



University of
Nottingham

UK | CHINA | MALAYSIA

Virtual Machine Part 1

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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

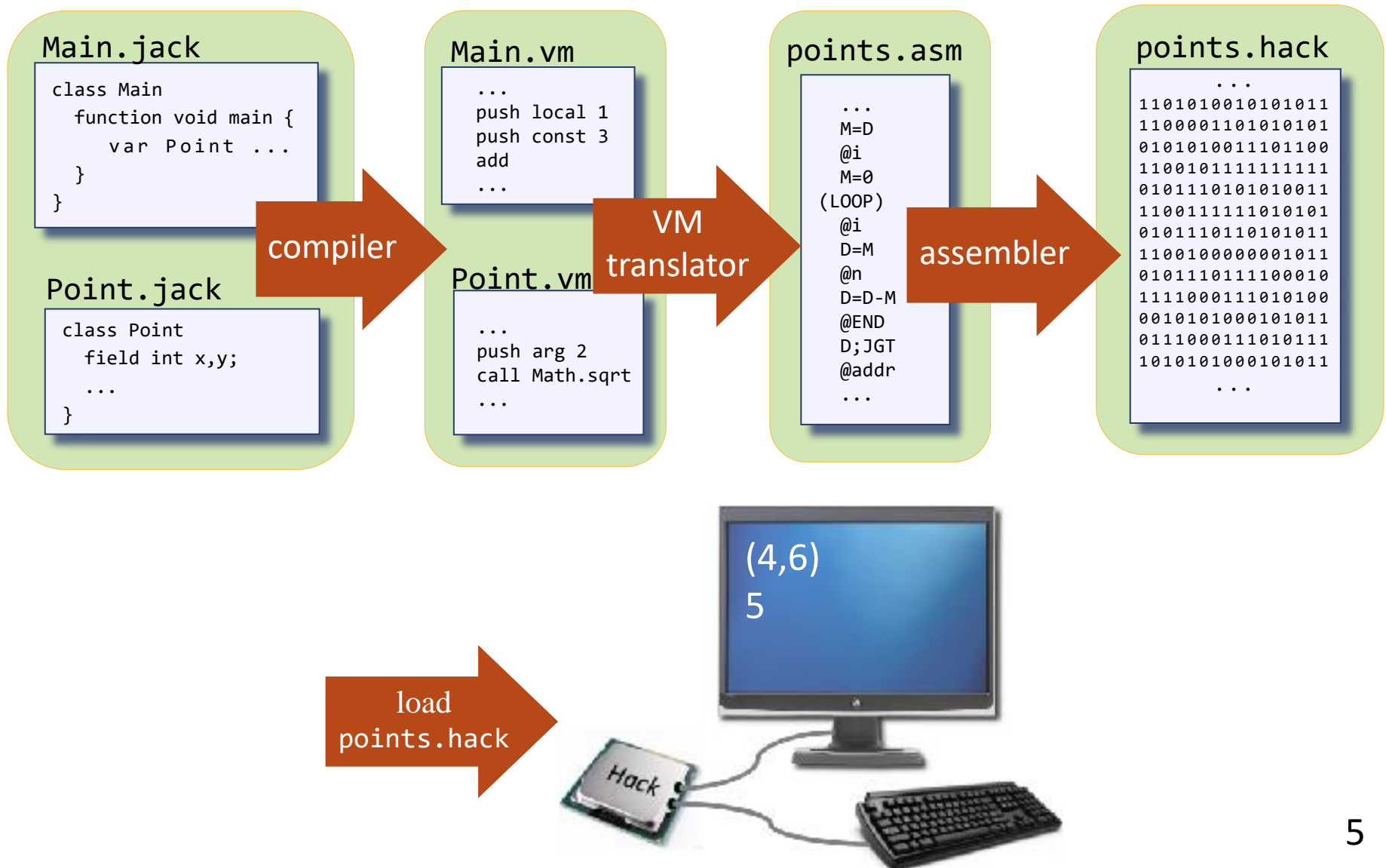
Issues:

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

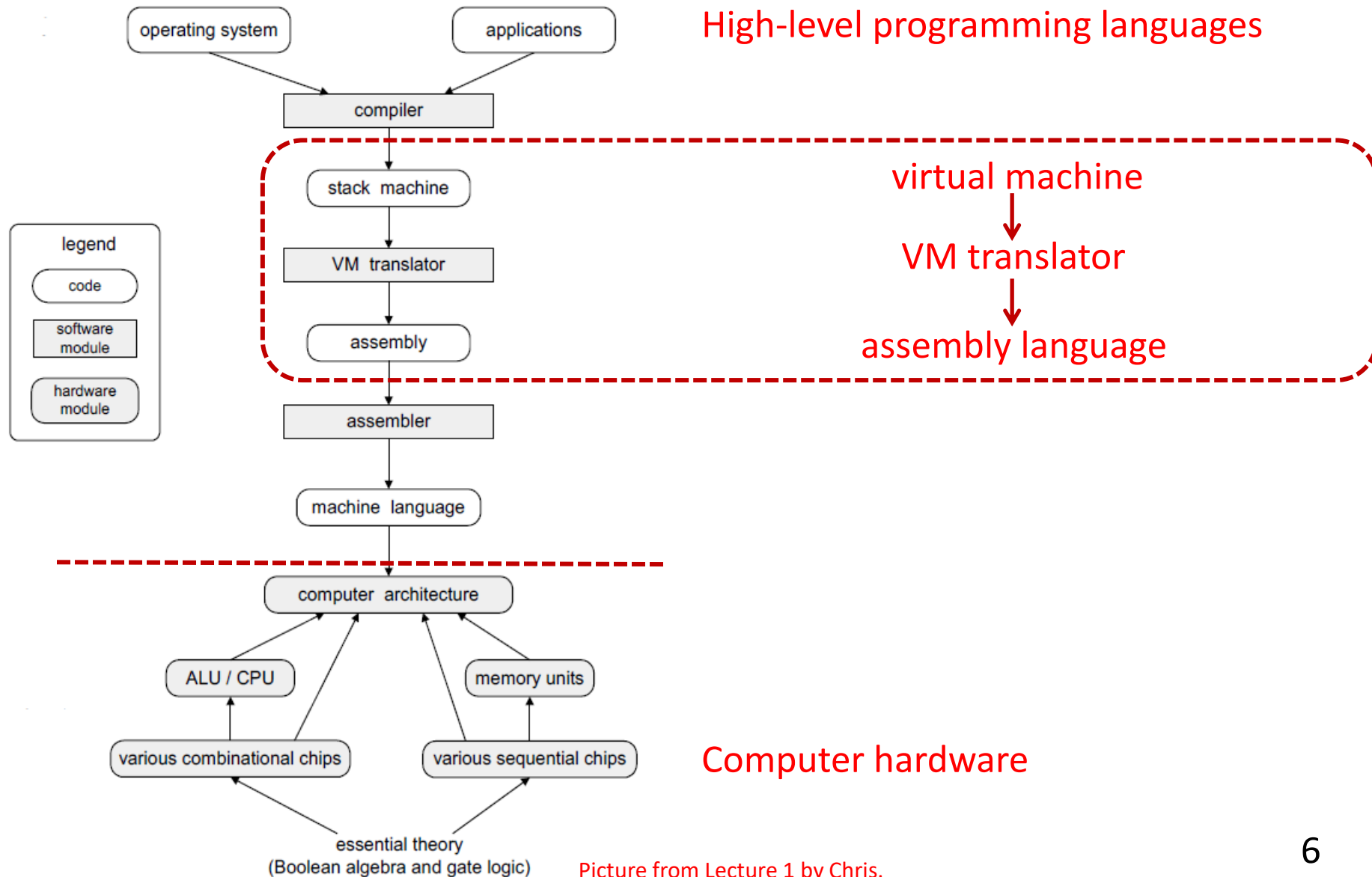
- Q: What makes the abstraction work?
- A:
 - Operating system,
 - Compiler,
 - Virtual machine,
 - Assembler.



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

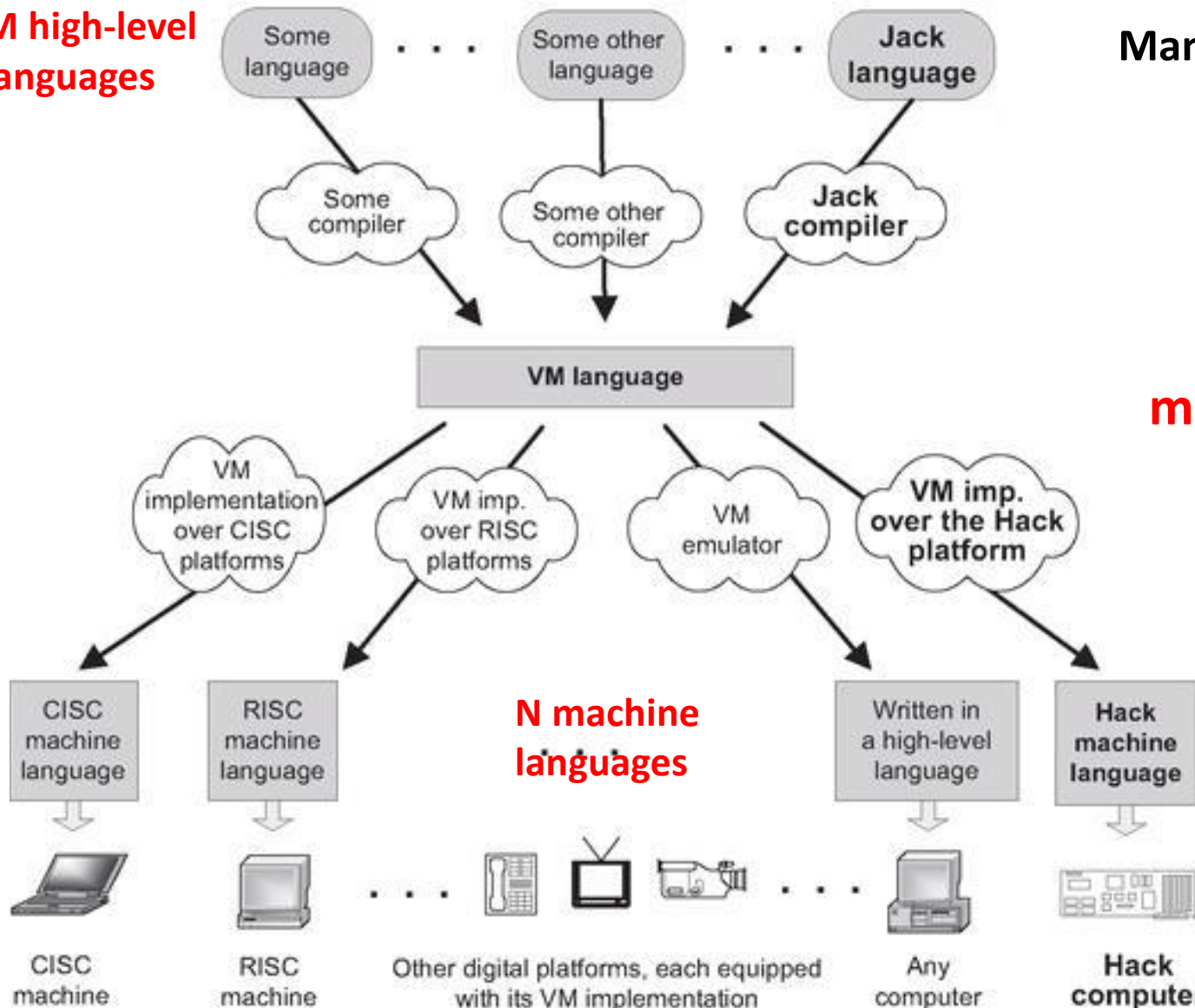
VM translator

N machine languages

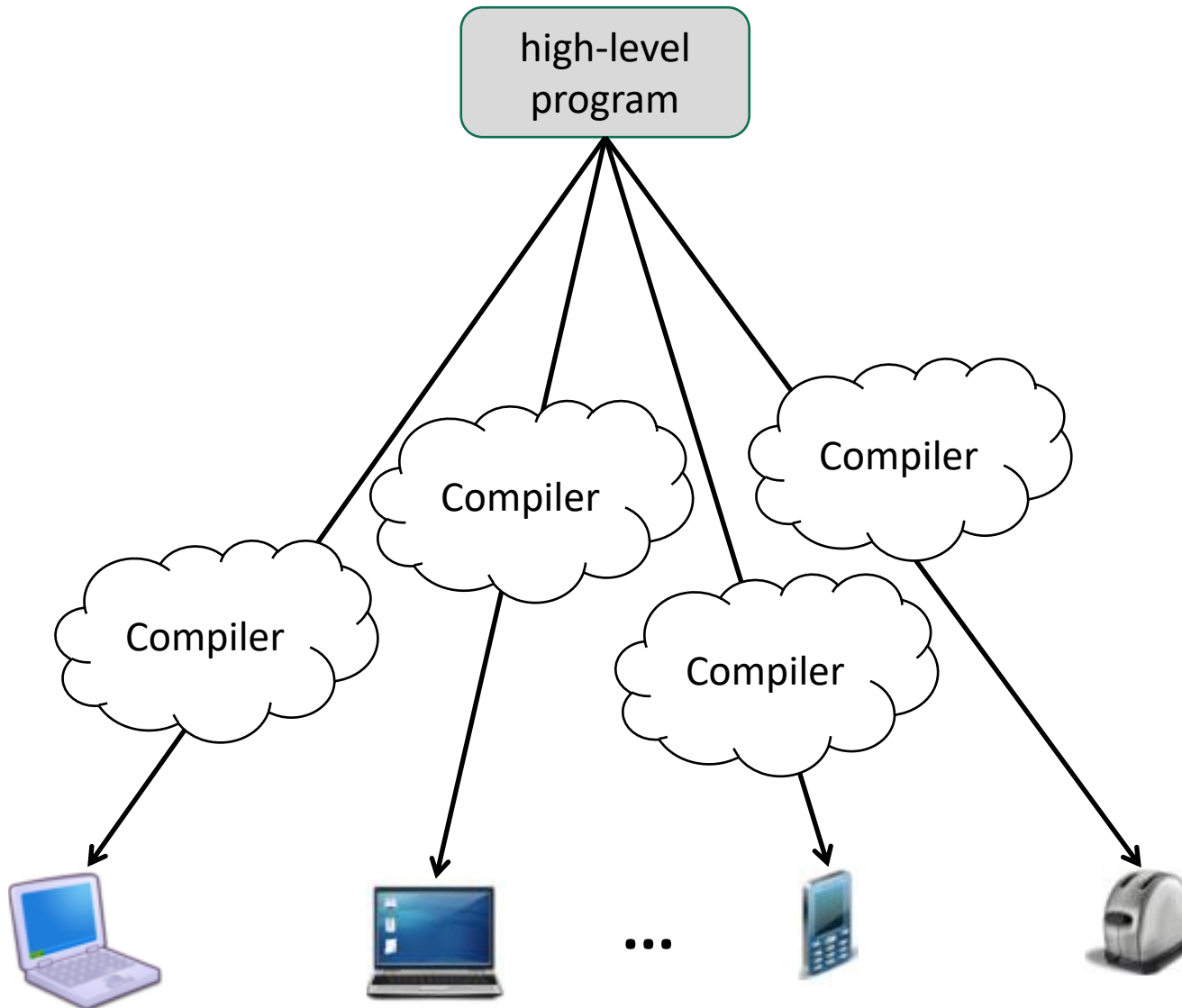
Machine language

Many computer hardwares

10

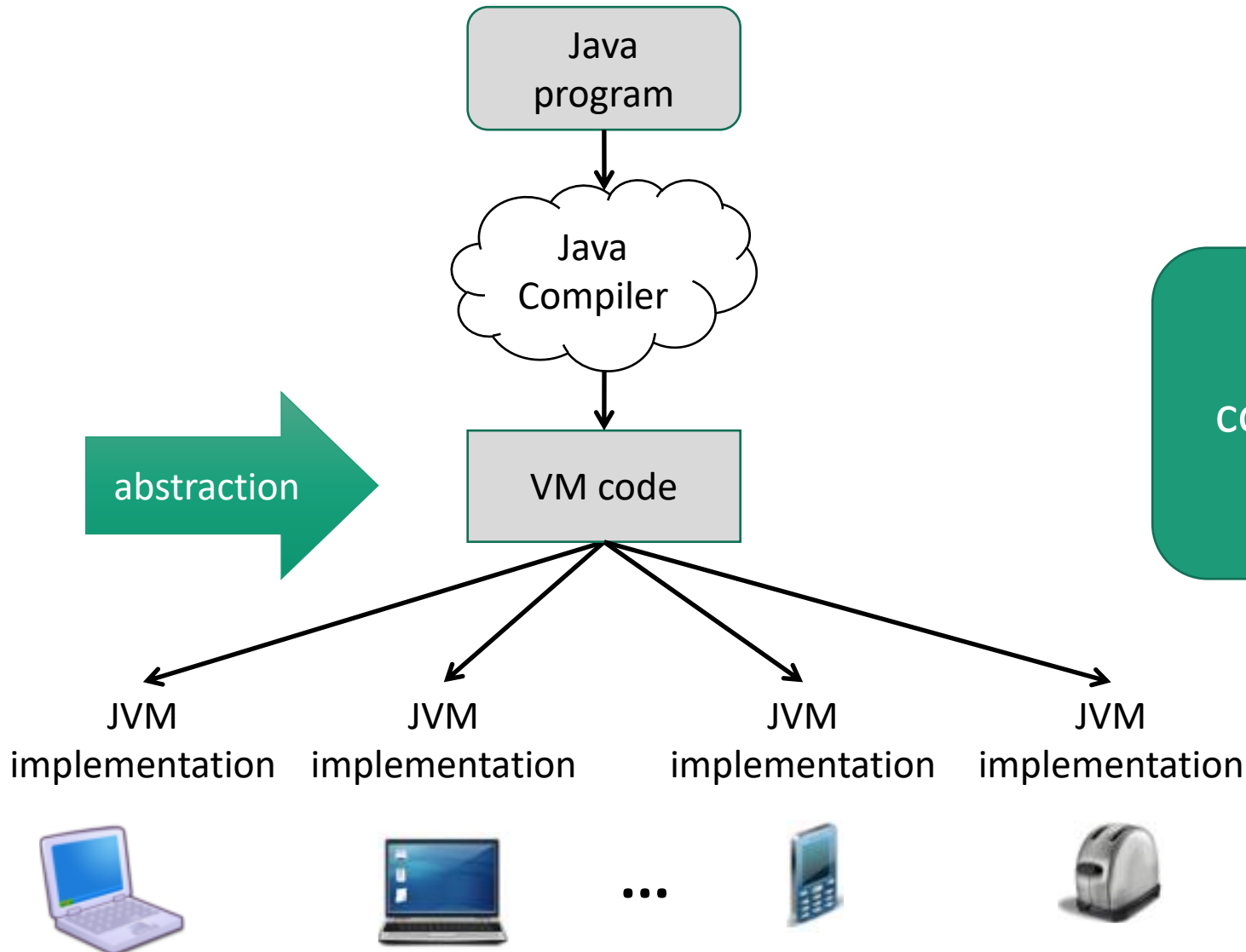


Program compilation: 1-tier



One compiler for
each device!

Program compilation: 2-tier



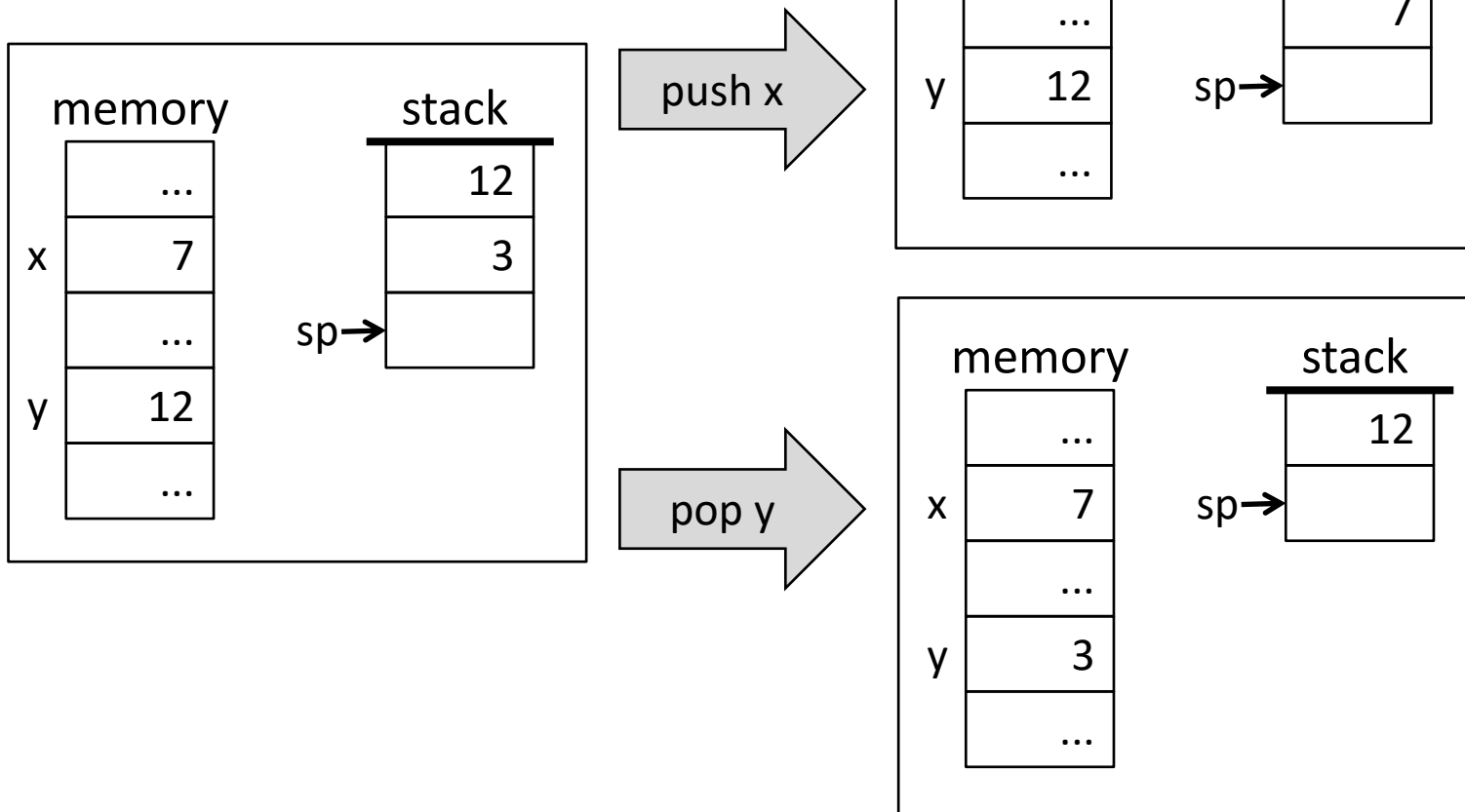
One Java
compiler for all
devices!

Stack machine model

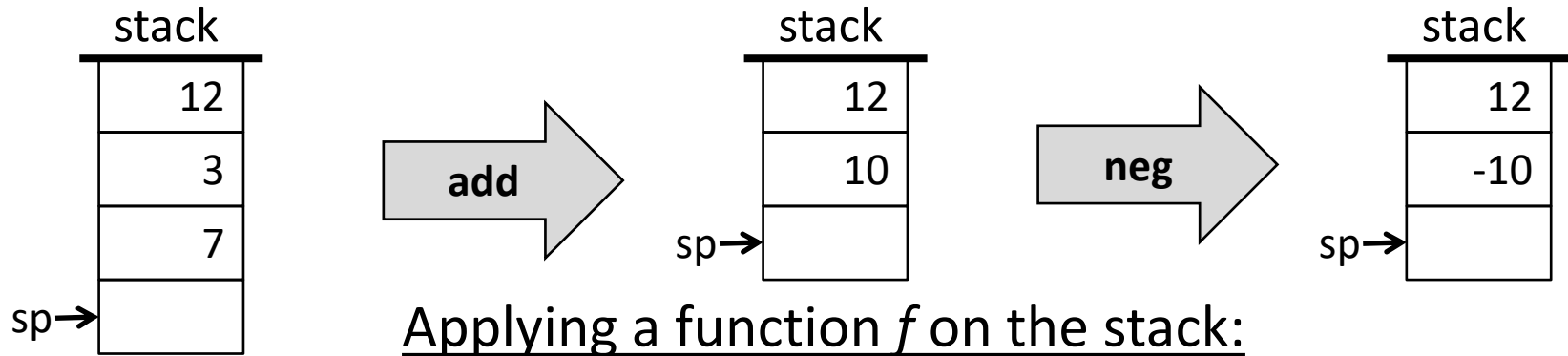
- Question: where will the operands and the results of the VM operations reside?
- Answer: put them on a stack data structure.
- Stack:
 - push: add an element at the stack's **top**.
 - pop: remove the **top** element.



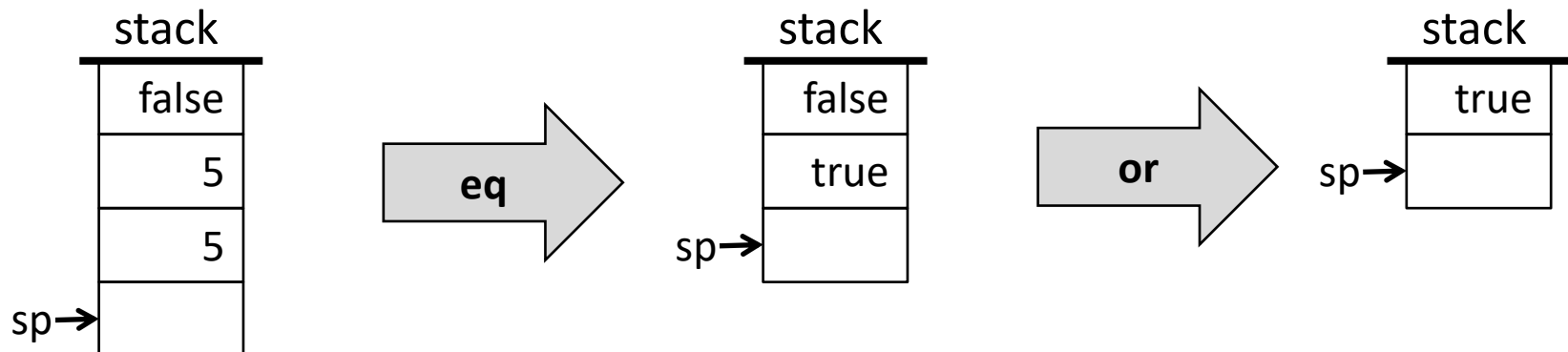
Stack



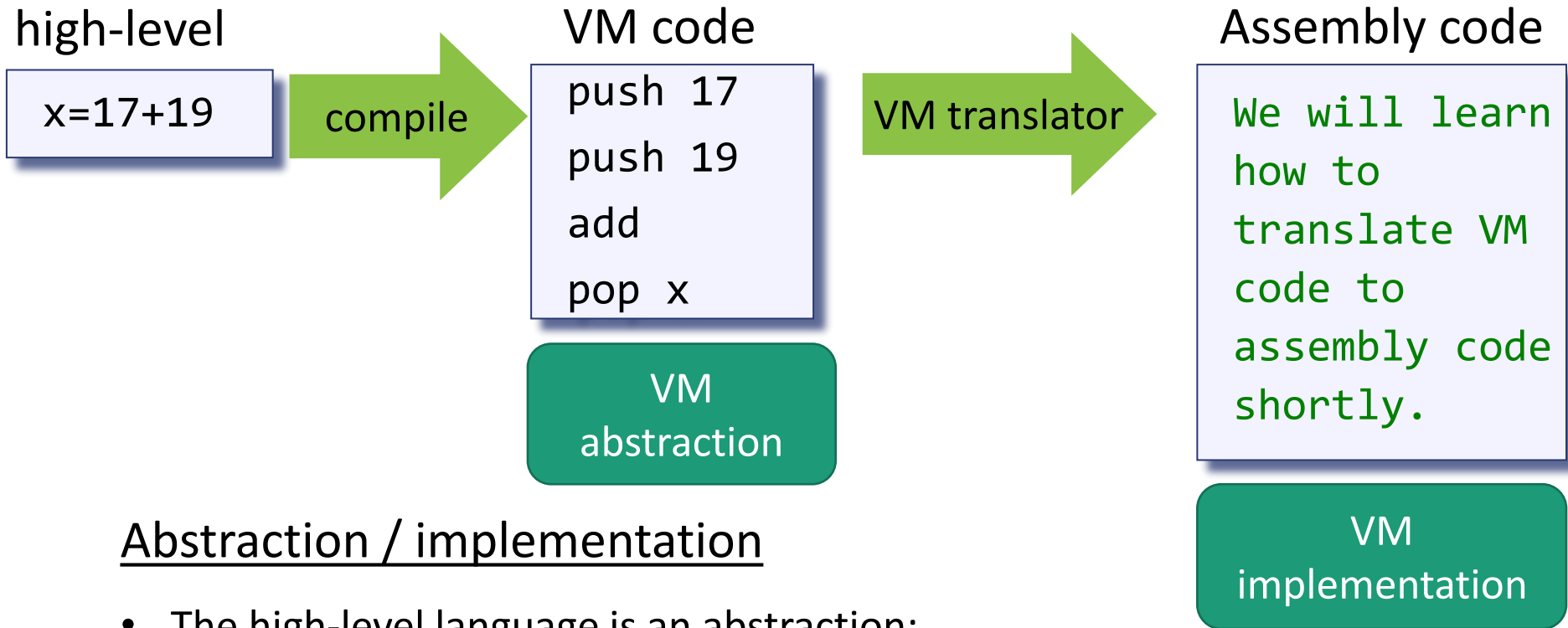
Stack arithmetic



- **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.

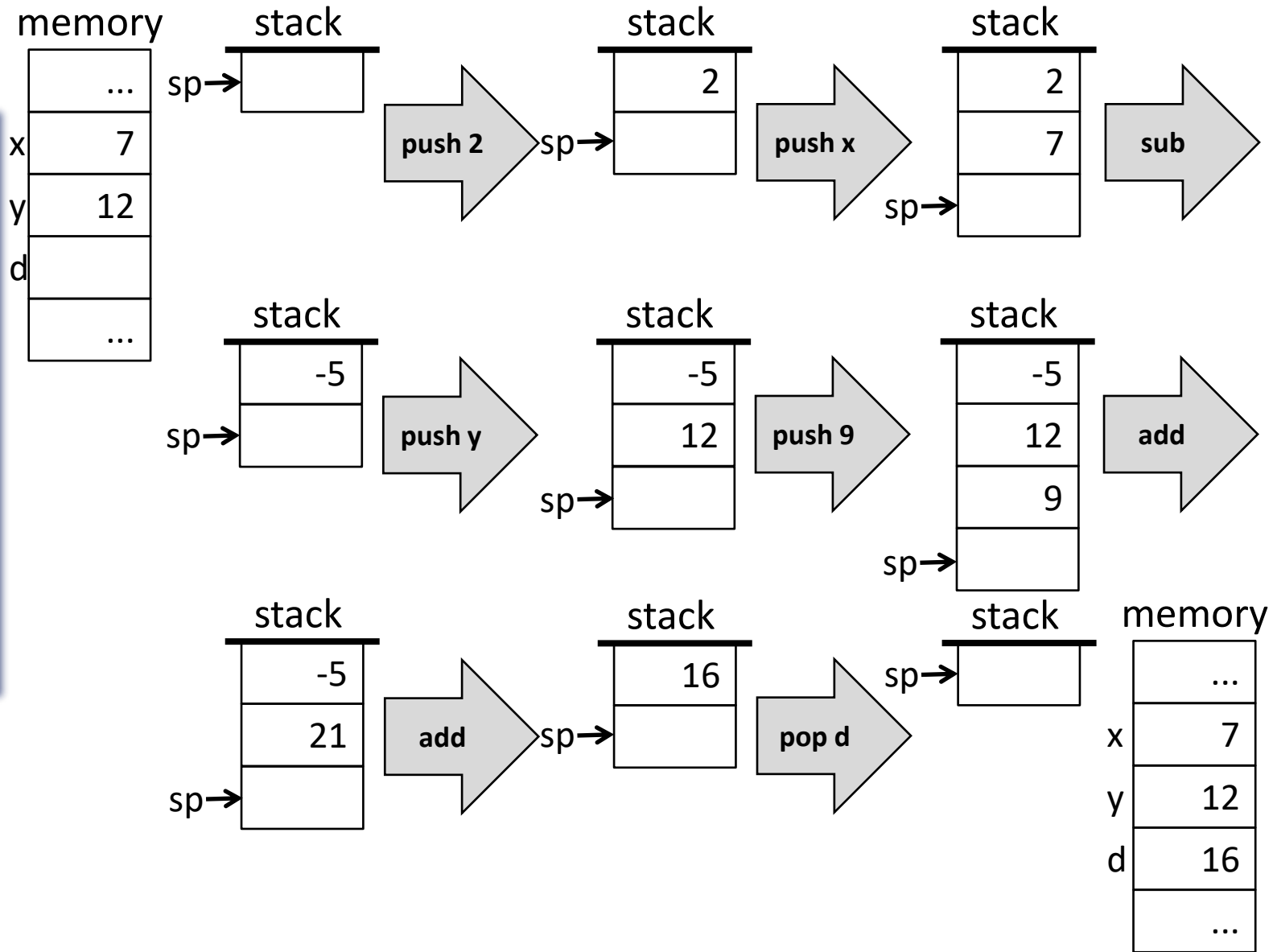
Outlines

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 - Arithmetic / logical commands
 - Memory segment commands
 - Branching commands
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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
```

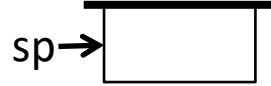
```
sub
```

```
pop d
```

memory

| | |
|---|-----|
| | ... |
| x | 7 |
| y | 12 |
| d | |
| | ... |

stack



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
```

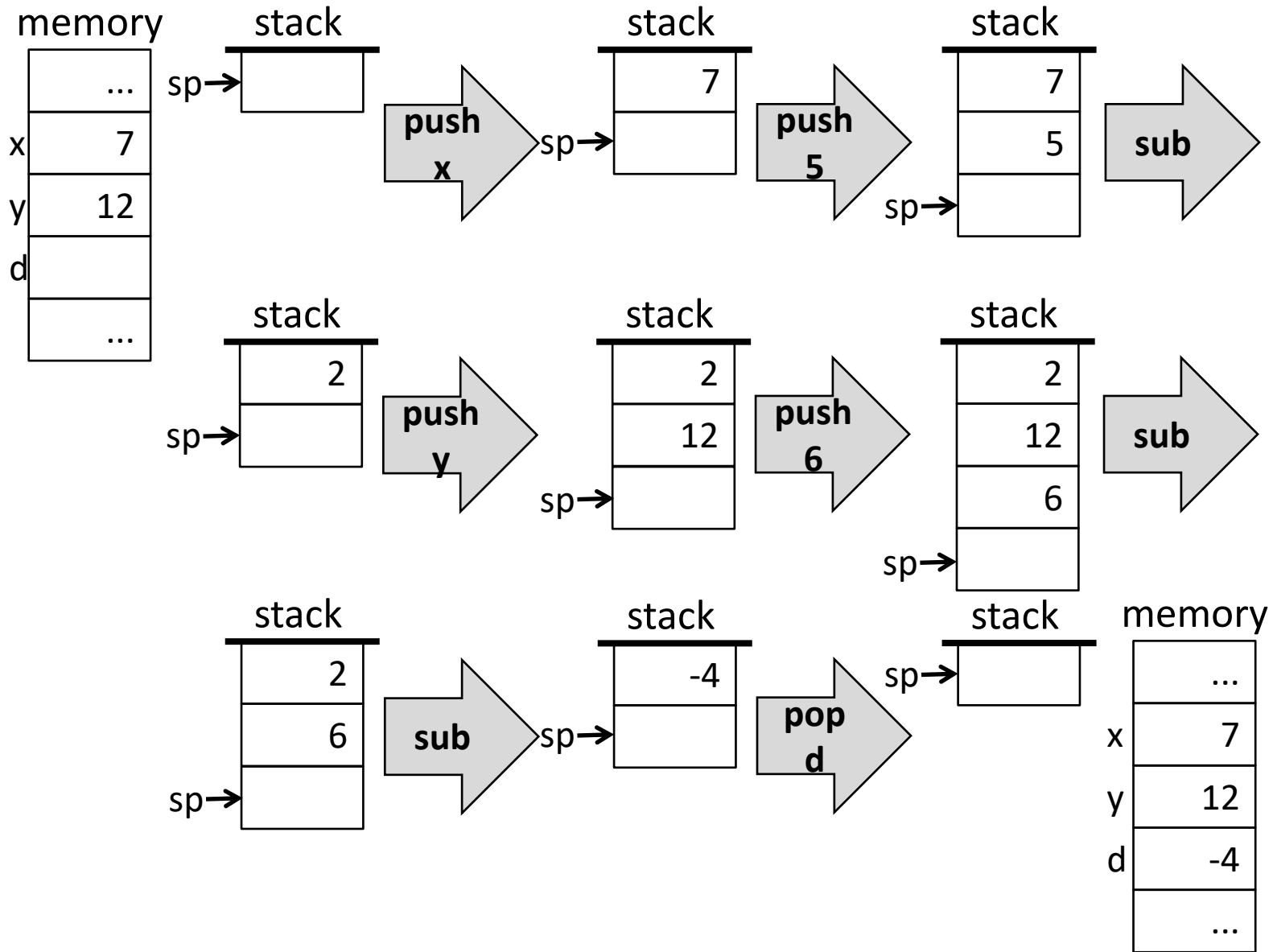
```
push y
```

```
push 6
```

```
sub
```

```
sub
```

```
pop d
```

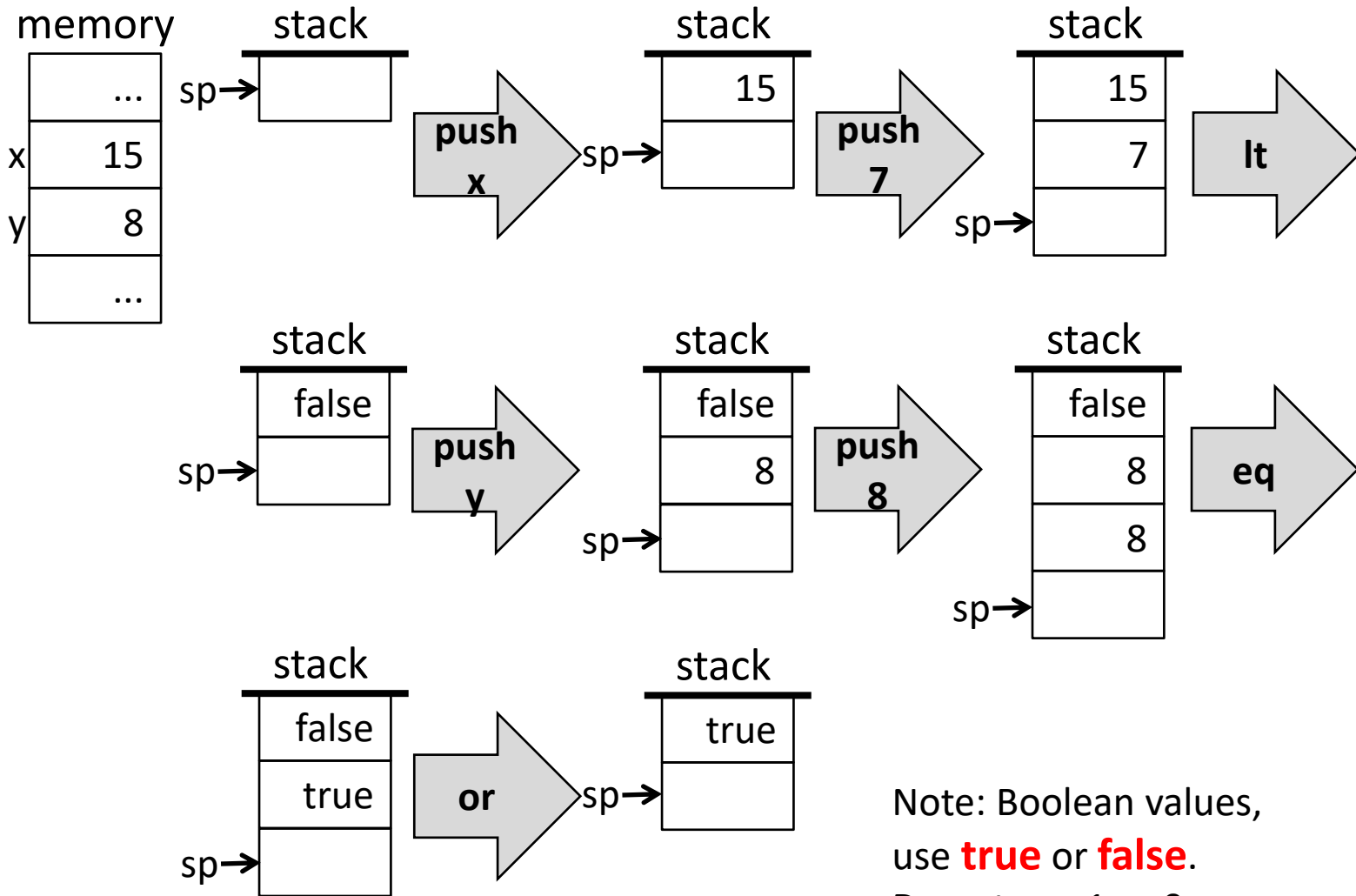


Logical commands

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
```

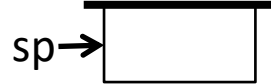
```
gt
```

```
and
```

memory

| | |
|---|-----|
| | ... |
| x | 15 |
| y | 8 |
| | ... |

stack



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

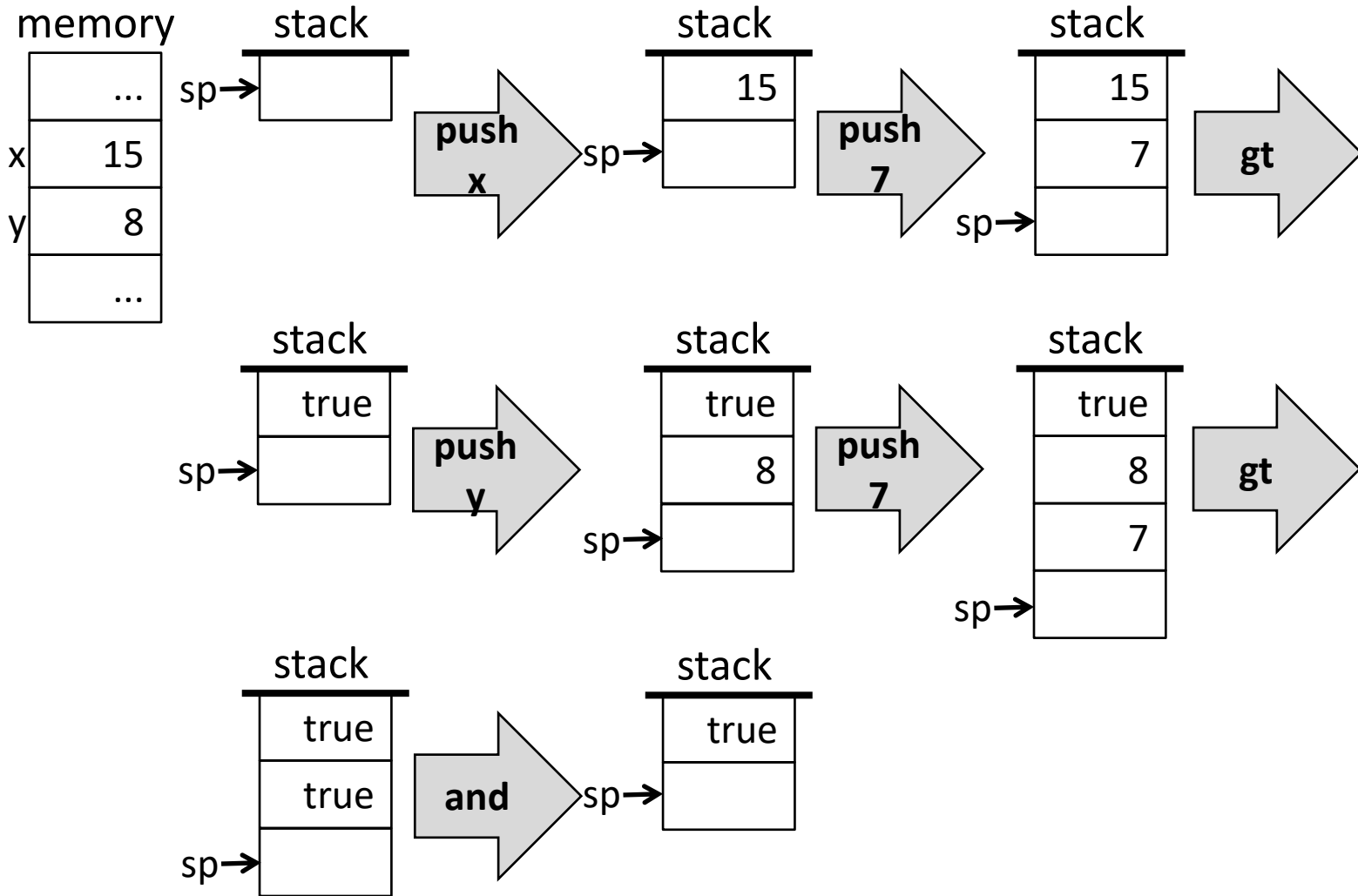
gt

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 | $x \text{ and } y$ | boolean |
| or | $x \text{ or } y$ | 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    static 0  
push y     argument 1  
add  
pop c      local 2  
...
```

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

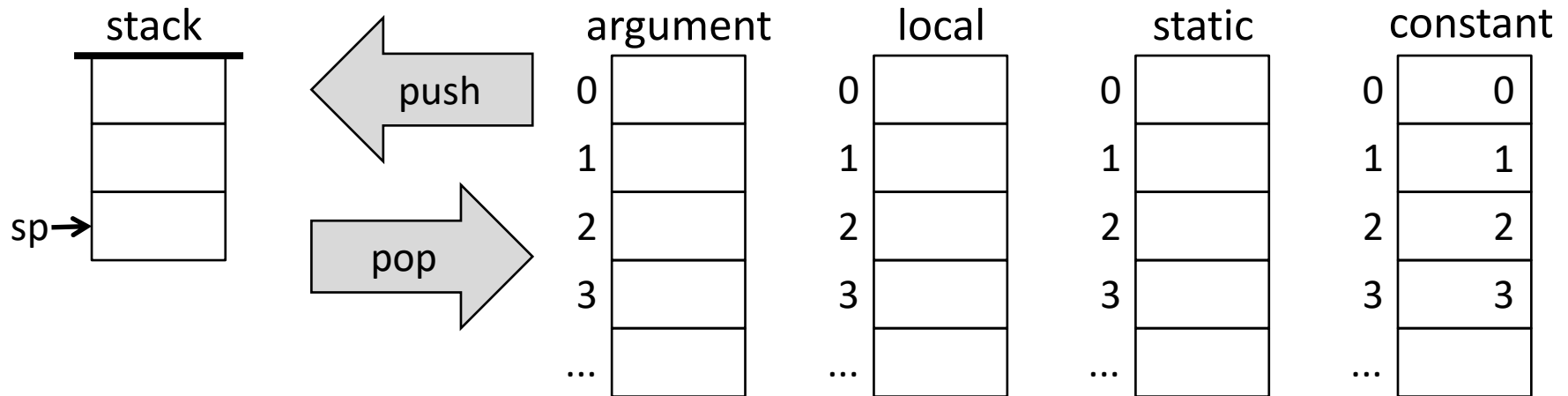
Variable kinds

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

Virtual memory segments:

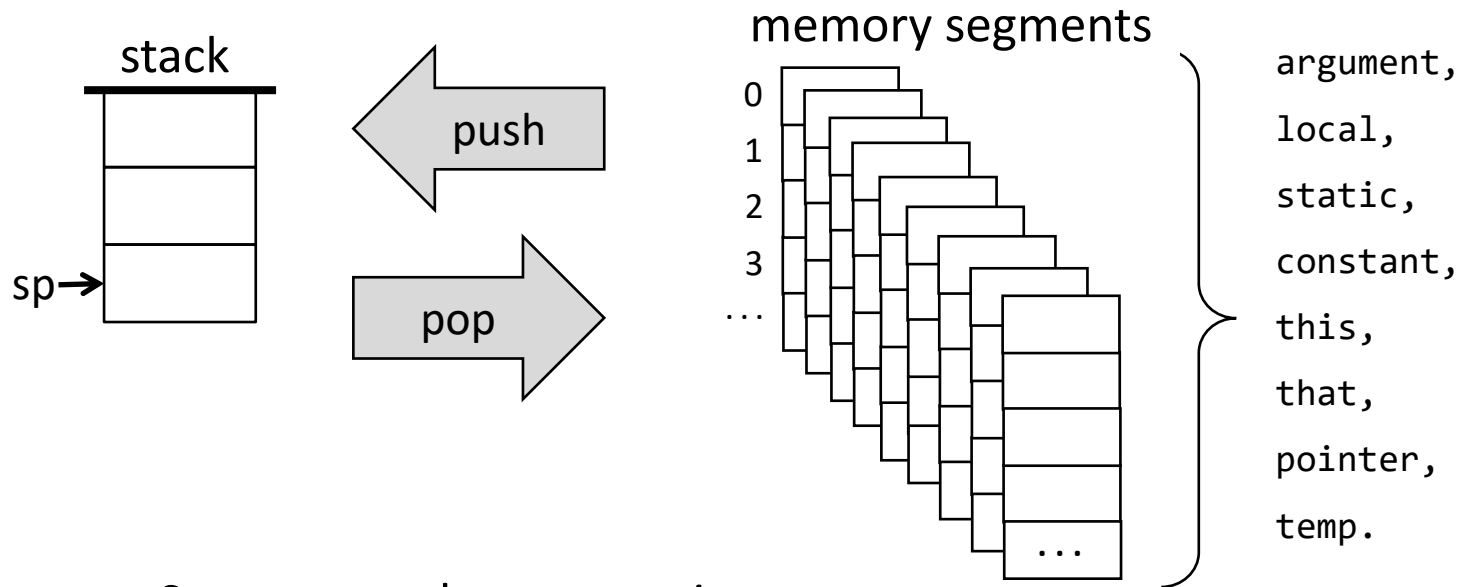
| argument | | local | | static | |
|----------|---|-------|---|--------|----|
| 0 | x | 0 | a | 0 | s1 |
| 1 | y | 1 | b | 1 | s2 |
| 2 | | 2 | c | 2 | |
| 3 | | 3 | | 3 | |
| ... | | ... | | ... | |

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.

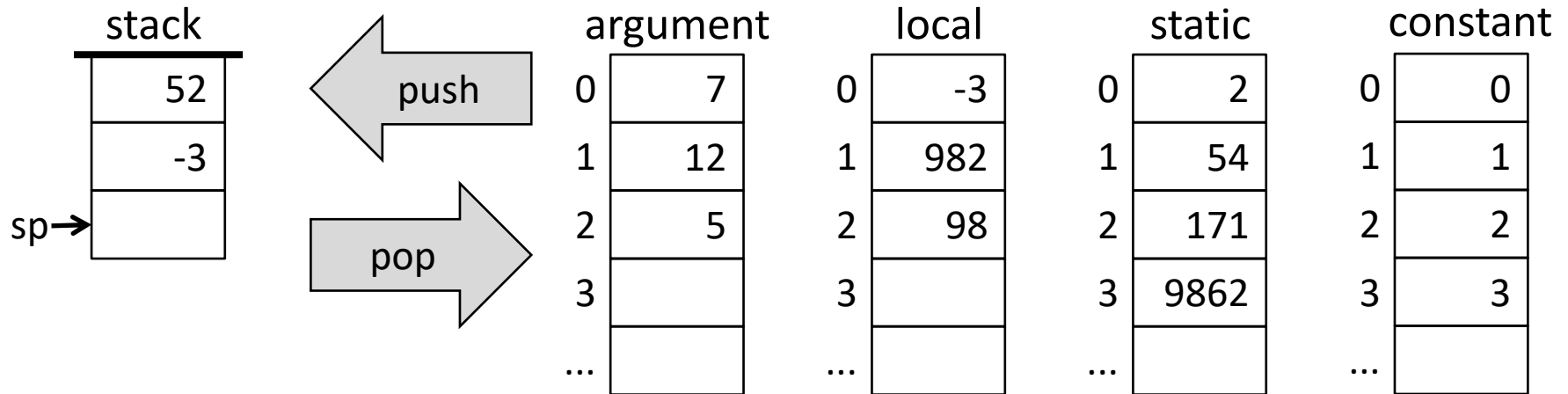
Syntax: `pop segment i`

Where *segment* is: argument, local, static,

this, that, pointer, or temp

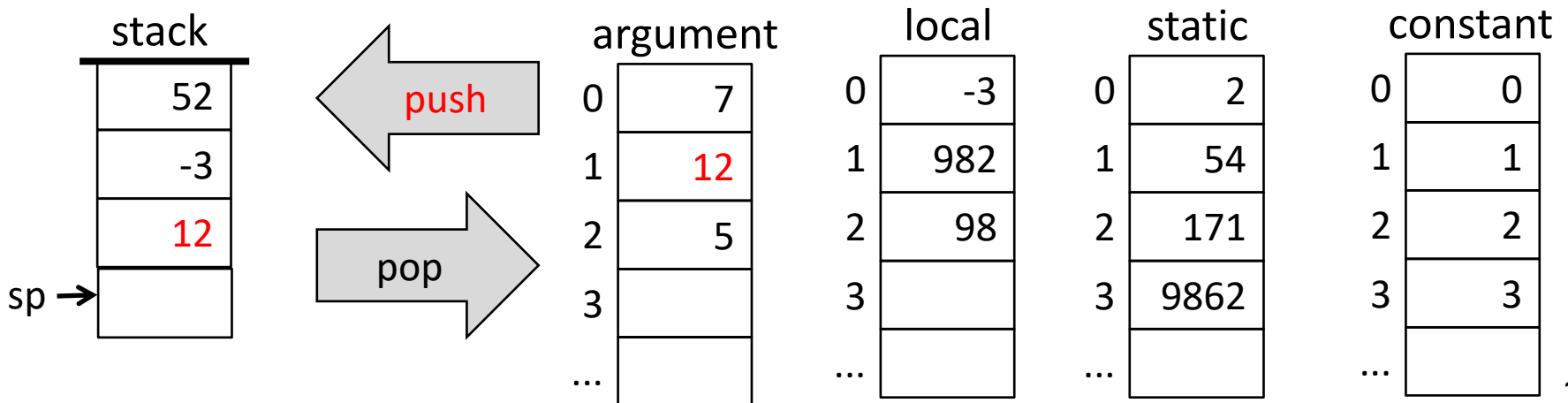
and *i* is a non-negative integer.

Memory segment commands

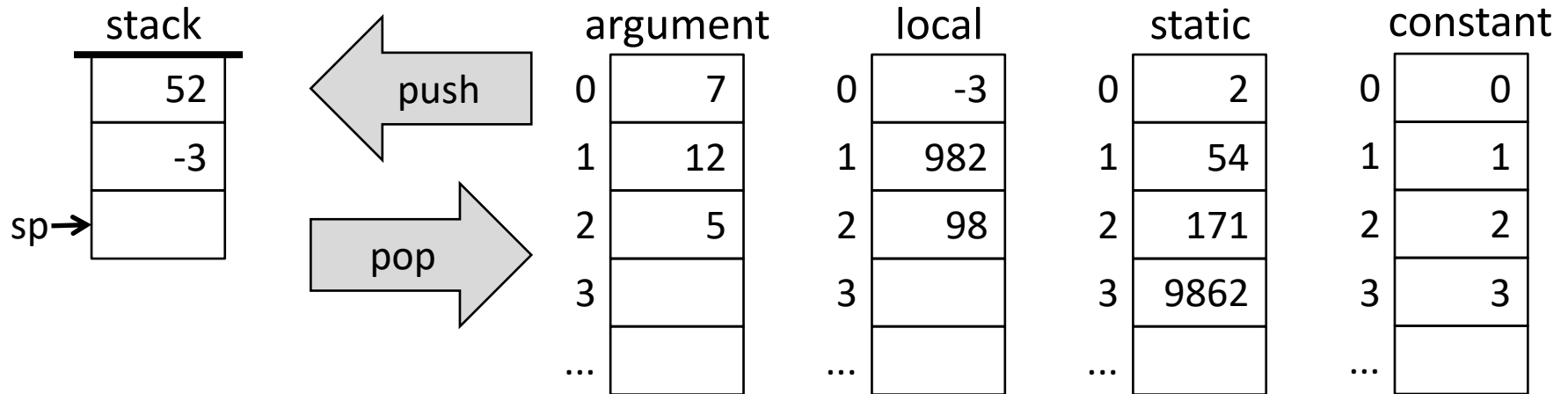


let static 2 = argument 1

push argument 1
pop static 2



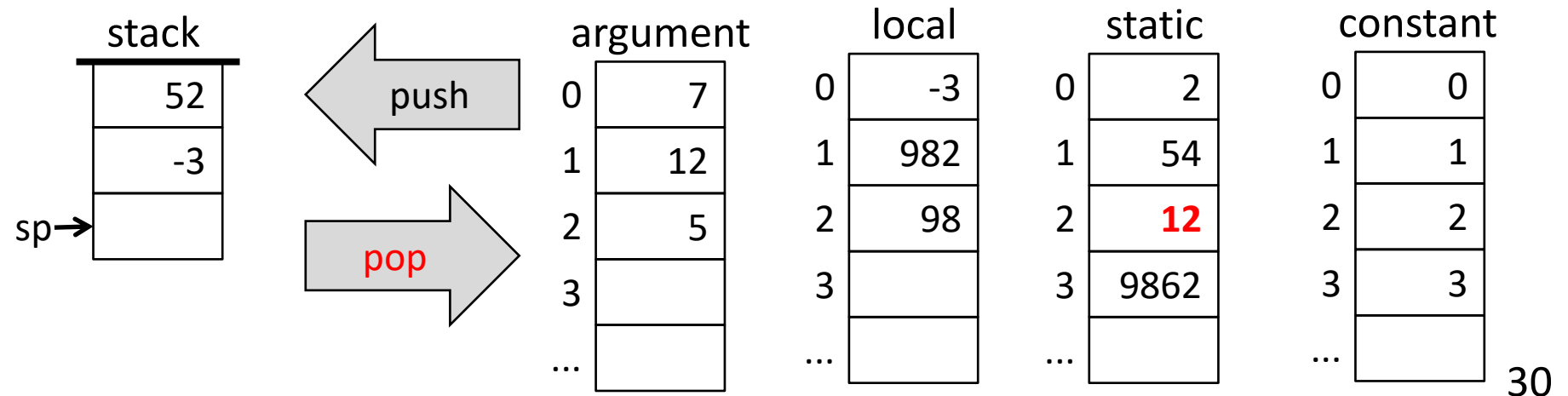
Memory segment commands



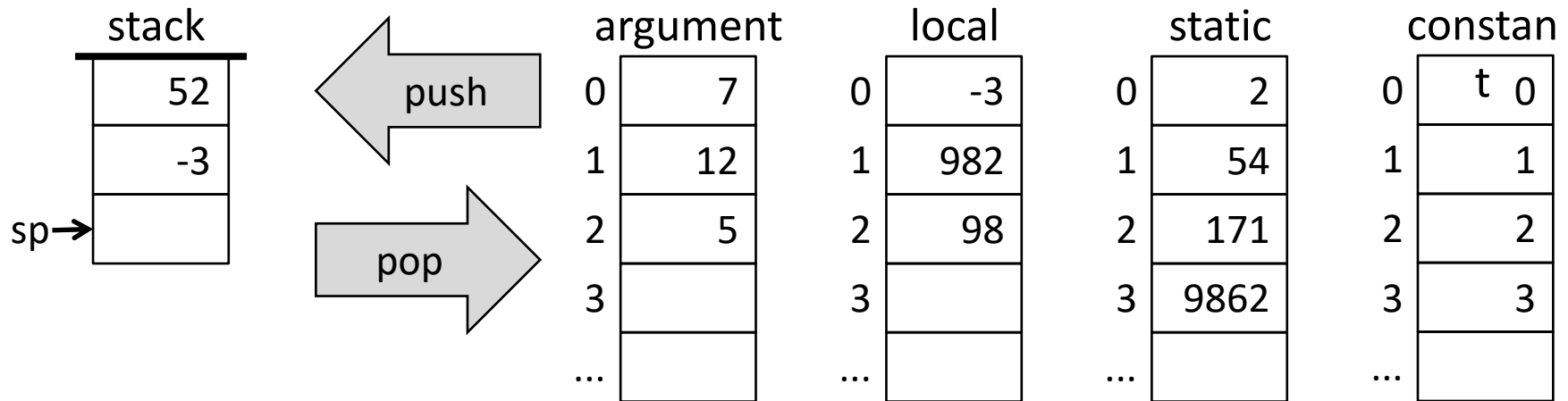
let static 2 = argument 1

push argument 1

pop static 2



Quiz: memory segment commands

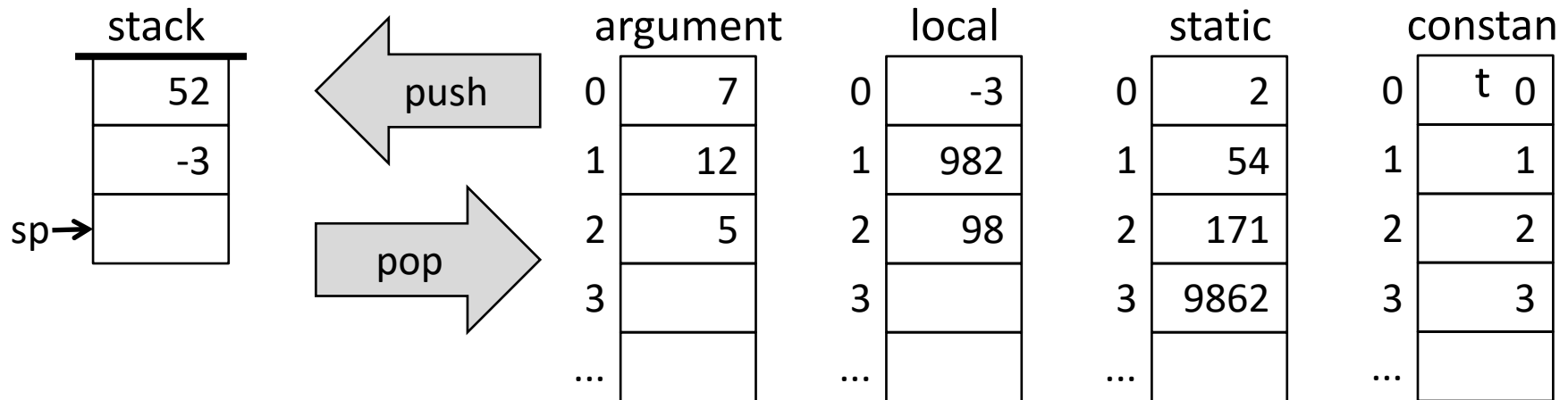


let local 2 = argument 1

How do stack and memory segments change?

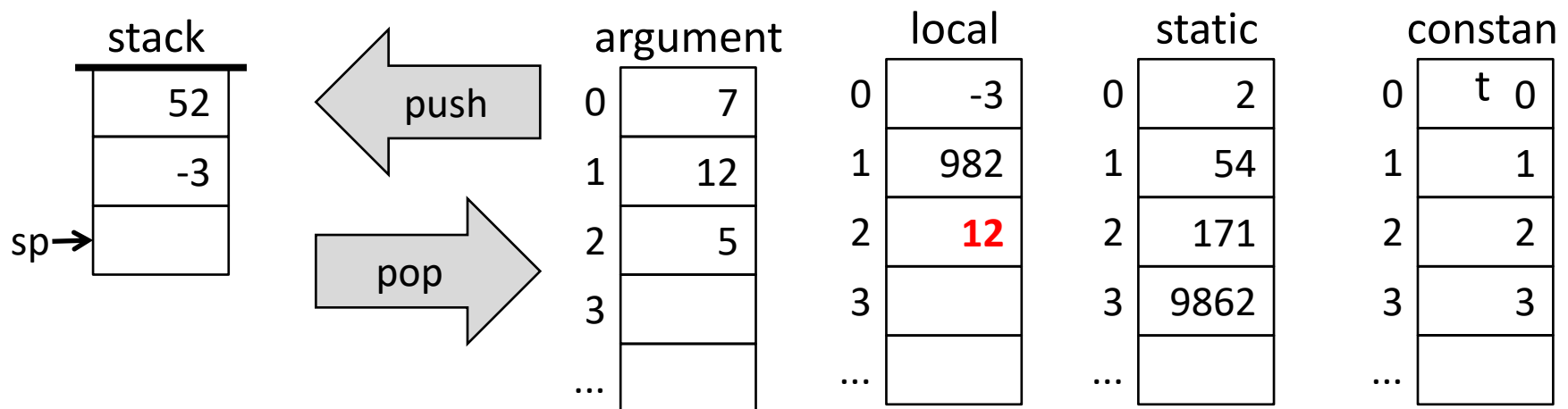
Please write down the key steps for stack operation and memory changes, similarly as last example.

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

High-level code

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

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push a
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call div
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goto CONTINUE
label A_NEQ_ZERO
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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
```

Program control

VM branching commands:

- *goto label*
- *if-goto label*
- *label label*

VM function commands:

- *call function*
- *function function*
- *return*

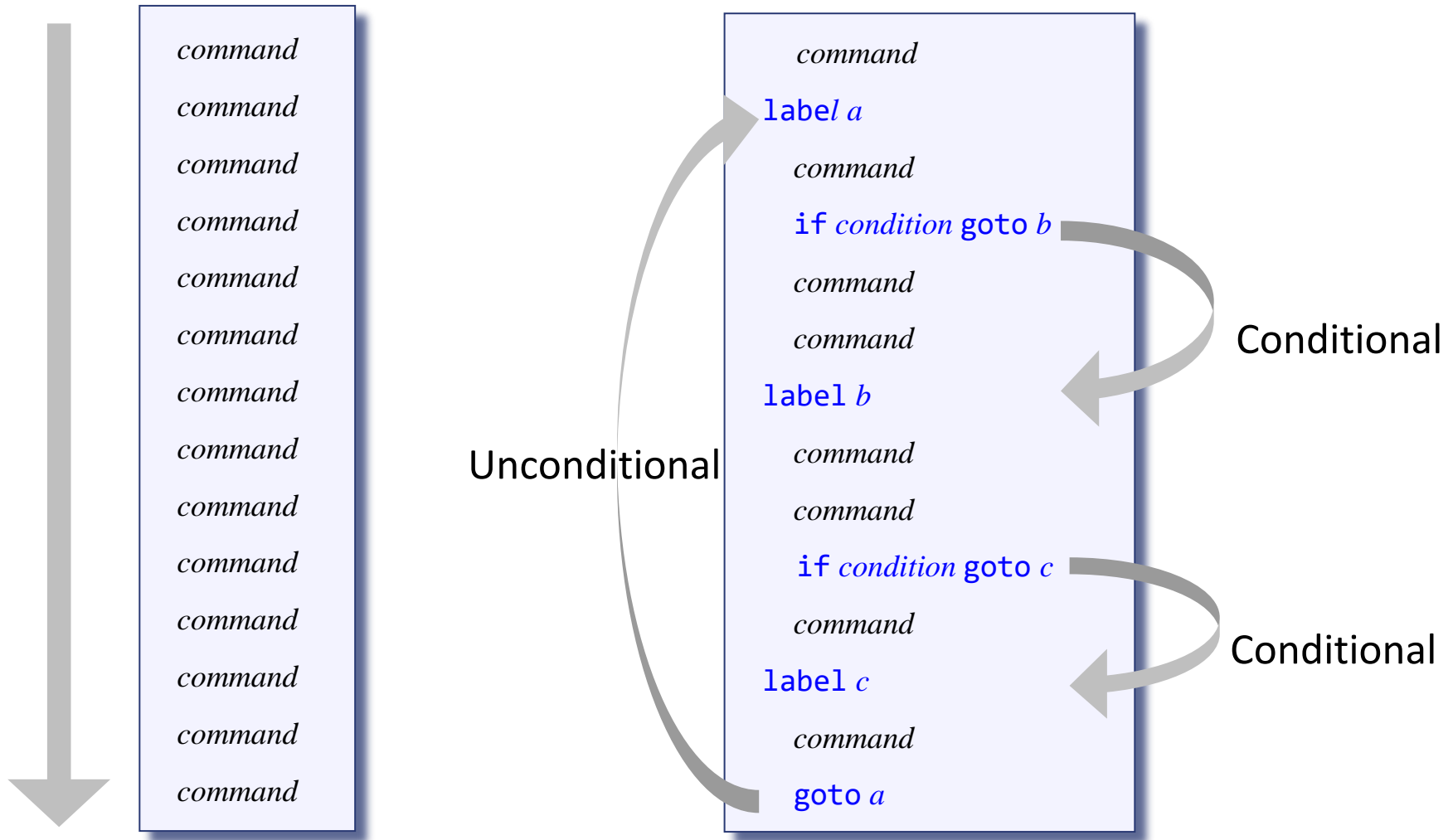
Challenges:

- 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;
}
```



compiler

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* = push
 - 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.

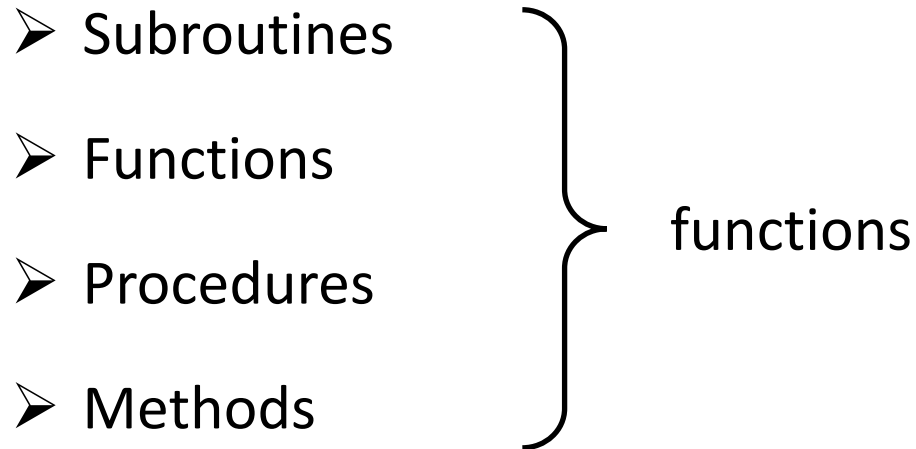
The assembly language has similar branching commands.

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Functions

- High-level programming languages can be extended using:



(different names of the same thing)

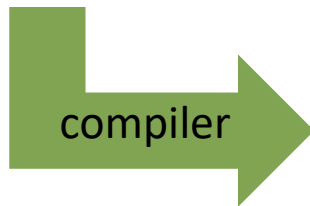
Functions in VM language

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;
}
```



compiler

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

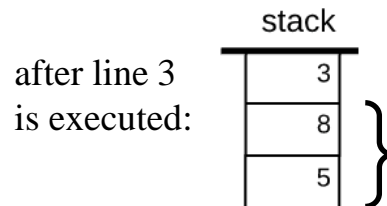
```
// Computes 3 + 8 * 5
0 function main 0
1 push constant 3
2 push constant 8
3 push constant 5
4 call mult 2 // 2 args
5 add
6 return
```

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
```

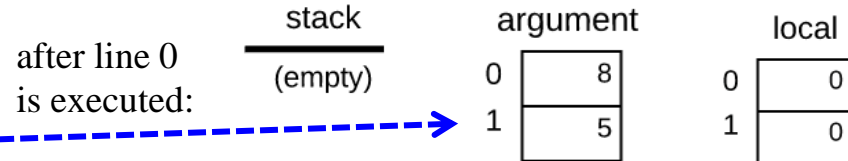
callee

main view:



after line 4
is executed:

mult view:



Functions in VM language: executing

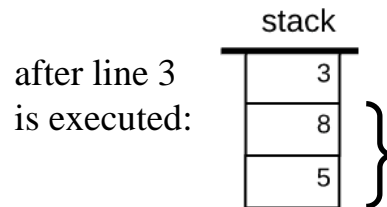
```
// Computes 3 + 5 * 8
0 function main 0
1 push constant 3
2 push constant 8
3 push constant 5
4 call mult 2 // 2 args
5 add
6 return
```

caller

```
// Computes the product of two given arguments
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4 pop local 1
5 label LOOP
6 push local 1
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  //... computes the product into local 0
19 label END
20 push local 0
21 return
```

callee

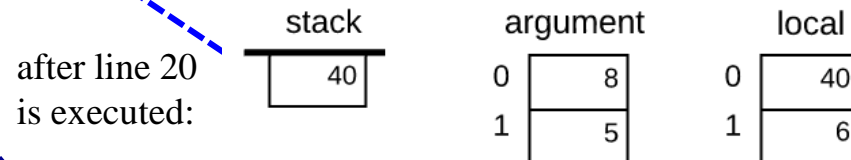
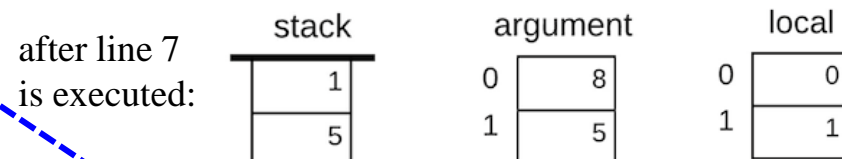
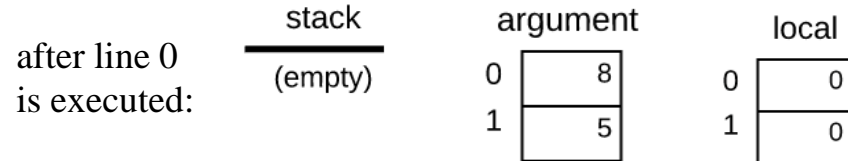
main view:



after line 4
is executed:

return

mult view:



Functions in VM language: executing

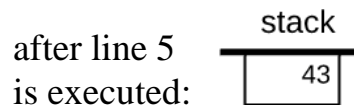
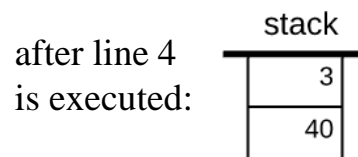
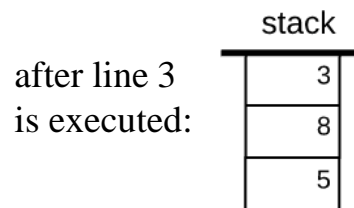
```
// Computes 3 + 5 * 8
0 function main 0
1 push constant 3
2 push constant 8
3 push constant 5
4 call mult 2 // 2 args
5 add
6 return
```

caller

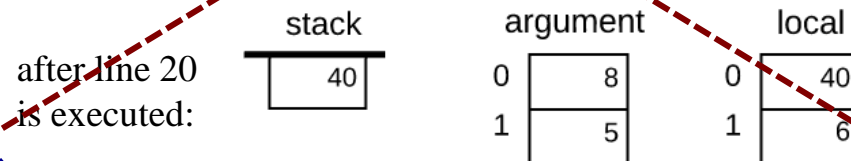
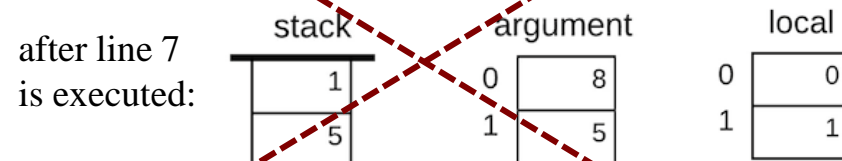
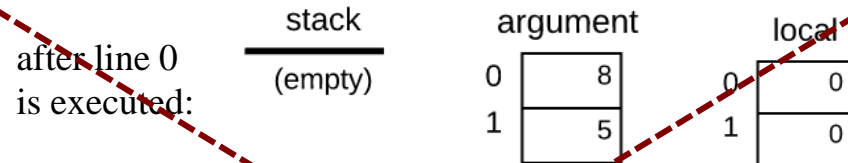
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4 pop local 1
5 label LOOP
6 push local 1
7 push argument 1
  //... computes the product into local 0
19 label END
20 push local 0
21 return
```

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
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 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



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5 label LOOP
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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

```
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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.

Summary

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