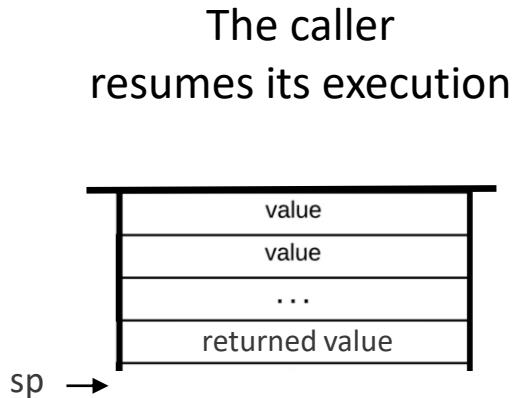
VM implementation (handling function):

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



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

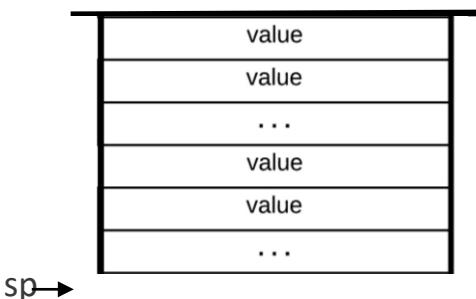
VM implementation (handling return):

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)

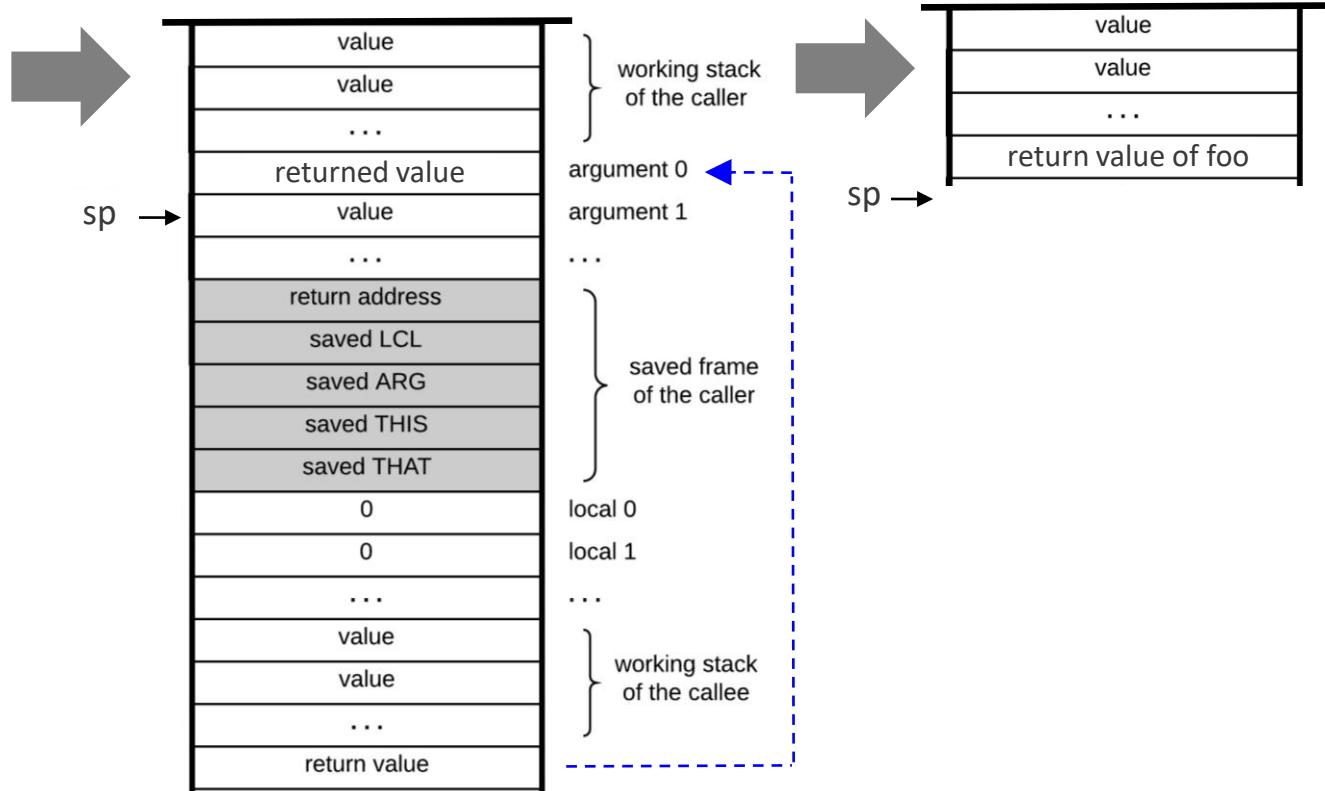
Recap: function call and return

The caller says:

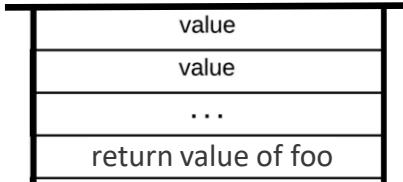
call foo nArgs



Implementation:



The caller resumes its execution

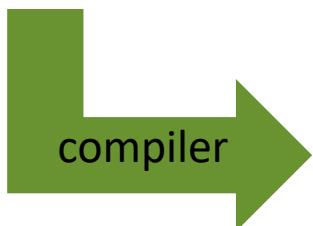


Example: factorial

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 0
    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 0
    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
```

global stack



Run-time example

VM program

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

function factorial 0
    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
```

global stack

main: 3

Run-time example

VM program

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

function factorial 0
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
```

global stack

main:	3
-------	---

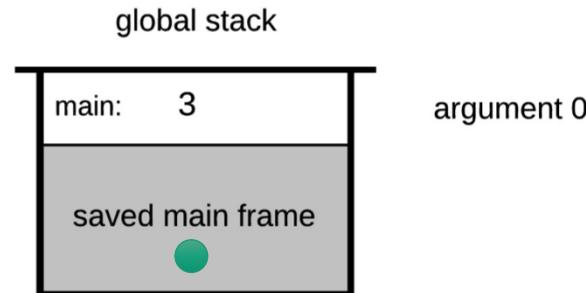
argument 0

Run-time example

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

  function factorial 0
    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
```

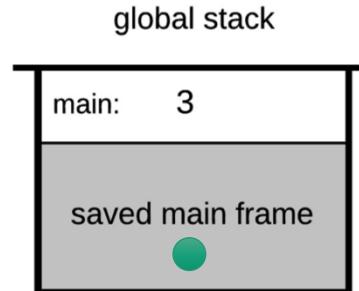


Run-time example

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

function factorial 0
    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
```



argument 0

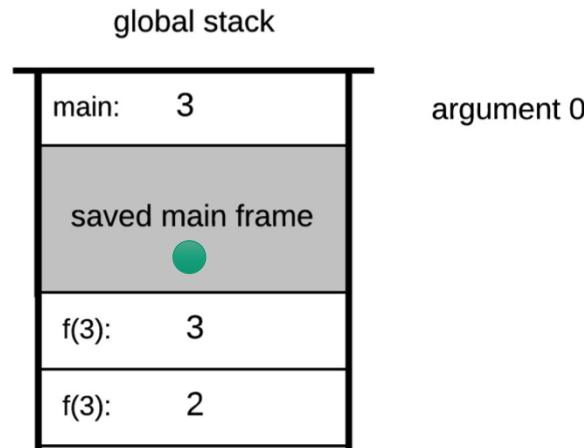
impact on the
global stack
not shown

Run-time example

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

function factorial 0
    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
```

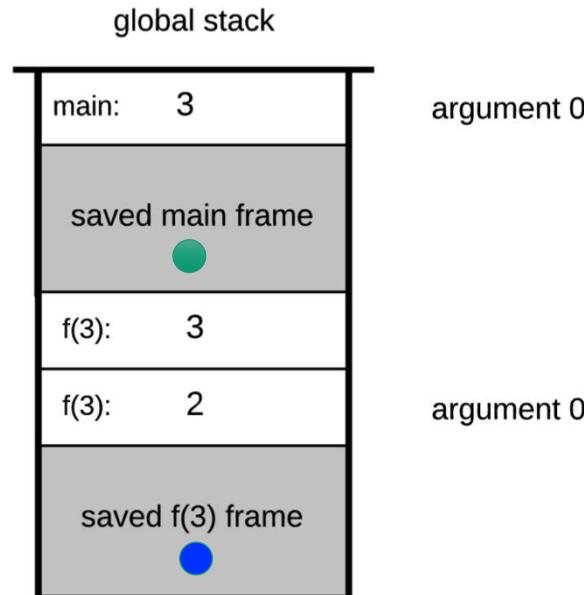


Run-time example

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

function factorial 0
    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
```

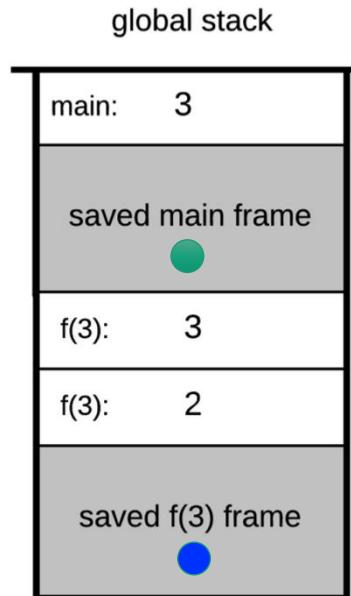


Run-time example

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

function factorial 0
    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
```



argument 0

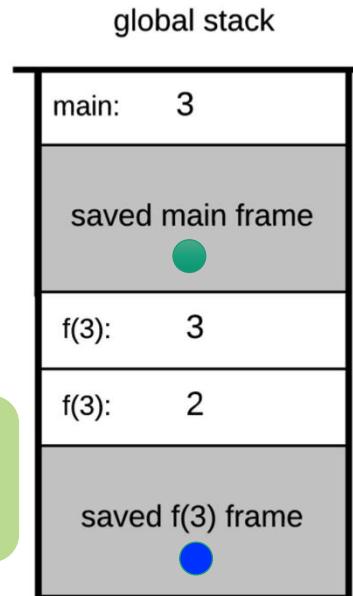
argument 0

Run-time example

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

function factorial 0
    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
```



argument 0

argument 0

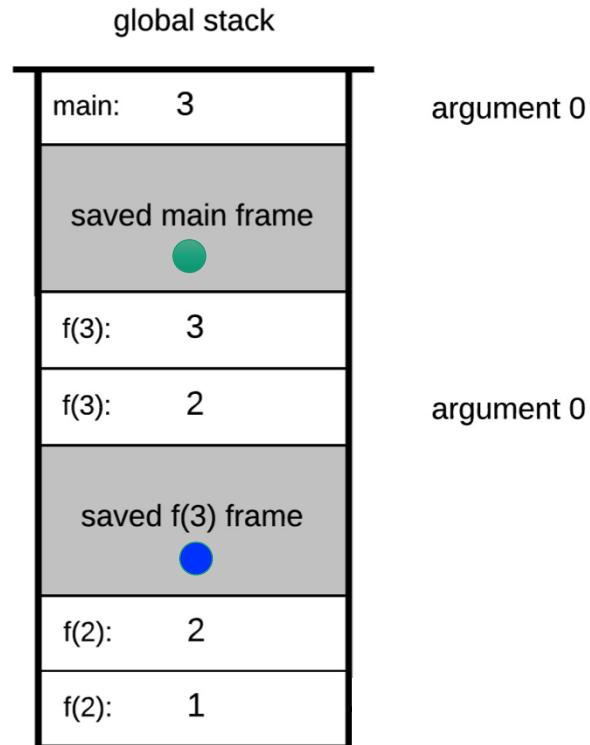
impact on the
global stack
not shown

Run-time example

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

function factorial 0
    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
```

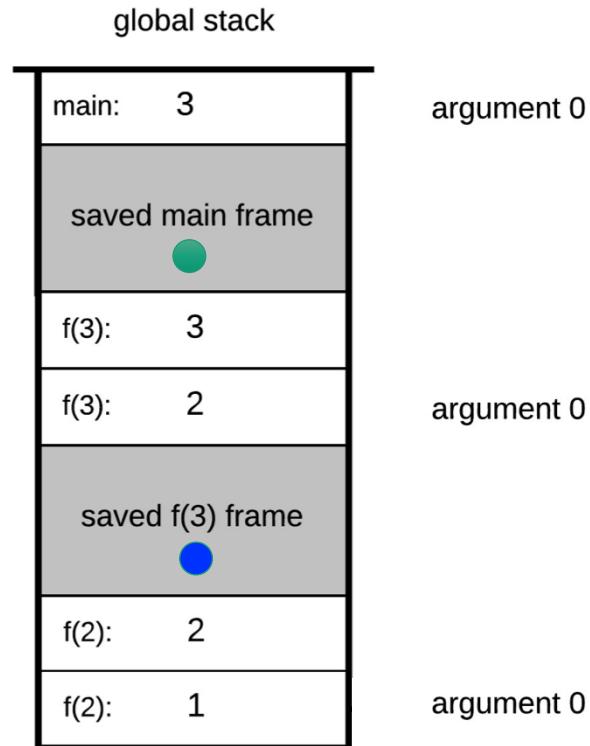


Run-time example

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

function factorial 0
    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
```

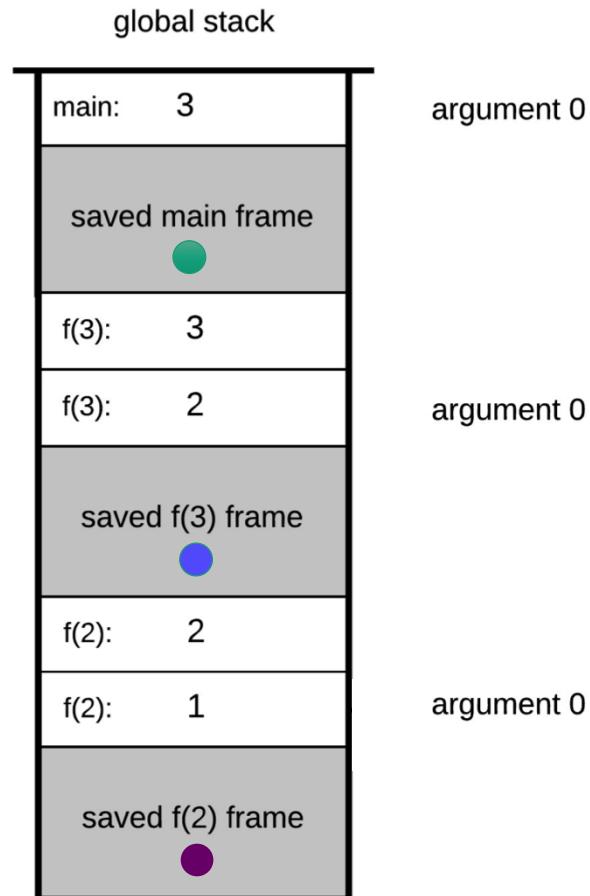


Run-time example

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

function factorial 0
    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
```

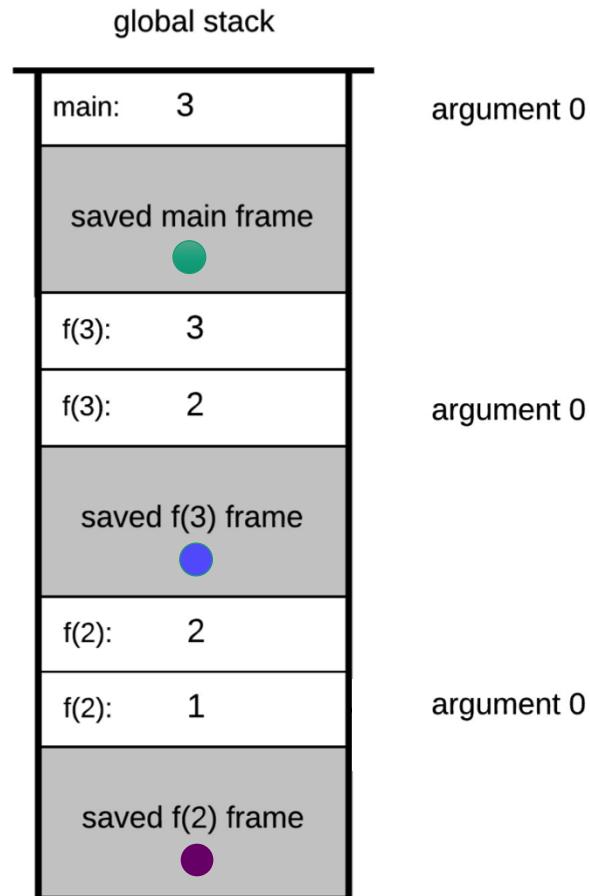


Run-time example

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

function factorial 0
    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
```

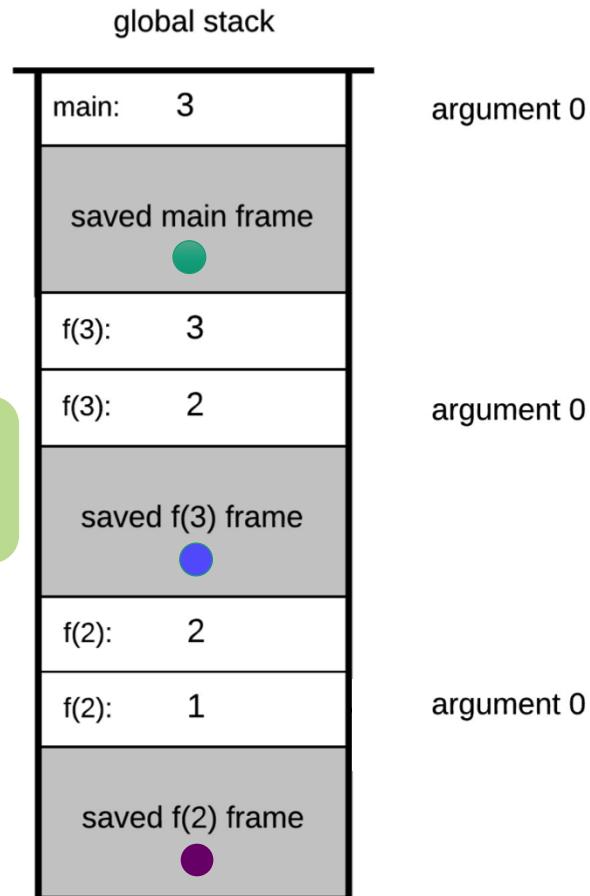


Run-time example

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

function factorial 0
    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
```

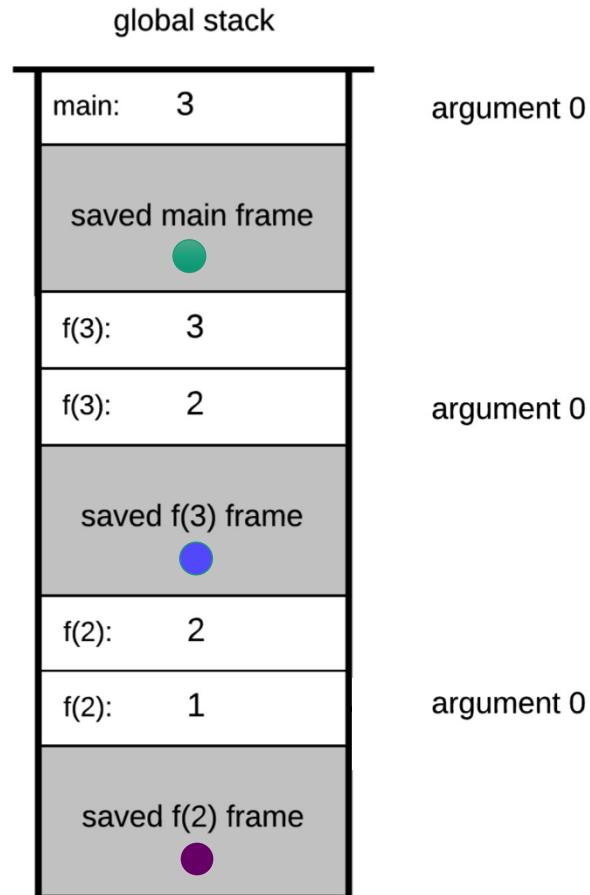


Run-time example

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

function factorial 0
    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
```

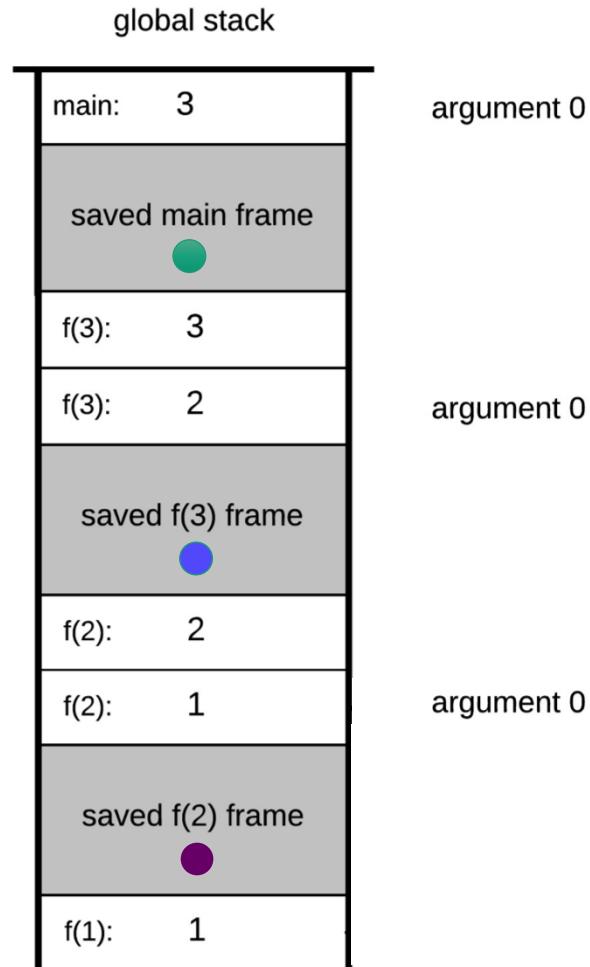


Run-time example

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

function factorial 0
    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
```

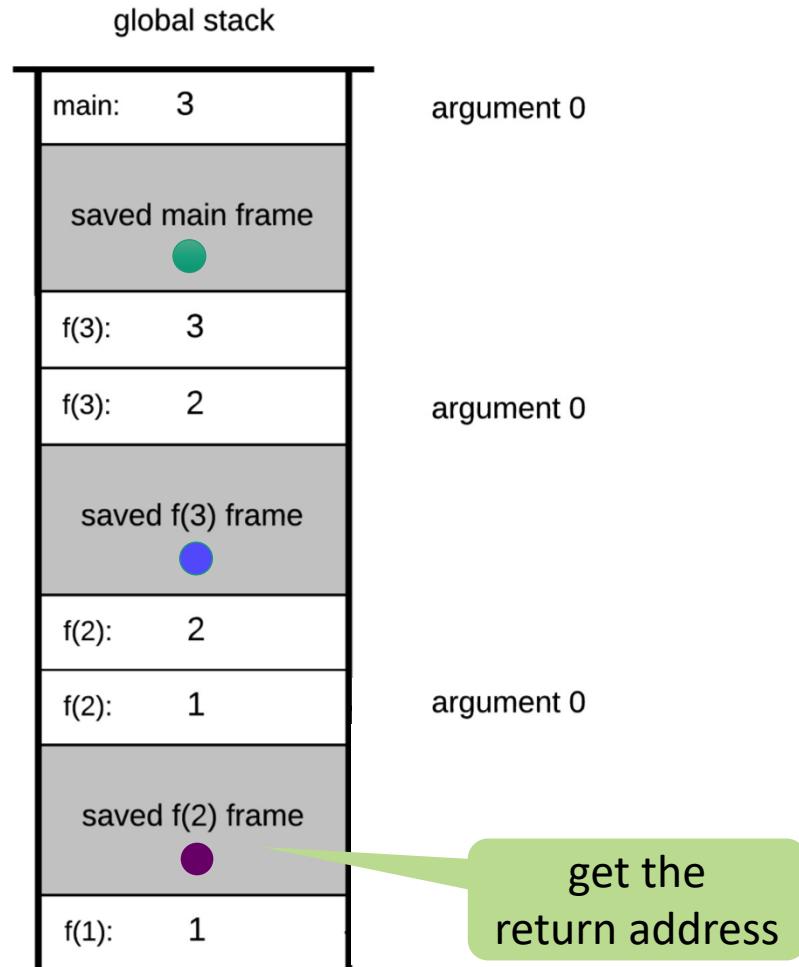


Run-time example

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

function factorial 0
    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
```

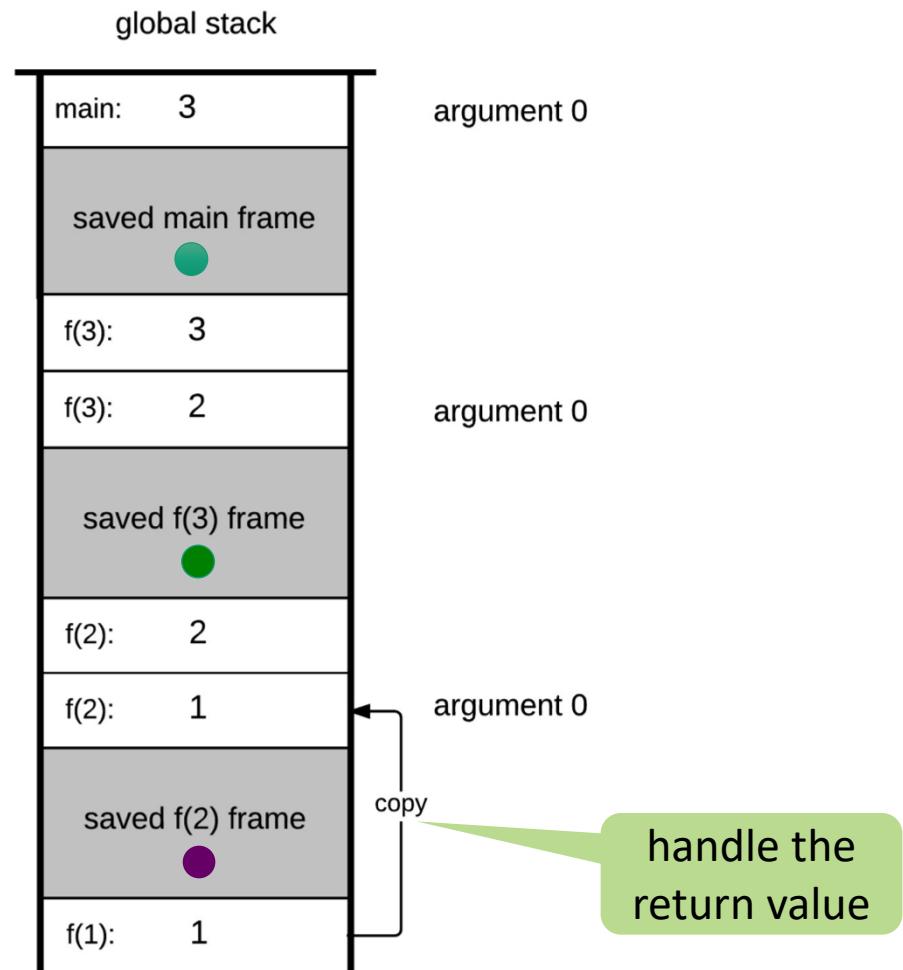


Run-time example

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

function factorial 0
    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
```

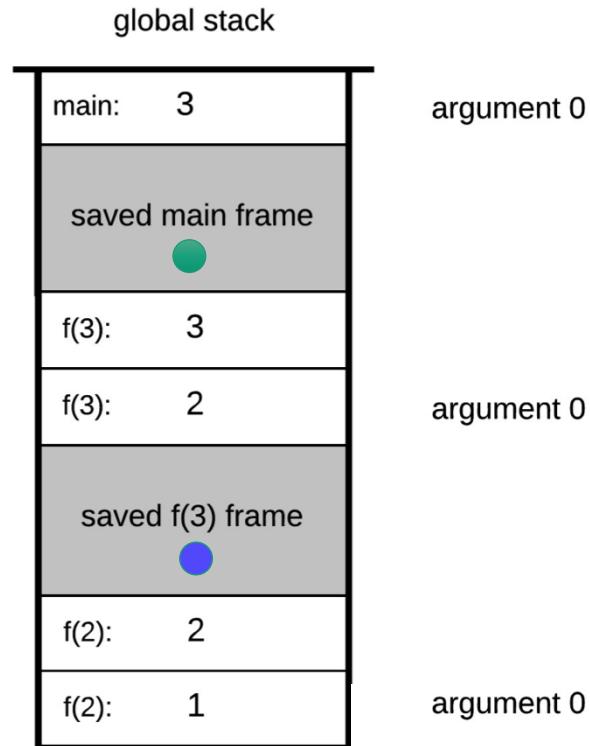


Run-time example

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

function factorial 0
    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
```

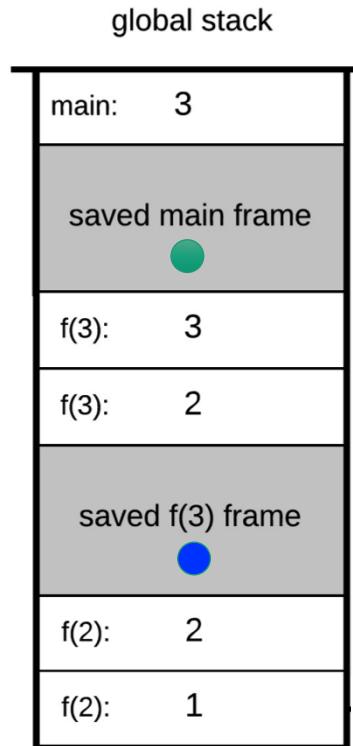


Run-time example

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

function factorial 0
    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
```



argument 0

argument 0

argument 0

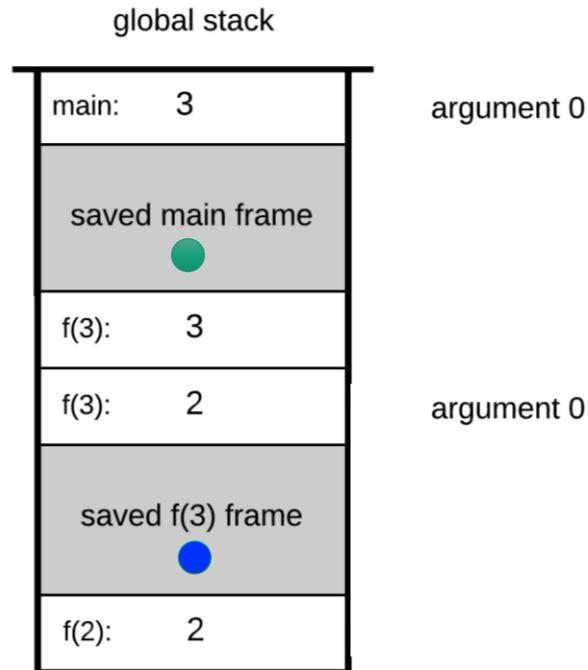
impact on the global
stack not shown
(except for end result)

Run-time example

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

function factorial 0
    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
```

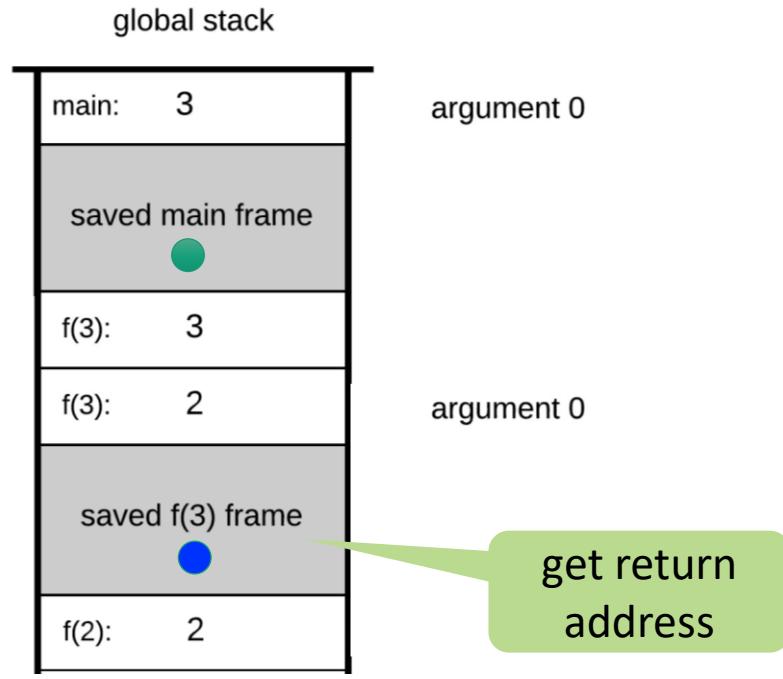


Run-time example

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

function factorial 0
    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
```

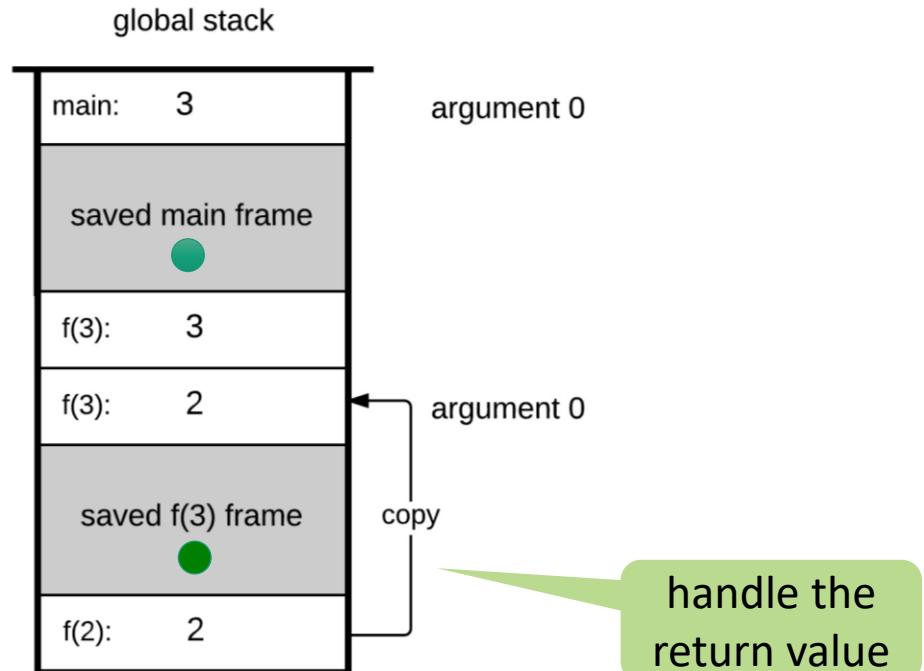


Run-time example

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

function factorial 0
    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
```

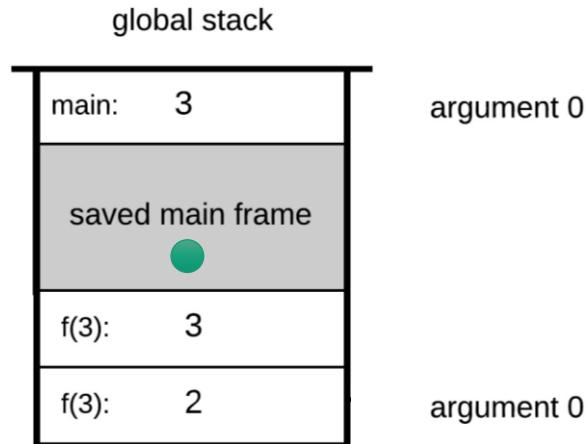


Run-time example

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

function factorial 0
    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
```



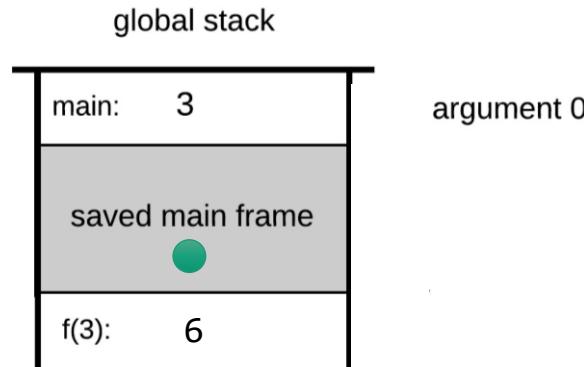
impact on the global
stack not shown
(except for end result)

Run-time example

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

function factorial 0
    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
```

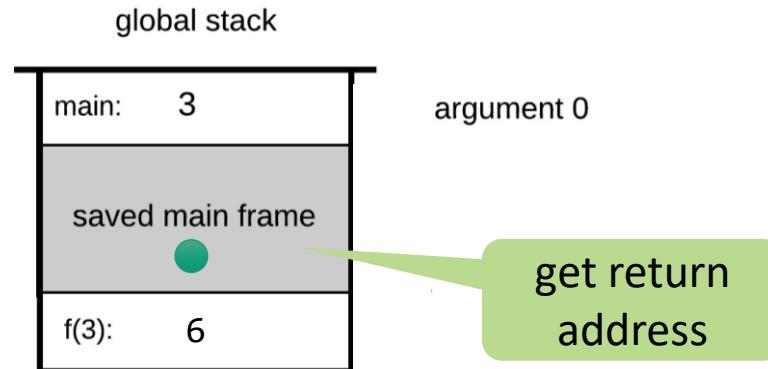


Run-time example

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

function factorial 0
    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
```

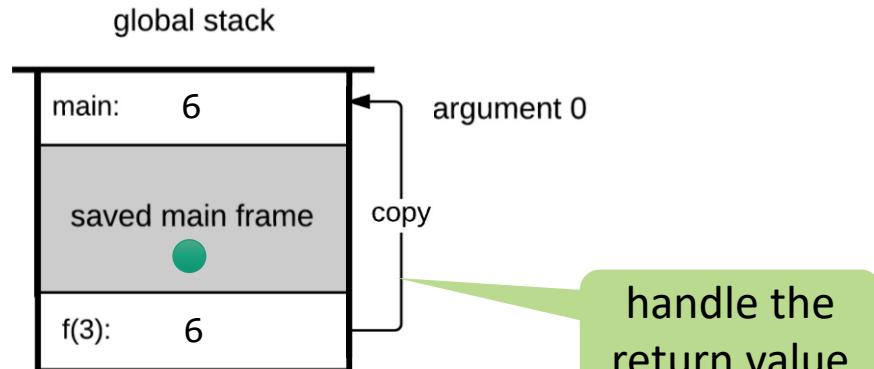


Run-time example

```
function main 0
    push constant 3
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    return

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

global stack

main:	6
-------	---

Run-time example

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

function factorial 0
    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
```

global stack

main:	6
-------	---

Recap

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

function factorial 0
    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

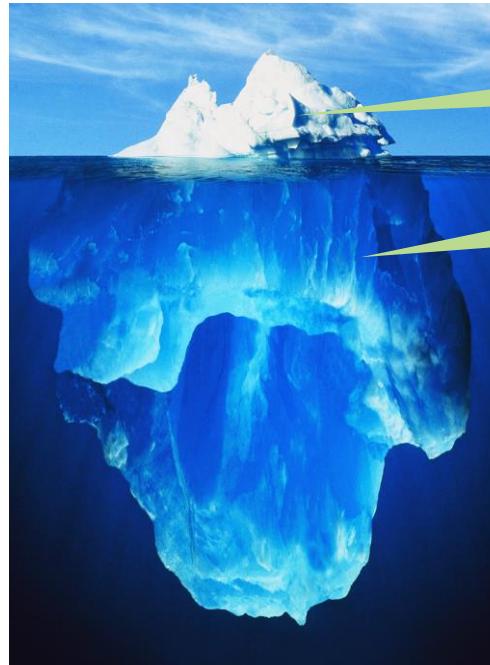
function mult 2
    // Code omitted
```

global stack



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

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



abstraction

implementation

Detailed implementation of function

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
```

caller

callee

We focus on VM function commands:

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

Contract: the caller'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

caller

- 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)

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

caller

- 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
```

VM translator

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)
```

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 <i>current command</i> . 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:

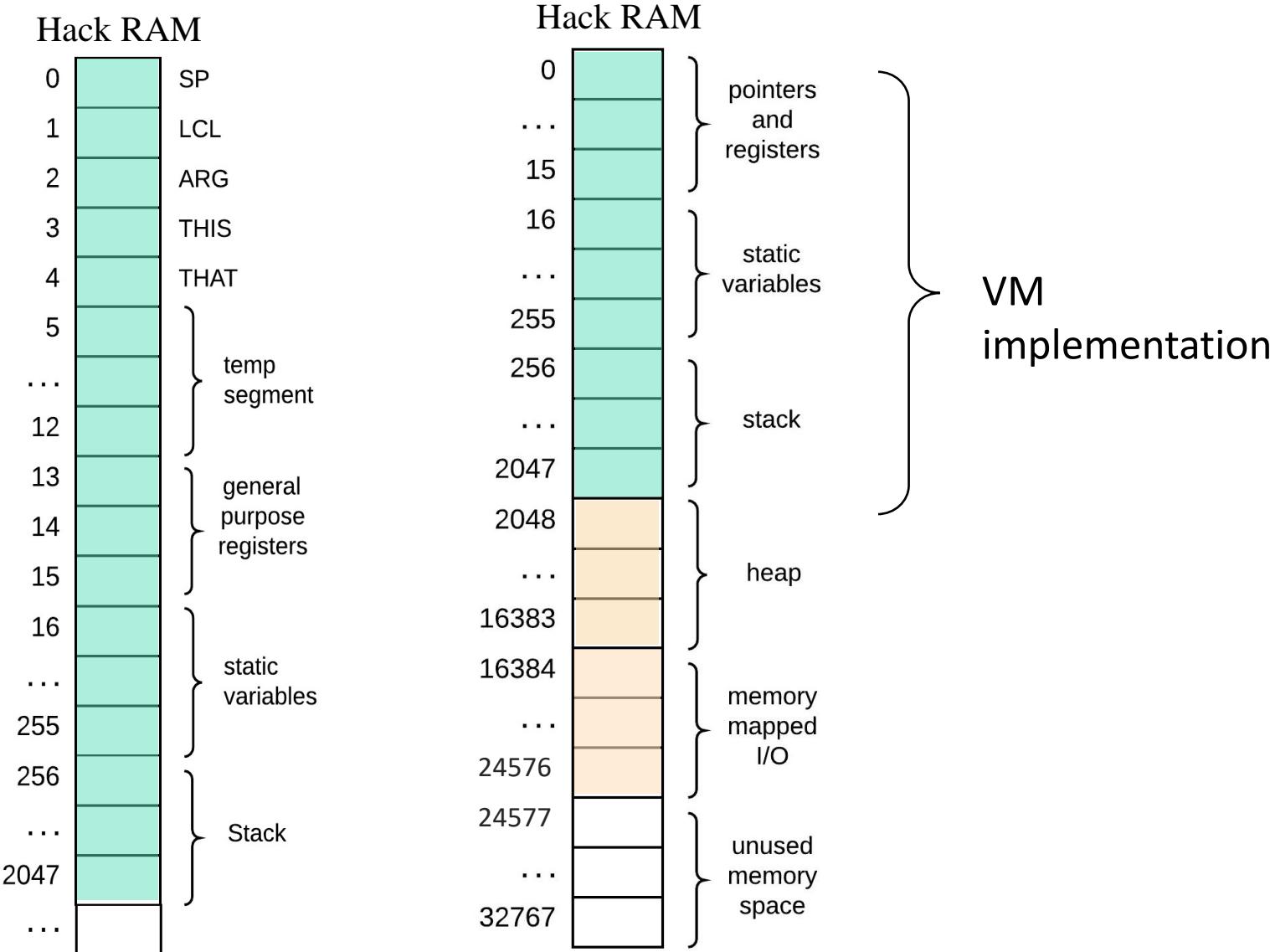
```
// Bootstrap code (should be  
written in assembly)
```

```
SP = 256
```

```
call Sys.init
```

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

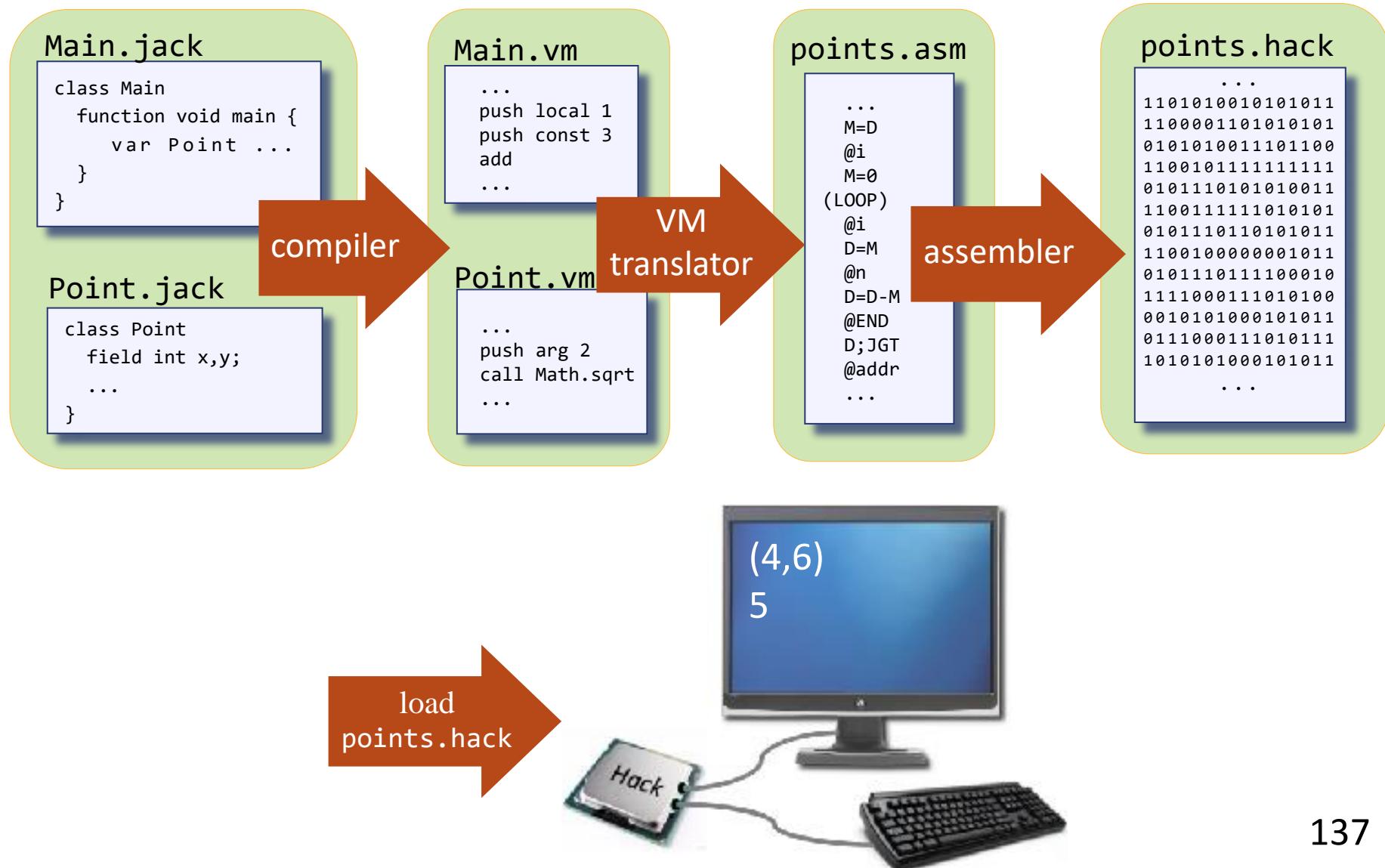
Standard mapping of the VM on the Hack platform



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



Summary

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

Acknowledgement

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- You may find more information on:
www.nand2tetris.org.

