

Chapter 7

Virtual Machine, Part I

These slides support chapter 7 of the book

The Elements of Computing Systems

By Noam Nisan and Shimon Schocken

MIT Press

Virtual machine: lecture plan

Overview

- 
- The road ahead
 - Program compilation

VM implementation platforms

- VM emulator
- VM translator

VM abstraction

- the stack
- memory segments

The VM translator

- Proposed implementation
- Building it (project 7)

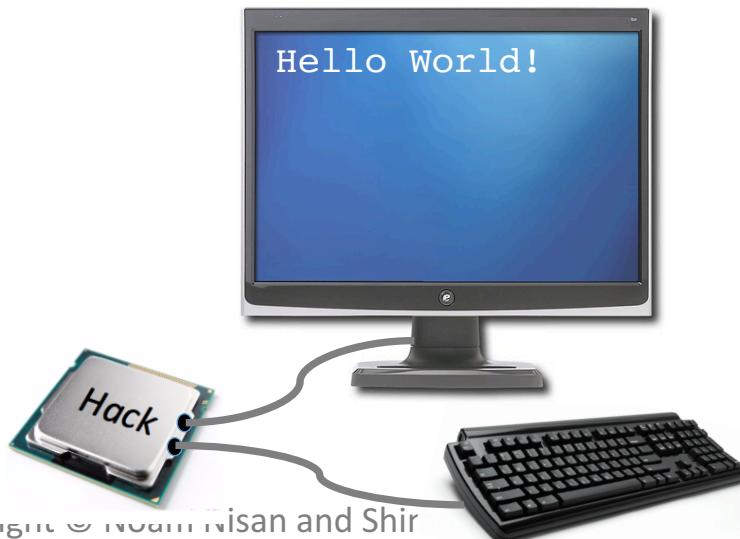
VM implementation

- the stack
- memory segments

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;
    }
}
```



Hello World Below

Jack program

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

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?



Hello World Below

Jack program

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

abstraction

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

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



Hello World Below

Jack program

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

abstraction

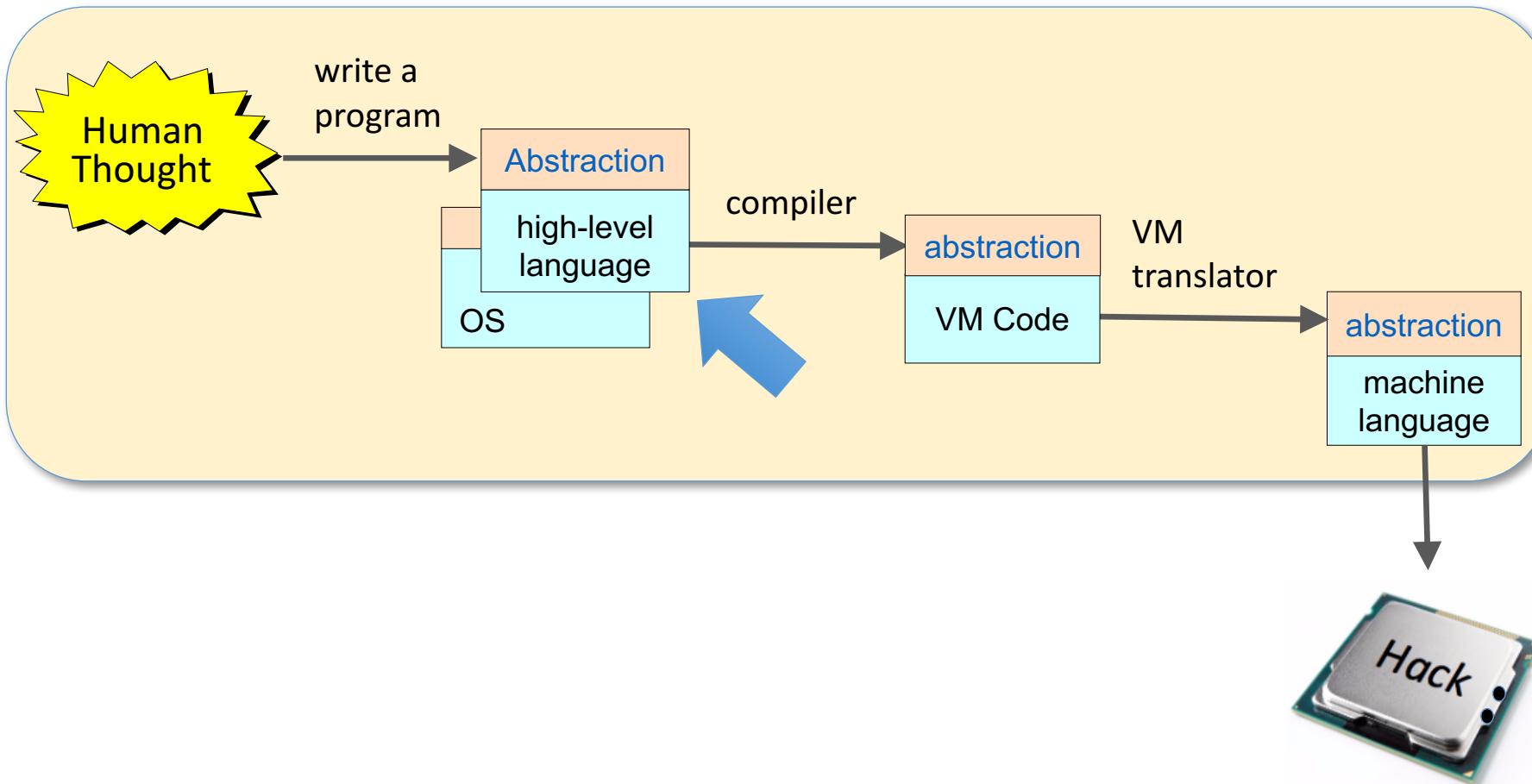
Q: What makes the abstraction work?

- A:
- Assembler
 - Virtual machine
 - Compiler
 - Operating system

Chapters 6-12



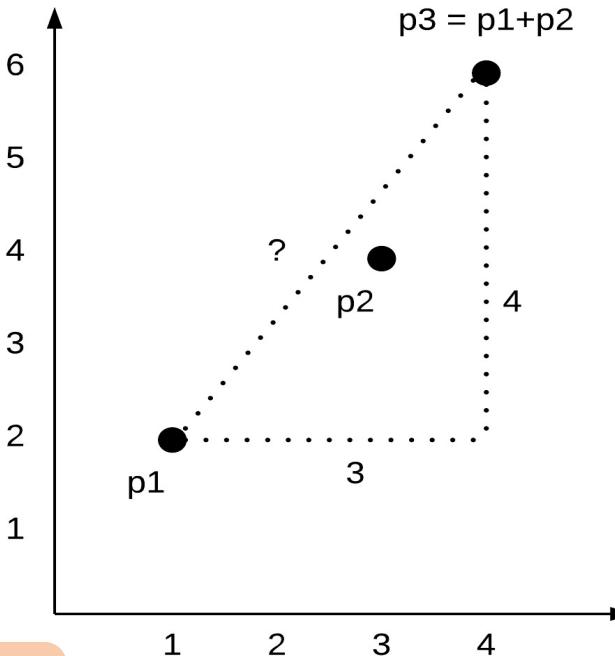
The big picture



High-level programming

```
/** Demo: working with Point objects */
class Main {
    function void main() {
        var Point p1, p2, p3;
        let p1 = Point.new(1,2);
        let p2 = Point.new(3,4);
        let p3 = p1.plus(p2);
        do p3.print();
        do Output.println();
        do Output.putInt(p1.distance(p3));
        return;
    }
}
```

Written in the
Jack language



```
class Point { // API
    /** Constructs a new point with the given coordinates */
    constructor Point new(int ax, int ay) {}

    /** Returns the point which is this point plus the other point */
    method Point plus(Point other) {}

    /** Cartesian distance between this and the other point */
    method int distance(Point other) {

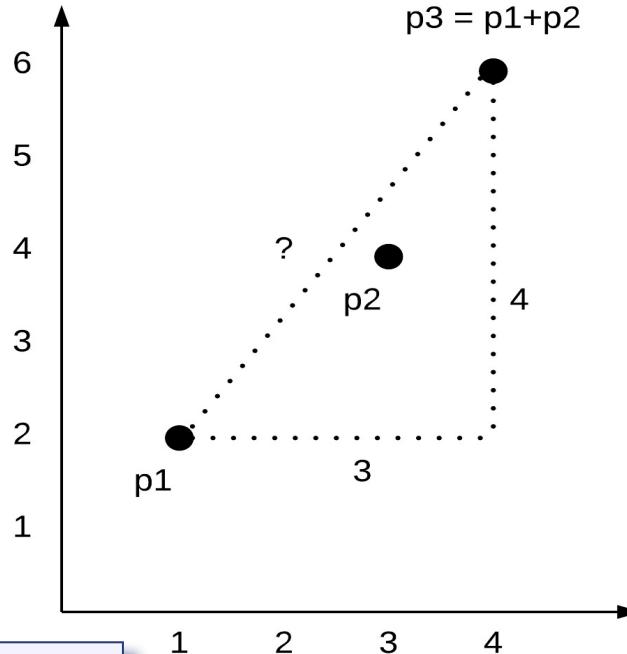
        /** Prints this point, as (x,y) */
        method void print() {
            ...
        }
    }
}
```



High-level programming

```
/** Demo: working with Point objects */
class Main {
    function void main() {
        var Point p1, p2, p3;
        let p1 = Point.new(1,2);
        let p2 = Point.new(3,4);
        let p3 = p1.plus(p2);
        do p3.print();
        do Output.println();
        do Output.putInt(p1.distance(p3));
        return;
    }
}
```

```
/** Represents a Point */
class Point {
    field int x, y;
    static int pointCount;
    /** Constructs a new point */
    constructor Point new(int ax, int ay) {
        let x = ax;
        let y = ay;
        let pointCount = pointCount + 1;
        return this;
    }
    // More Point methods...
}
```



High-level programming / Point class

```
/** Represents a Point; Stored in the file Point.jack */
class Point {
    field int x, y; // the coordinates of this point
    static int pointCount; // the number of Point objects constructed so far
    /** Constructs a new point with the given coordinates */
    constructor Point new(int ax, int ay) {
        let x = ax;
        let y = ay;
        let pointCount = pointCount + 1;
        return this;
    }
    /** Returns the x coordinate of this point */
    method int getx() { return x; }

    /** Returns the y coordinate of this point */
    method int gety() { return y; }

    /** Returns the number of Point objects constructed so far */
    method int getPointCount() { return pointCount; }

    /** Returns the point which is this point plus the other point */
    method Point plus(Point other){
        return Point.new(x + other.getx(), y + other.gety());
    }
}
```

High-level programming / Point class

```
/** Represents a Point; Stored in the file Point.jack */
class Point {
    field int x, y; // the coordinates of this point
    static int pointCount; // the number of Point objects constructed so far
    // The methods from the previous slide...

    /** Returns the Cartesian distance between this and the other point */
    method int distance(Point other) {
        var int dx, dy;
        let dx = x - other.getx();
        let dy = y - other.gety();
        return Math.sqrt((dx*dx)+(dy*dy));
    }

    /** Prints this point, as (x,y) */
    method void print() {
        do Output.printString("(");
        do Output.printInt(x);
        do Output.printString(",");
        do Output.printInt(y);
        do Output.printString(")");
        return;
    }
} // class Point ends here
```

Jack has the look and feel of
a typical high-level, object-
based language

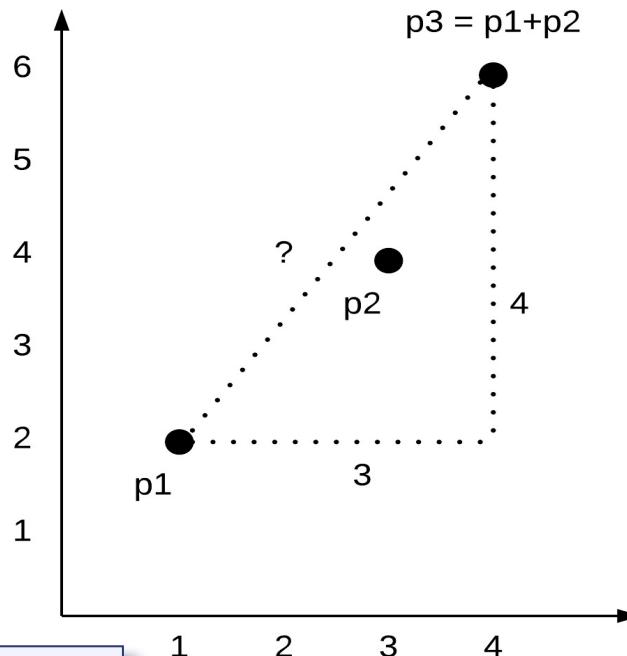
Recap

```
/** Demo: working with Point objects */
class Main {
    function void main() {
        var Point p1, p2, p3;
        let p1 = Point.new(1,2);
        let p2 = Point.new(3,4);
        let p3 = p1.plus(p2);
        do p3.print();
        do Output.println();
        do Output.putInt(p1.distance(p3));
        return;
    }
}
```

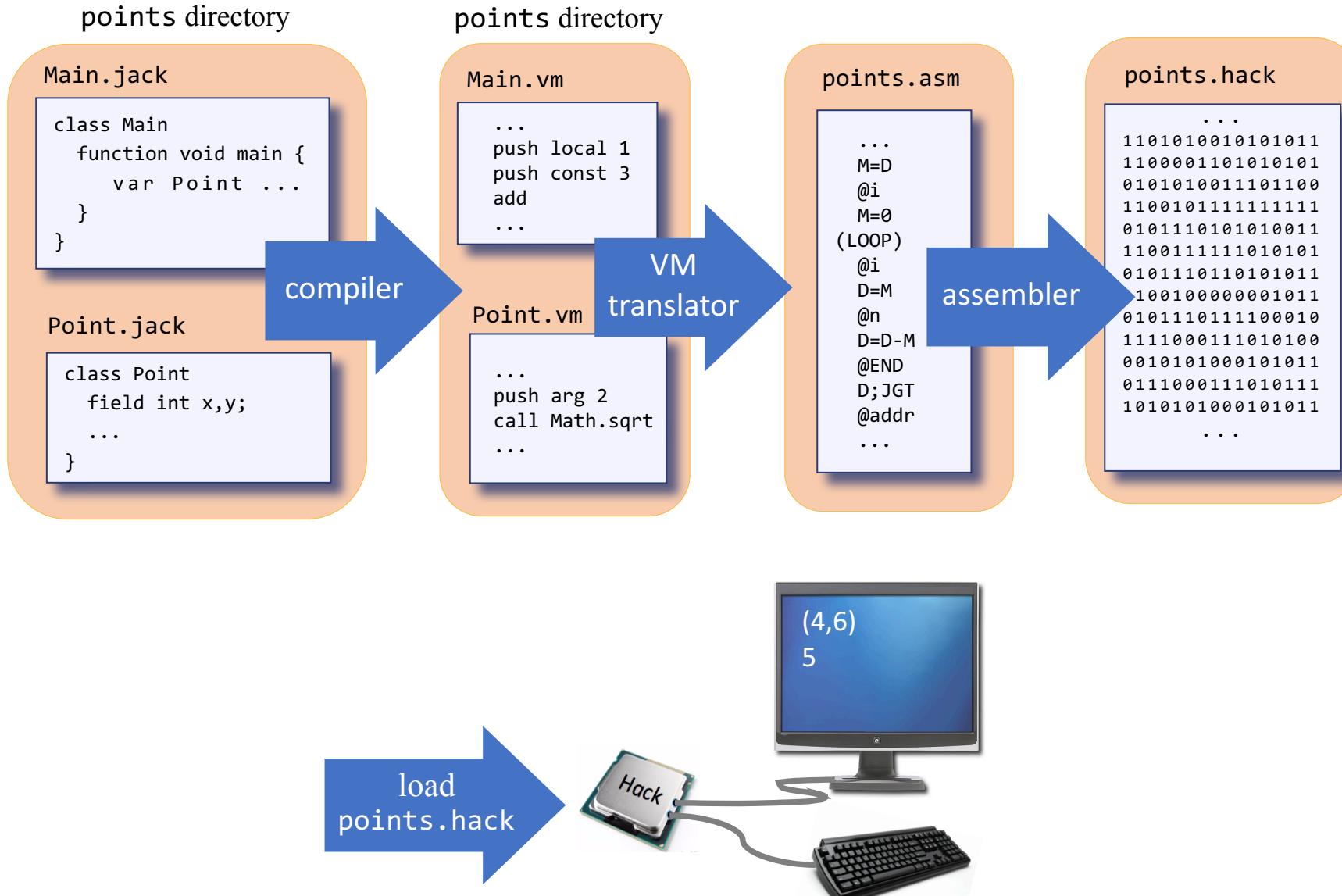
Main.jack

Point.jack

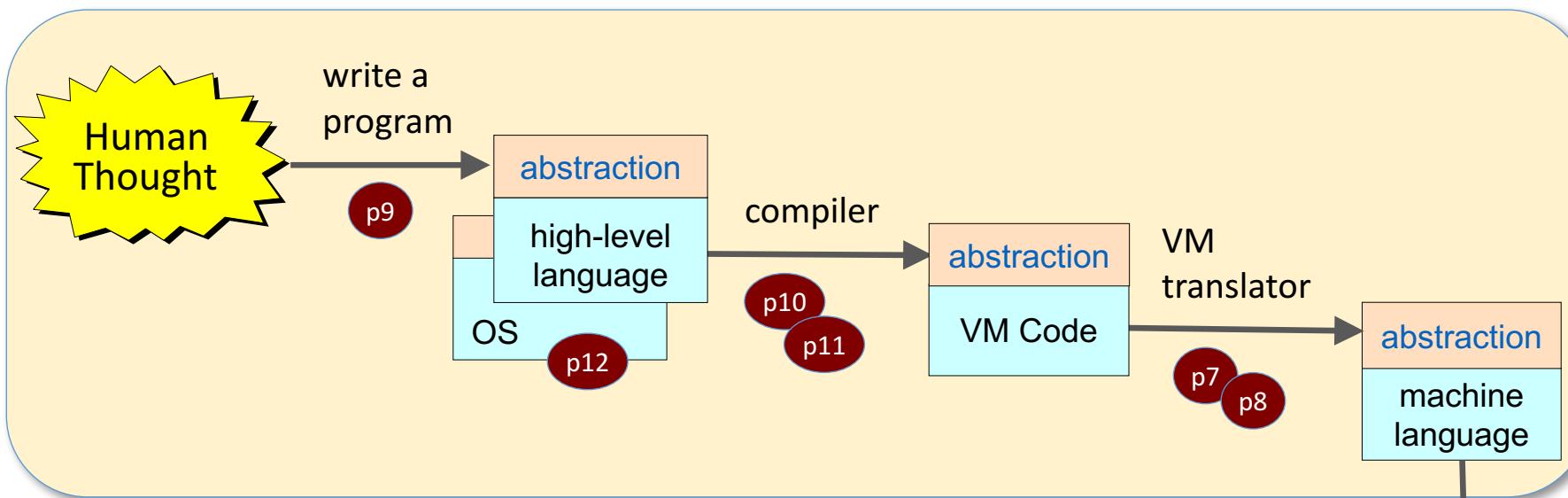
```
/** Represents a Point */
class Point {
    field int x, y;
    static int pointCount;
    /** Constructs a new point */
    constructor Point new(int ax, int ay) {
        let x = ax;
        let y = ay;
        let pointCount = pointCount + 1;
        return this;
    }
    // More Point methods...
}
```



From high-level to low-level



The road ahead



Projects:

p7, p7: building a virtual machine

p9: writing a computer game

p10, p11: developing a compiler

p12: developing an operating system



- (p1)
- (p2)
- (p3)
- (p4)
- (p5)
- (p6)

Virtual machine: lecture plan

Overview

- ✓ The road ahead
- ➡ • Program compilation

VM implementation platforms

- VM emulator
- VM translator

VM abstraction

- the stack
- memory segments

The VM translator

- Proposed implementation
- Building it (project 7)

VM implementation

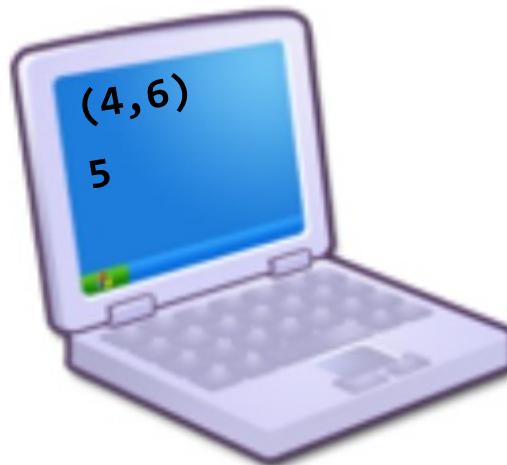
- the stack
- memory segments

The big picture

High-level program

```
/** Demo: working with Point objects */
class Main {
    function void main() {
        var Point p1, p2, p3;
        let p1 = Point.new(1,2);
        let p2 = Point.new(3,4);
        let p3 = p1.plus(p2);
        do p3.print(); // prints (4,6)
        do Output.println();
        do Output.putInt(p1.distance(p3));
        return;
    }
}
```

```
/** Represents a Point */
class Point {
    field int x, y;
    static int pointCount;
    /** Constructs a new point */
    constructor Point new(int ax, int ay) {
        let x = ax;
        let y = ay;
        let pointCount = pointCount + 1;
        return this;
    }
    ...
}
```



The big picture

High-level program

```
/** Demo: working with Point objects */
class Main {
    function void main() {
        var Point p1, p2, p3;
        let p1 = Point.new(1,2);
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        let p3 = p1.plus(p2);
        do p3.print(); // prints (4,6)
        do Output.println();
        do Output.putInt(p1.distance(p3));
        return;
    }
}
```

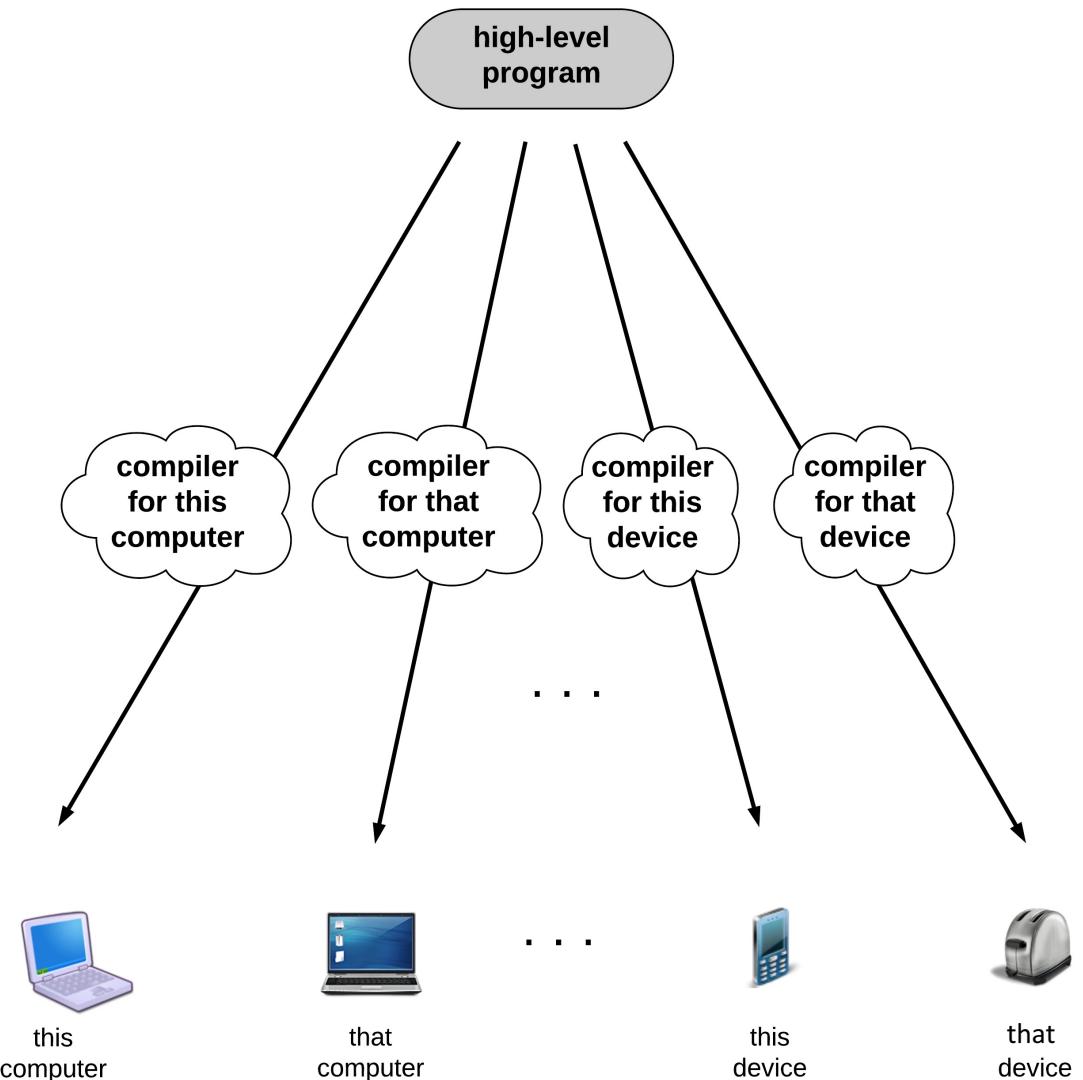
```
/** Represents a Point */
class Point {
    field int x, y;
    static int pointCount;
    /** Constructs a new point */
    constructor Point new(int ax, int ay) {
        let x = ax;
        let y = ay;
        let pointCount = pointCount + 1;
        return this;
    }
    ...
}
```



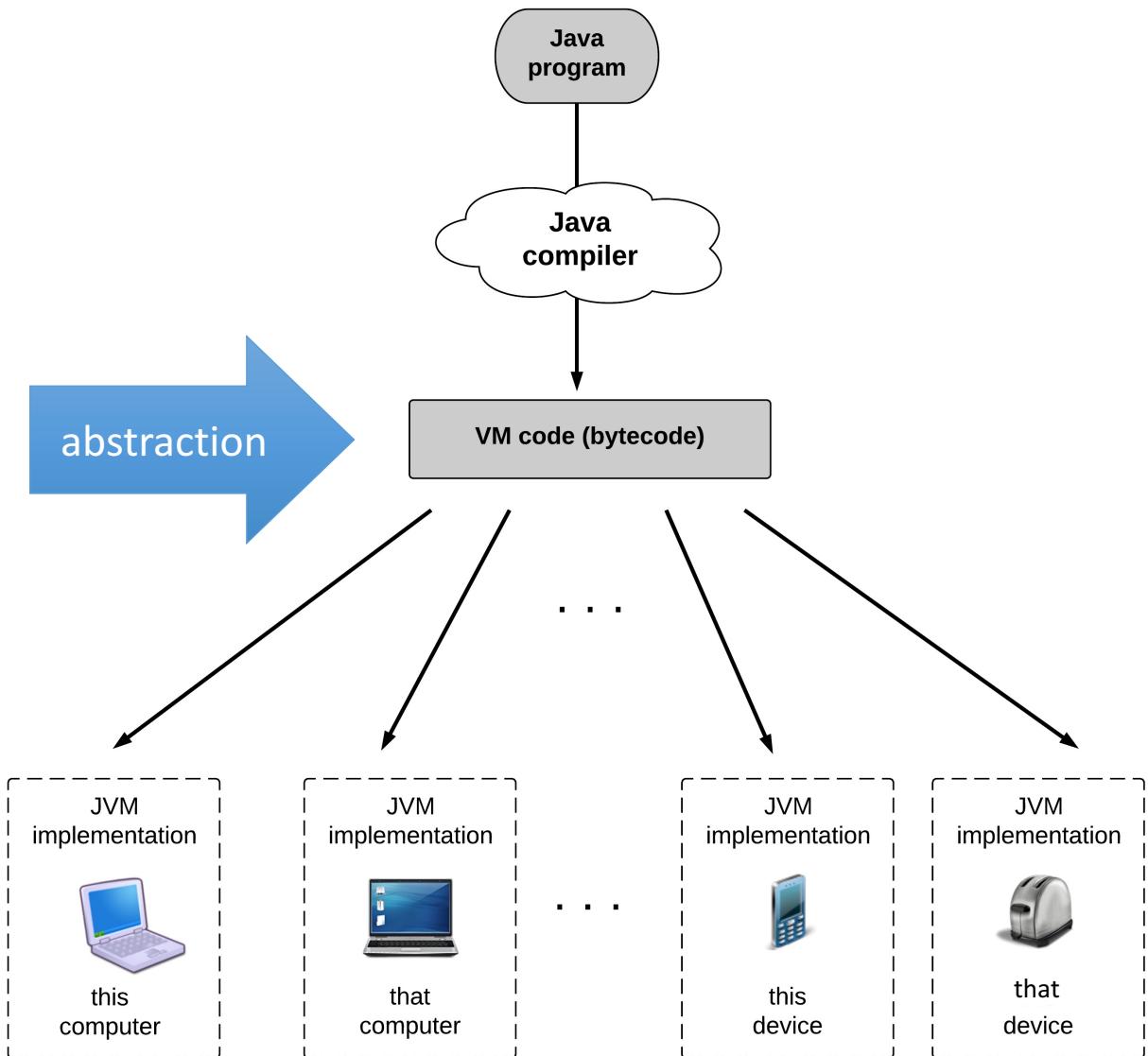
Low-level code

```
000000000010000
1110111111001000
000000000010001
1110101010001000
000000000010000
1111110000010000
0000000000000000
1111010011010000
000000000010010
1110001100000001
000000000010000
1111110000010000
000000000010001
000000000010000
1110111111001000
000000000010001
1110101010001000
000000000010000
1111110000010000
0000000000000000
1111010011010000
000000000010010
1110001100000001
000000000010000
1111110000010000
000000000010001
1111110000010000
...
...
```

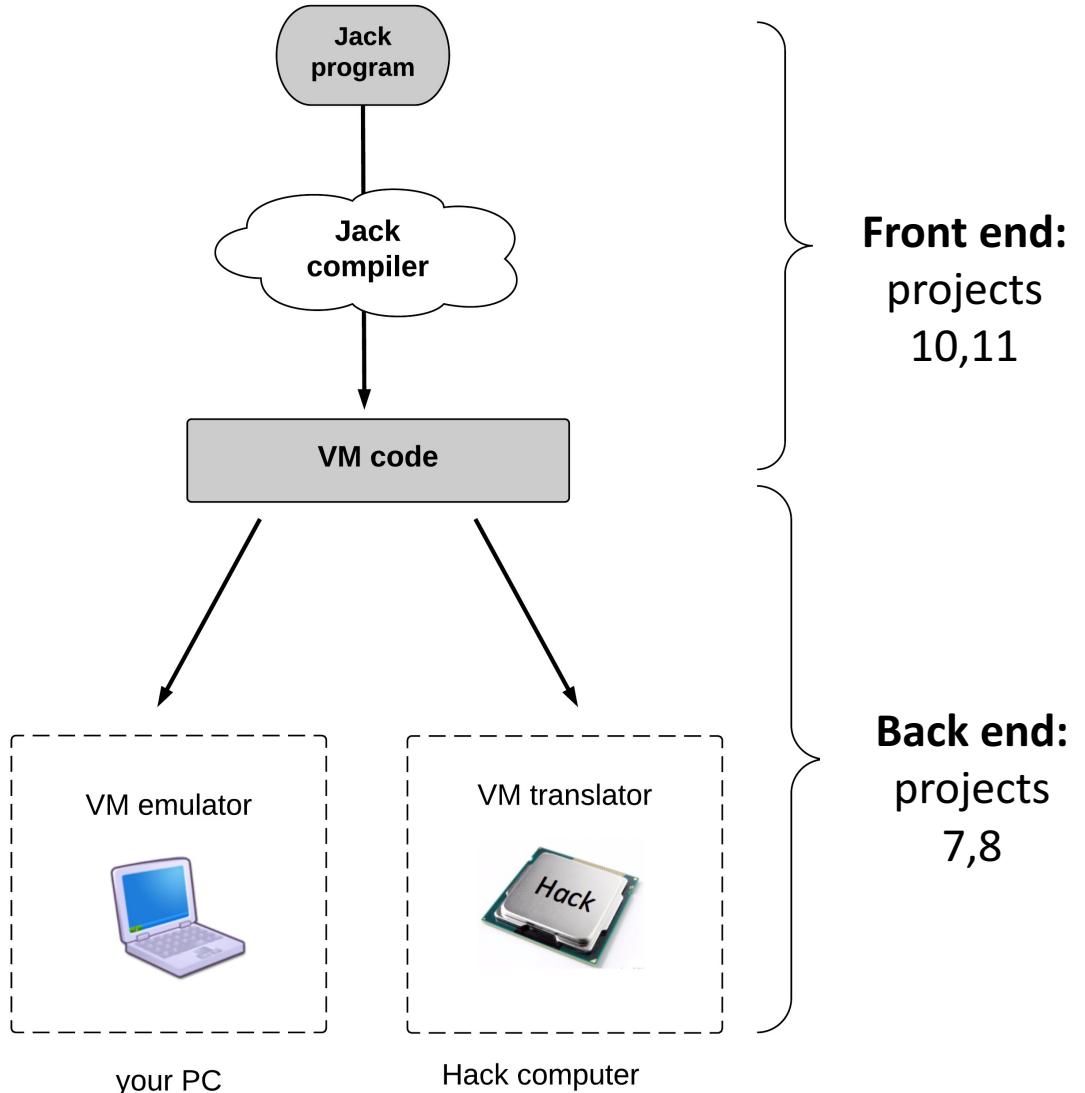
Program compilation: 1-tier



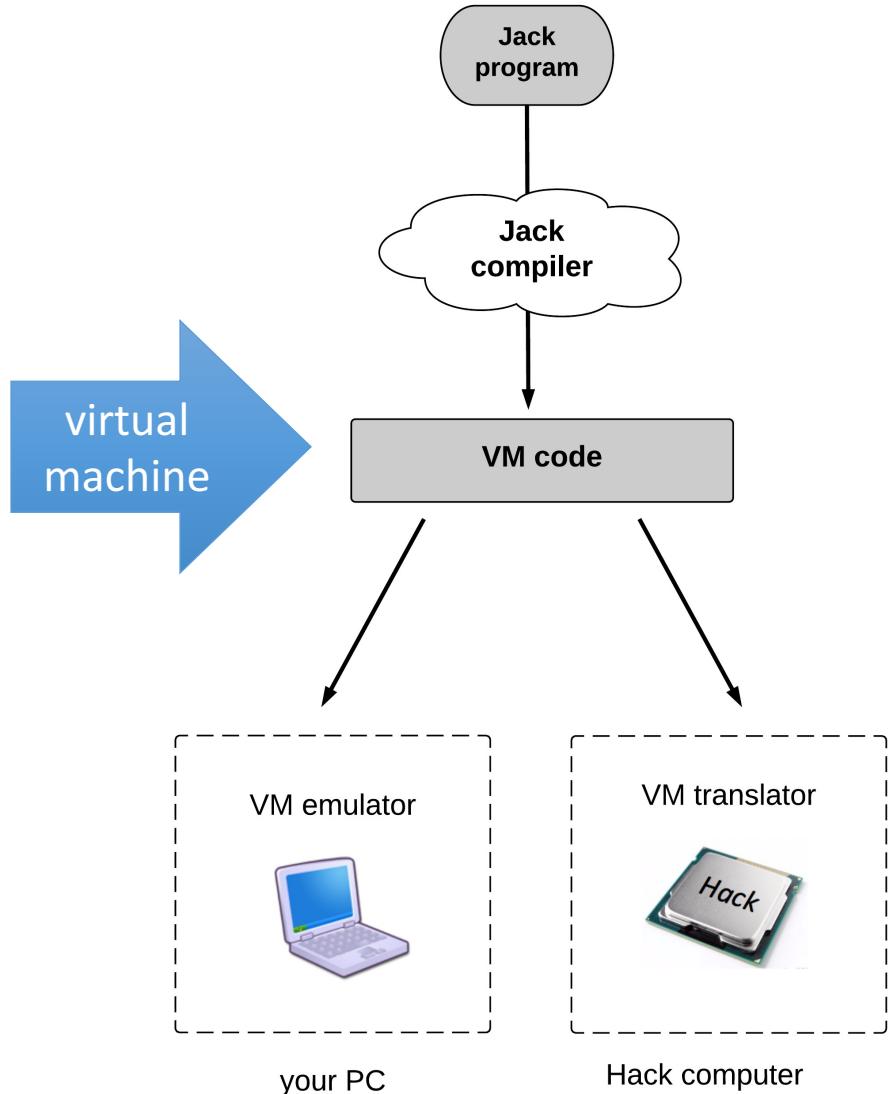
Program compilation: 2-tier



Jack compilation

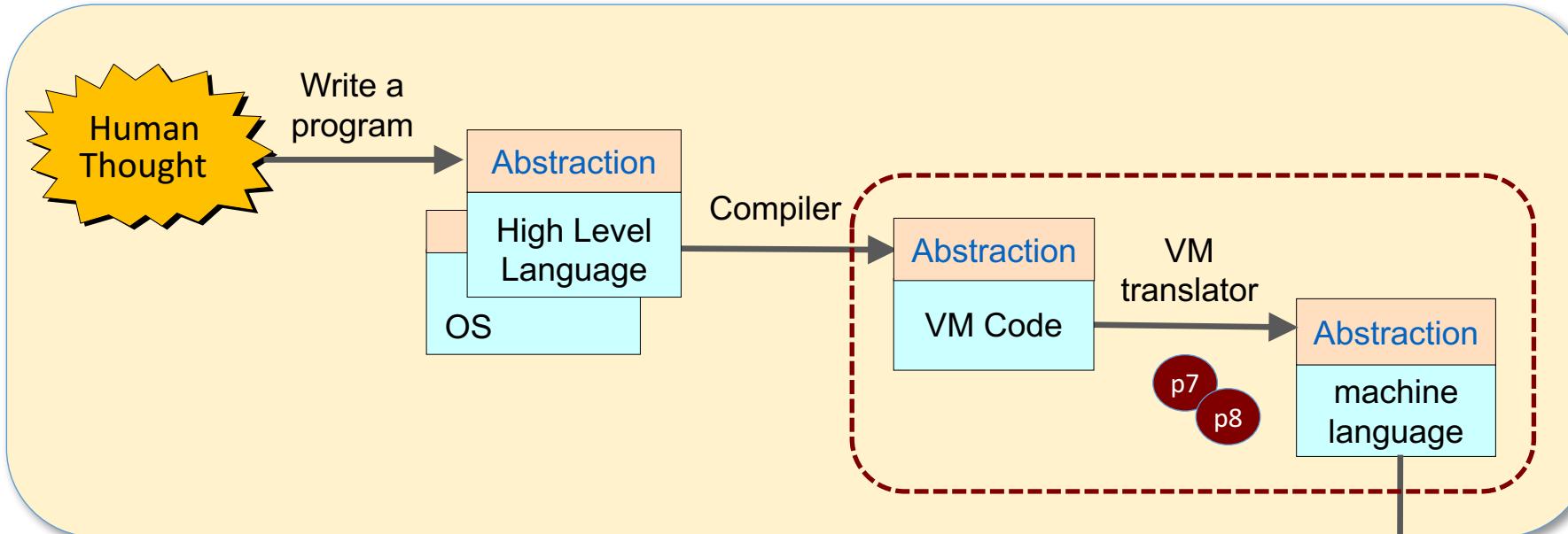


Jack compilation



Alan Turing (1912-1954)

The big picture



Virtual Machine (chapters 7-8)

- Understanding the VM abstraction
- Building a VM implementation



Take home lessons

- Compilation (big picture)
- Virtualization
- VM abstraction
- Stack processing
- VM implementation
- Pointers
- Programming.

Virtual machine: lecture plan

Overview

- ✓ The road ahead
- ✓ Program compilation

VM implementation platforms

- VM emulator
- VM translator

VM abstraction



- the stack
- memory segments

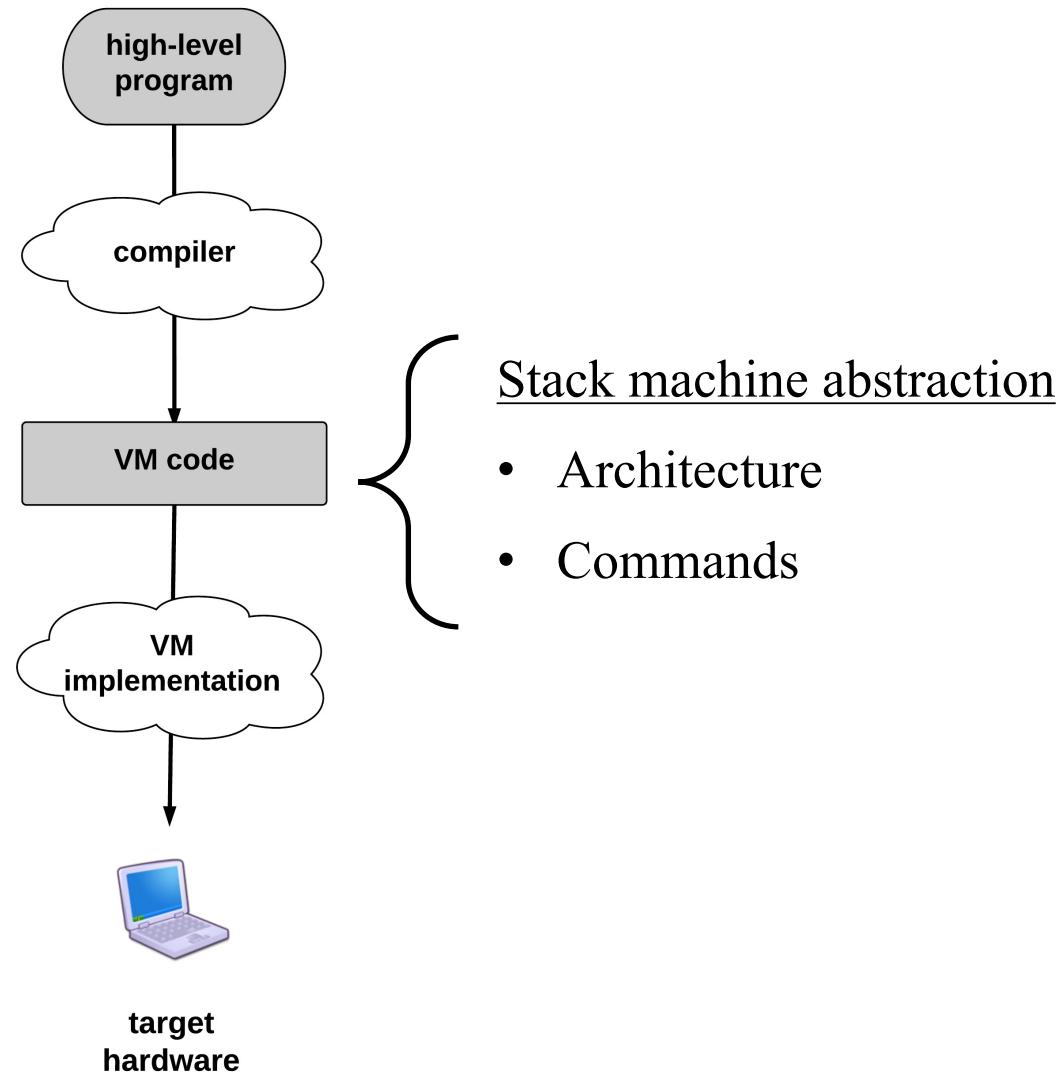
The VM translator

- Proposed implementation
- Building it (project 7)

VM implementation

- the stack
- memory segments

The big picture



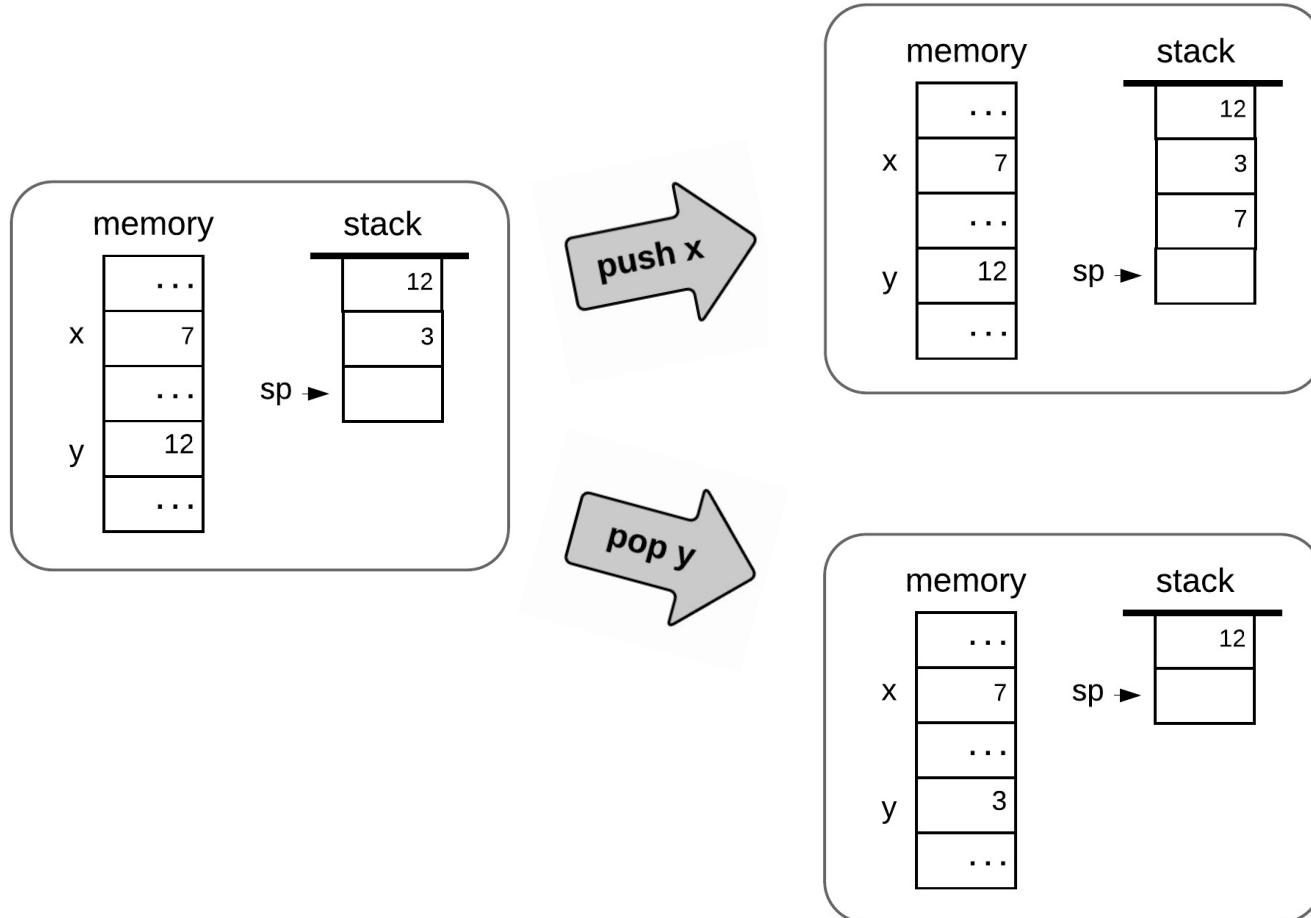
Stack



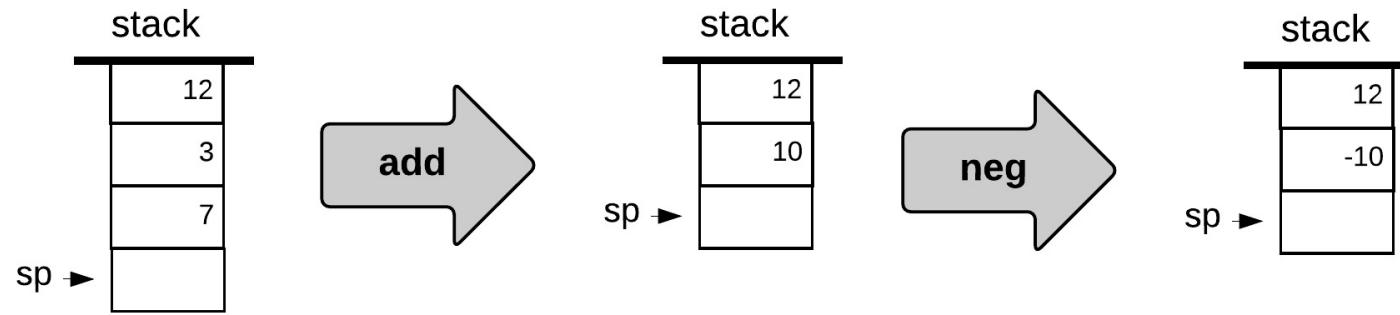
Stack operations:

- **push:** add an element at the stack's top
- **pop:** remove the top element

Stack

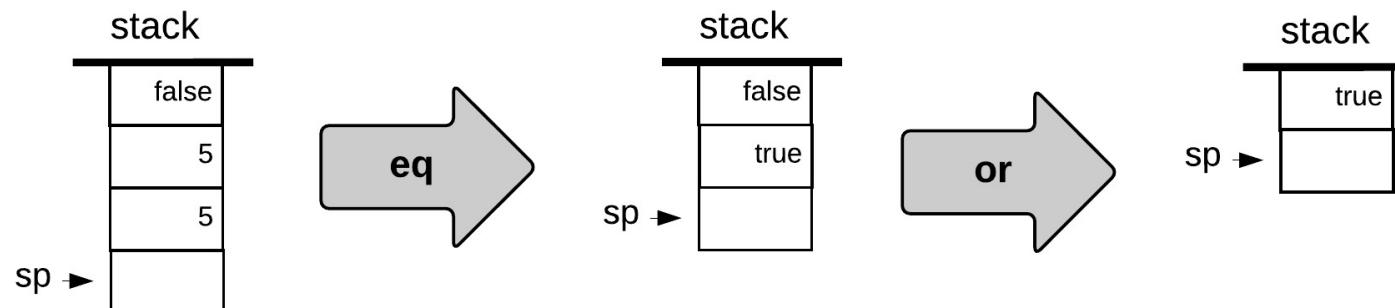


Stack arithmetic

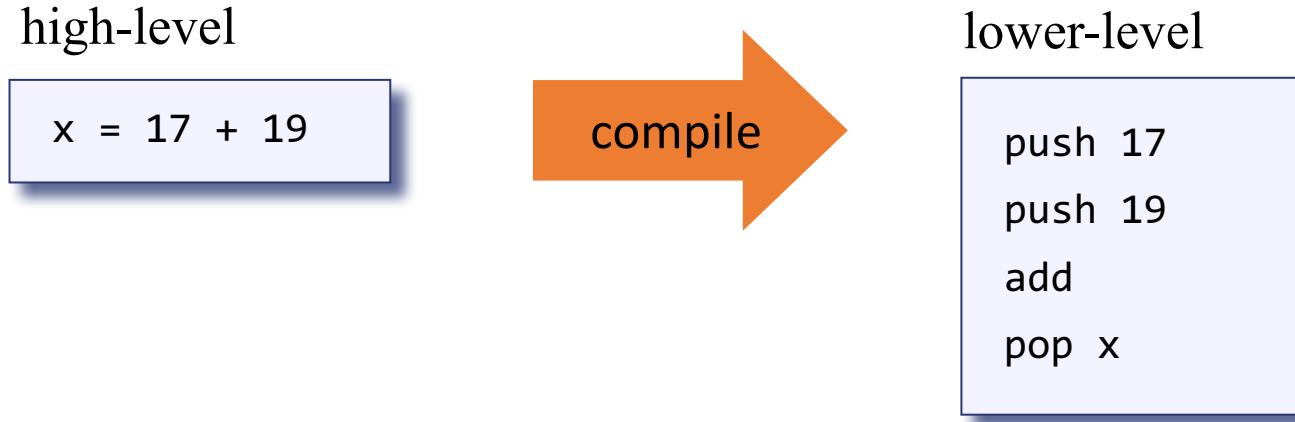


Applying a function f on the stack:

- pops the argument(s) from the stack
- Computes f on the arguments
- Pushes the result onto the stack.



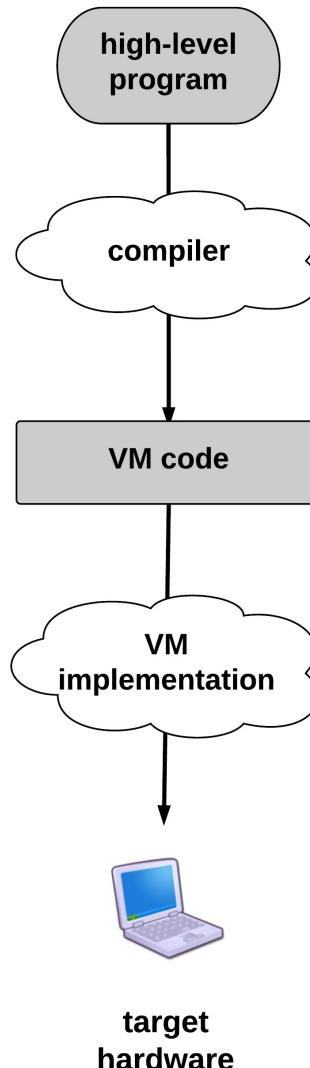
Stack arithmetic (big picture)



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... Stay tuned.

The stack machine model



Stack machine, manipulated by:

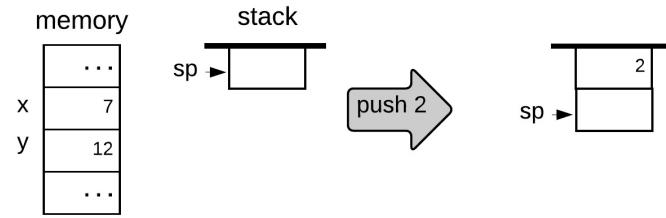
- Arithmetic / logical commands
- Memory segment commands
- Branching commands
- Function commands



Arithmetic commands

VM code

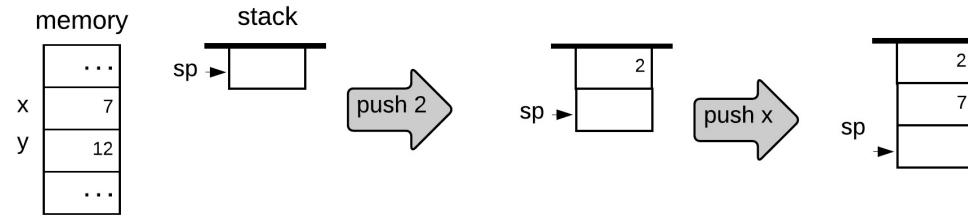
```
// d=(2-x)+(y+9)
push 2
push x
sub
push y
push 9
add
add
pop d
```



Arithmetic commands

VM code

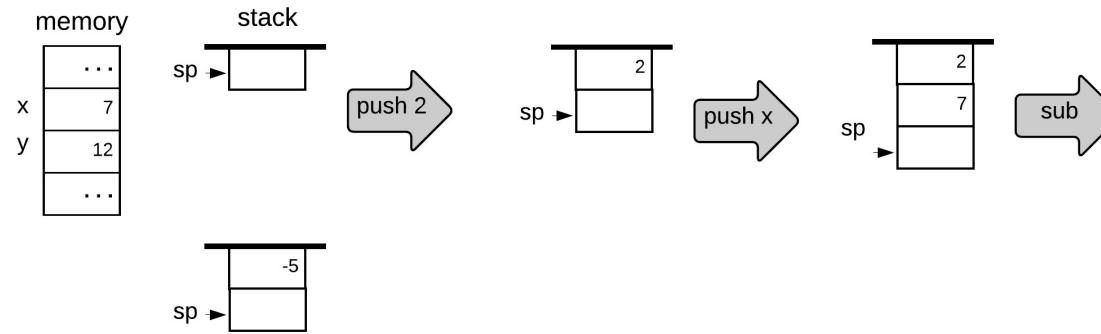
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Arithmetic commands

VM code

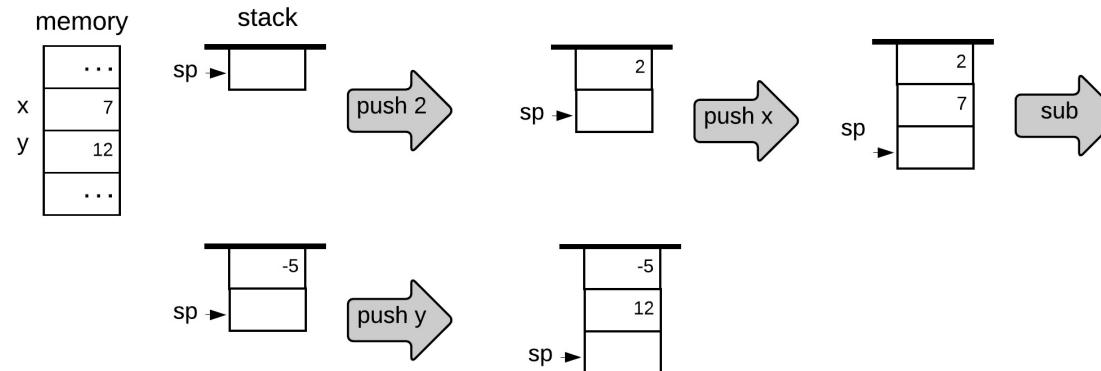
```
// d=(2-x)+(y+9)  
push 2  
push x  
sub  
push y  
push 9  
add  
add  
pop d
```



Arithmetic commands

VM code

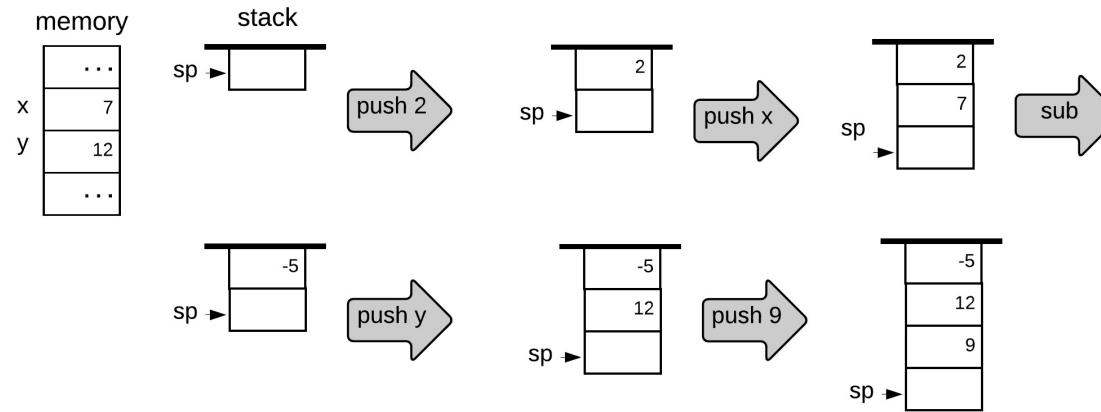
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Arithmetic commands

VM code

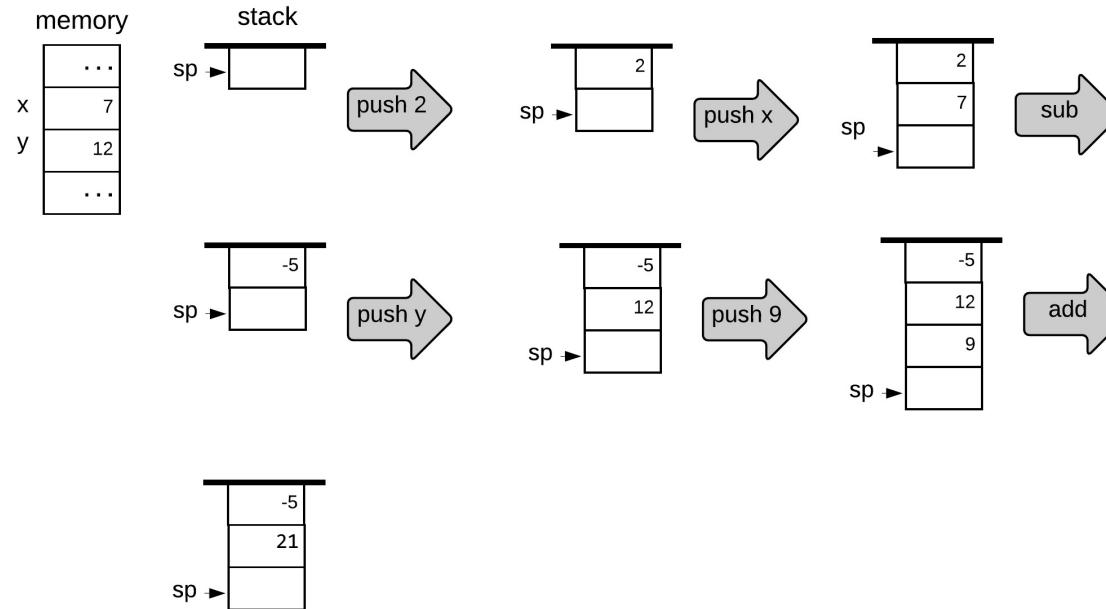
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Arithmetic commands

VM code

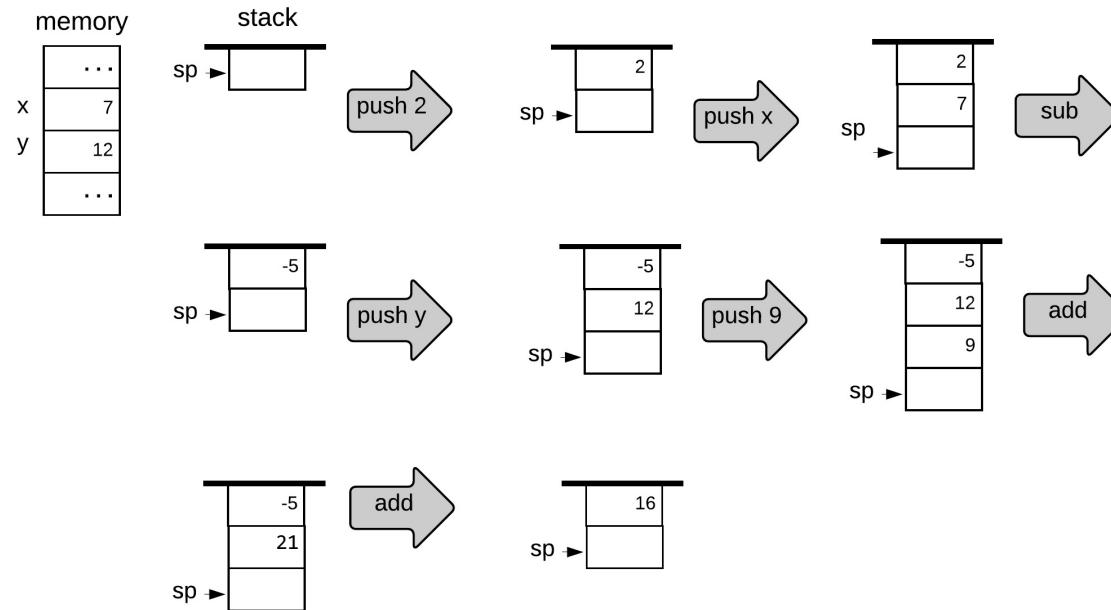
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```



Arithmetic commands

VM code

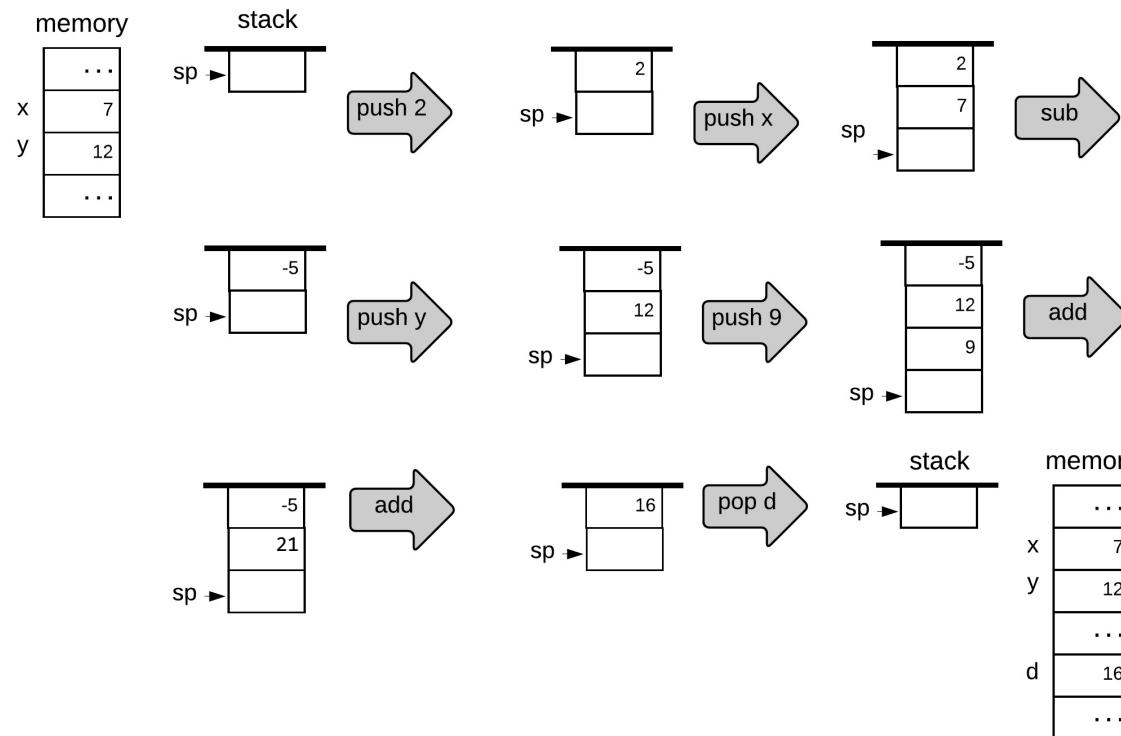
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add  
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```



Arithmetic commands

VM code

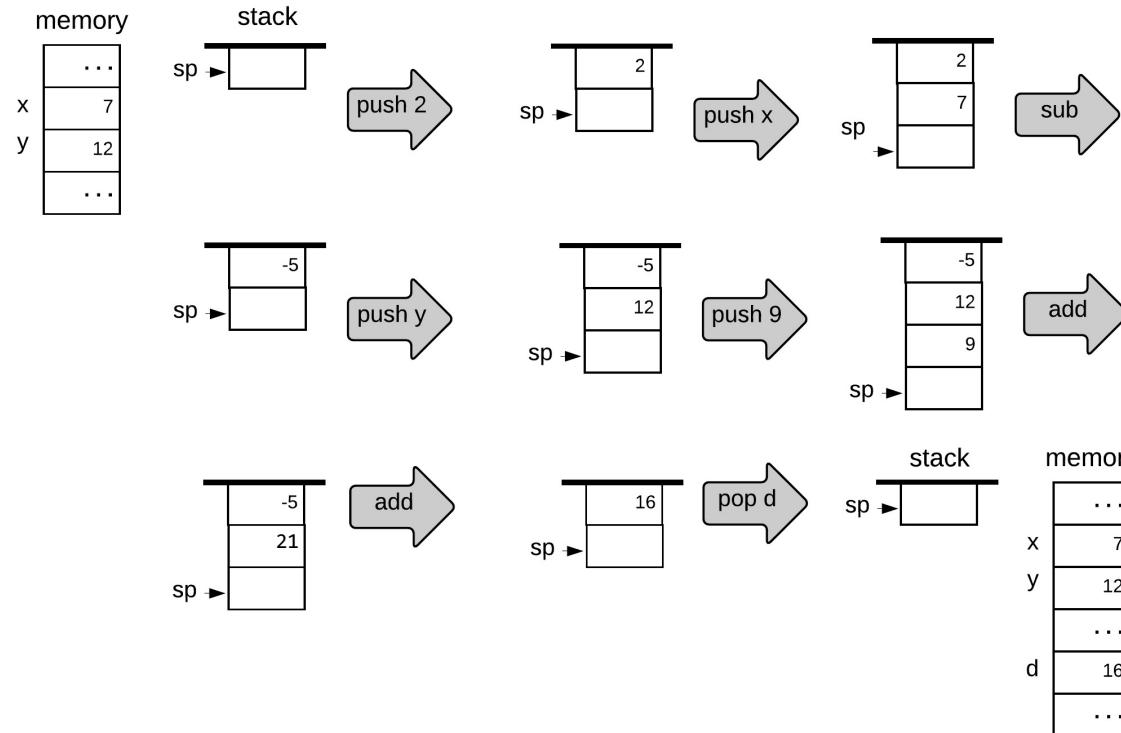
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push x  
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push y  
push 9  
add  
add  
pop d
```



Arithmetic commands

VM code

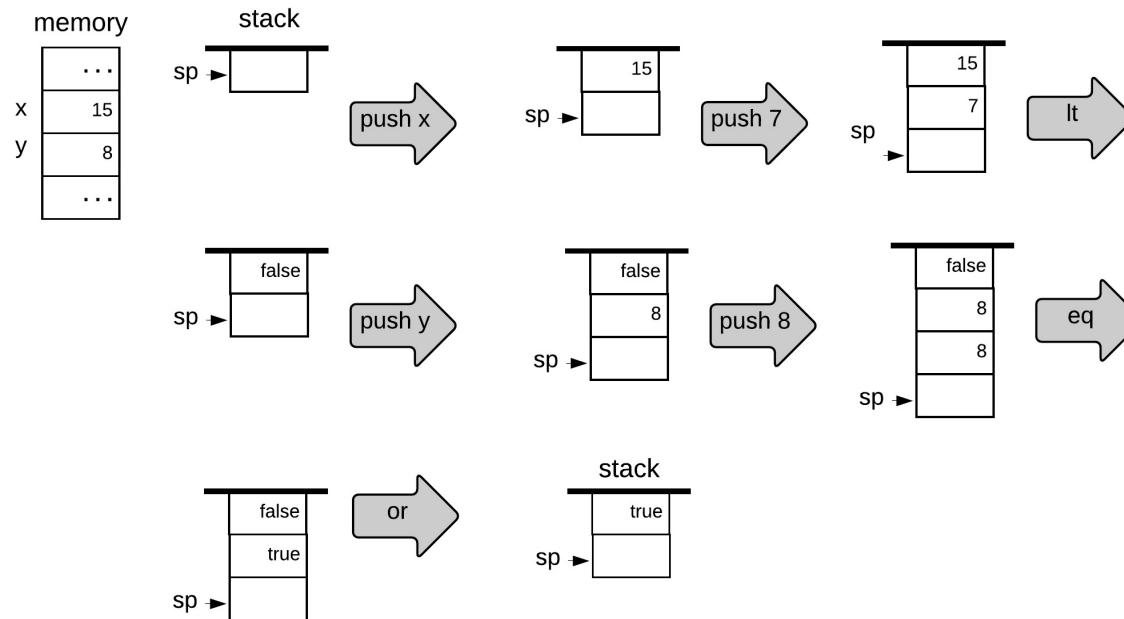
```
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push 2  
push x  
sub  
push y  
push 9  
add  
add  
pop d
```



Logical commands

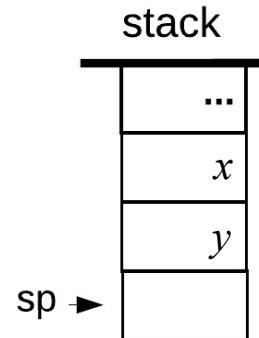
VM code

```
// (x<7) or (y==8)  
push x  
push 7  
lt  
push y  
push 8  
eq  
or
```



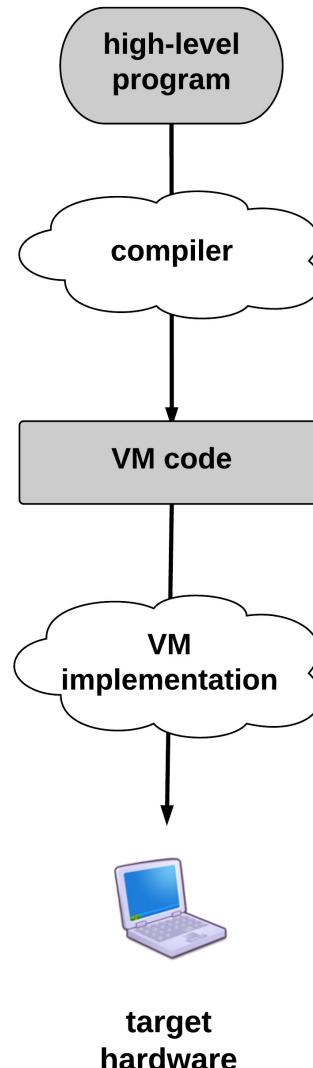
Arithmetic / Logical commands

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	$\text{not } x$	boolean



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

The stack machine model



Stack machine, manipulated by:

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



Virtual machine: lecture plan

Overview

- ✓ The road ahead
- ✓ Program compilation

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- VM translator

VM abstraction

- ✓ the stack
- • memory segments

The VM translator

- Proposed implementation
- Building it (project 7)

VM implementation

- the stack
- memory segments

The big picture

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;  
        ...  
    }  
}
```

Compiled VM code

```
...  
...  
...  
...  
push s1  
push y  
add  
pop c  
...  
...
```

compile

Variable kinds

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  
...  
...
```

Variable kinds

- Argument variables
- Local variables
- Static variables

(More kinds later)

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;  
        ...  
    }  
}
```

Compiled VM code

```
...  
...  
...  
...  
push s1  
push y  
add  
pop c  
...  
...
```

compile

Virtual memory segments:

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

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;  
        ...  
    }  
}
```

Compiled VM code

```
...  
...  
...  
...  
push static 0  
push y  
add  
pop c  
...  
...
```

compile

Virtual memory segments:

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

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;  
        ...  
    }  
}
```

Compiled VM code

```
...  
...  
...  
...  
push static 0  
push argument 1  
add  
pop c  
...  
...
```

compile

Virtual memory segments:

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

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

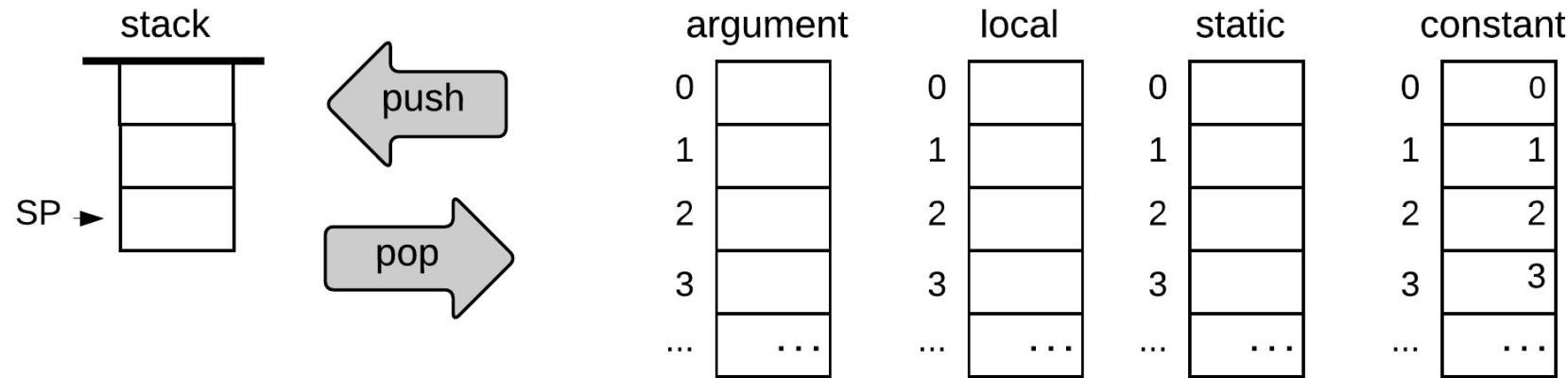
```
...  
...  
...  
...  
push static 0  
push argument 1  
add  
pop local 2  
...  
...
```

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
...

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

Memory segments

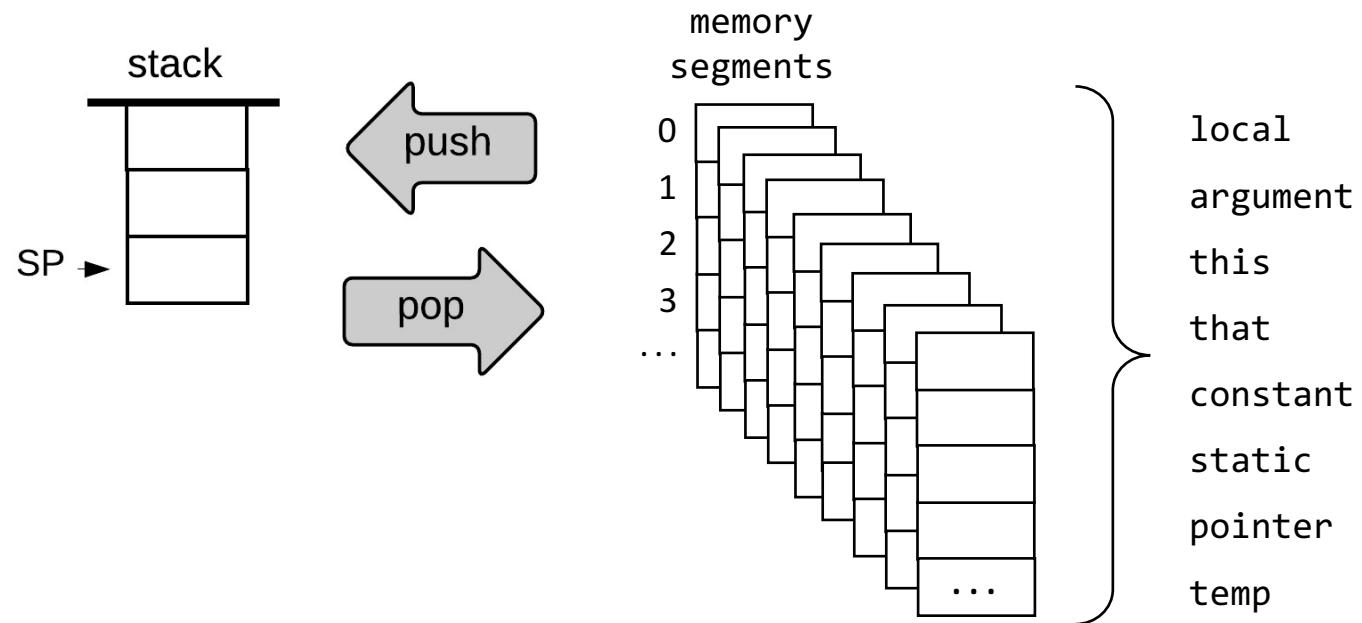


Syntax: `push / pop segment i`

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

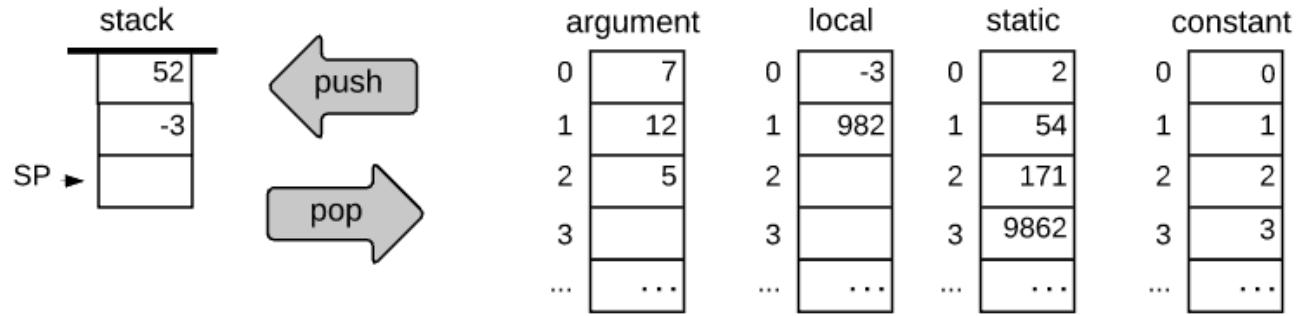
and *i* is a non-negative integer.

Syntax: `pop segment i`

Where *segment* is: argument, local, static,
this, that, pointer, or temp

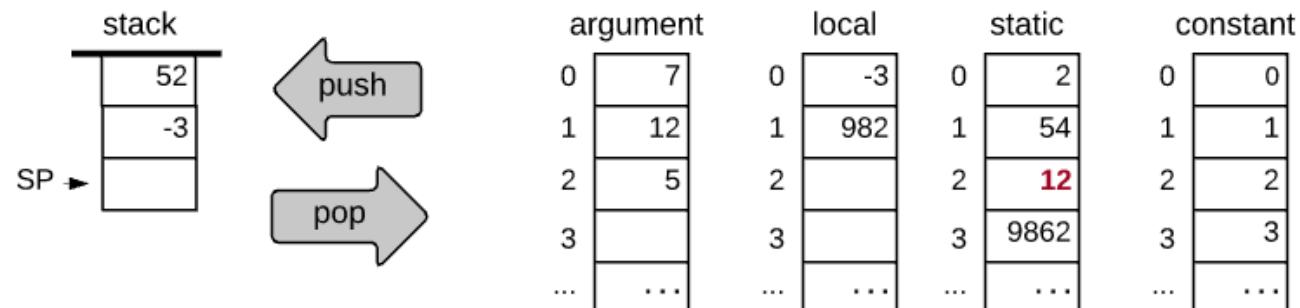
and *i* is a non-negative integer.

Quiz: write the missing code

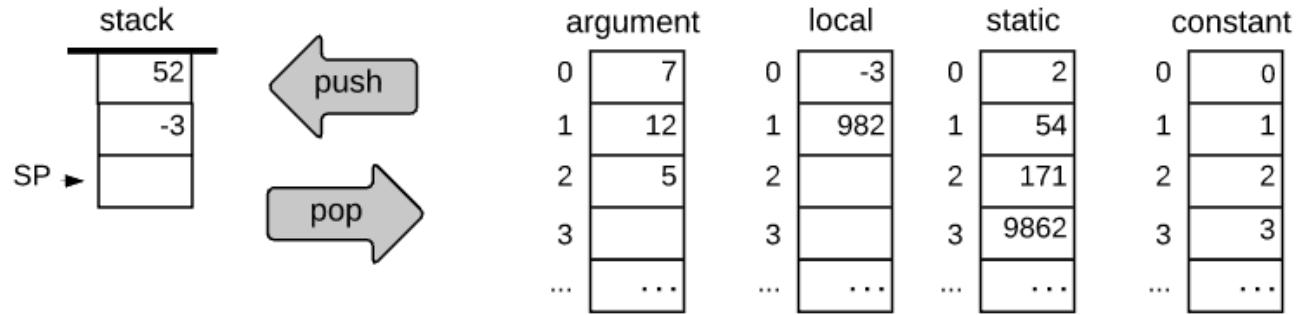


let static 2 = argument 1

?

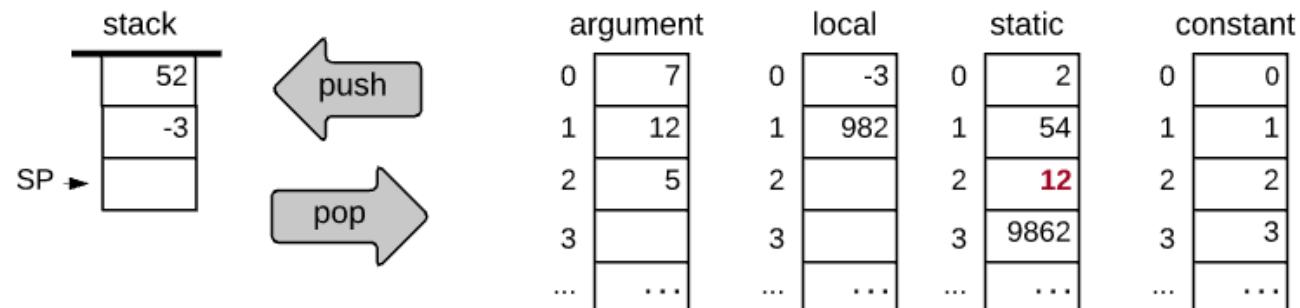


Quiz: write the missing code

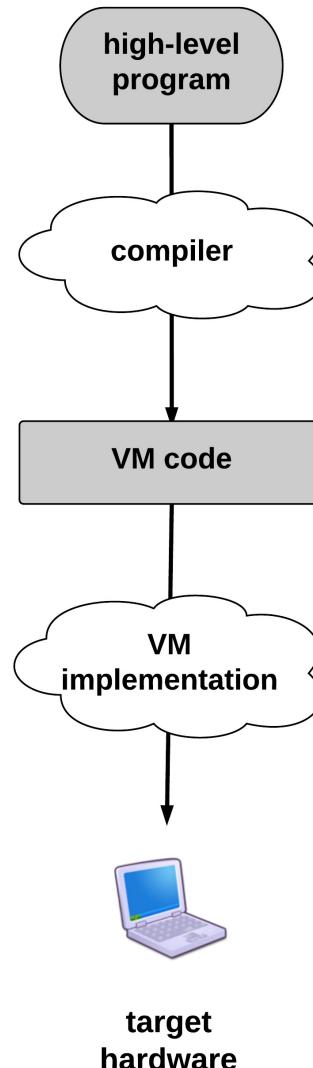


let static 2 = argument 1

push argument 1
pop static 2



The stack machine model



VM language:

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



Virtual machine: lecture plan

Overview

- ✓ The road ahead
- ✓ Program compilation

VM implementation platforms

- VM emulator
- VM translator

VM abstraction

- ✓ the stack
- ✓ memory segments

The VM translator

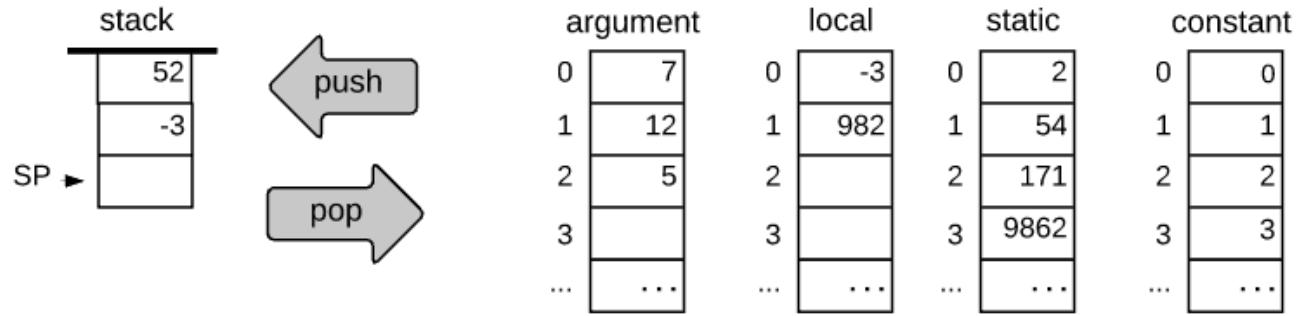
- Proposed implementation
- Building it (project 7)

VM implementation



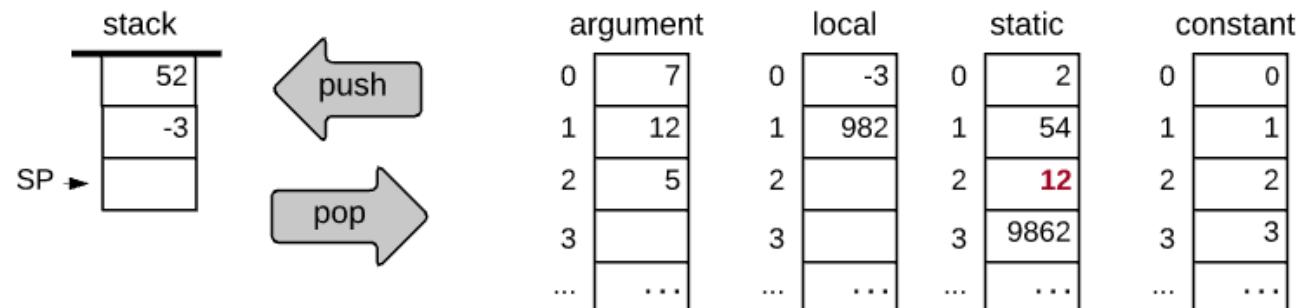
- the stack
- memory segments

The VM abstraction



let static 2 = argument 1

push argument 1
pop static 2



Pointer manipulation

Pseudo assembly code

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

In Hack:

@p

A=M

D=M

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

Notation:

*p // the memory location that p points at

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
```

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

Notation:

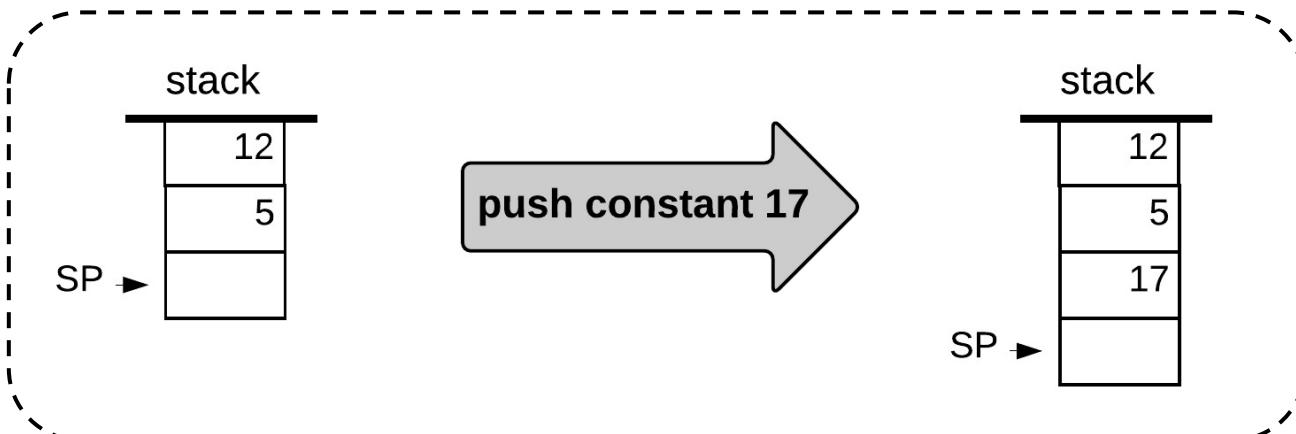
*p // the memory location that p points at

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

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

Stack implementation

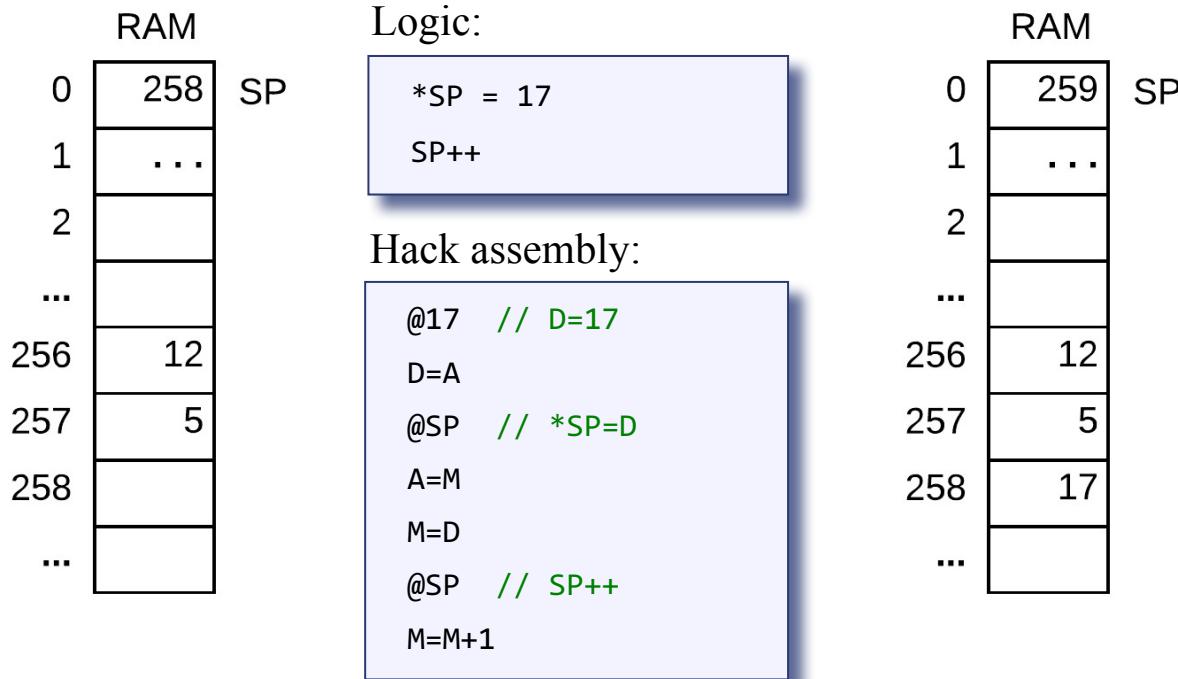
Abstraction:



Implementation:

Assumptions:

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



Stack implementation

VM code:

```
push constant i
```

VM translator

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 end up realizing the stack and the memory segments on the host platform.

Virtual machine: lecture plan

Overview

- ✓ The road ahead
- ✓ Program compilation

VM implementation platforms

- VM emulator
- VM translator

VM abstraction

- ✓ the stack
- ✓ memory segments

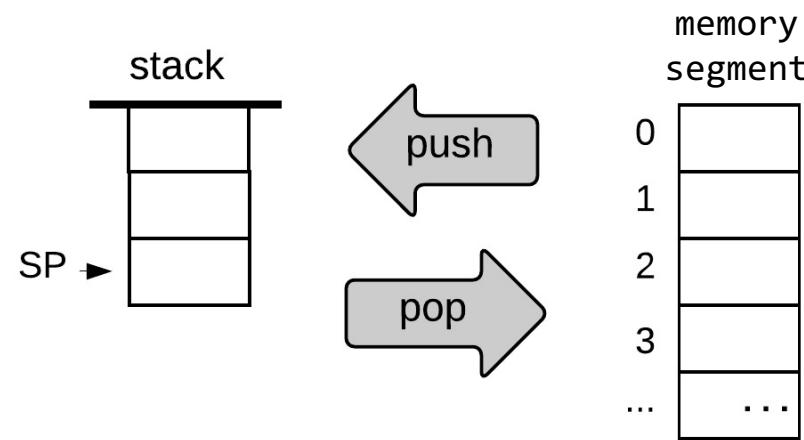
The VM translator

- Proposed implementation
- Building it (project 7)

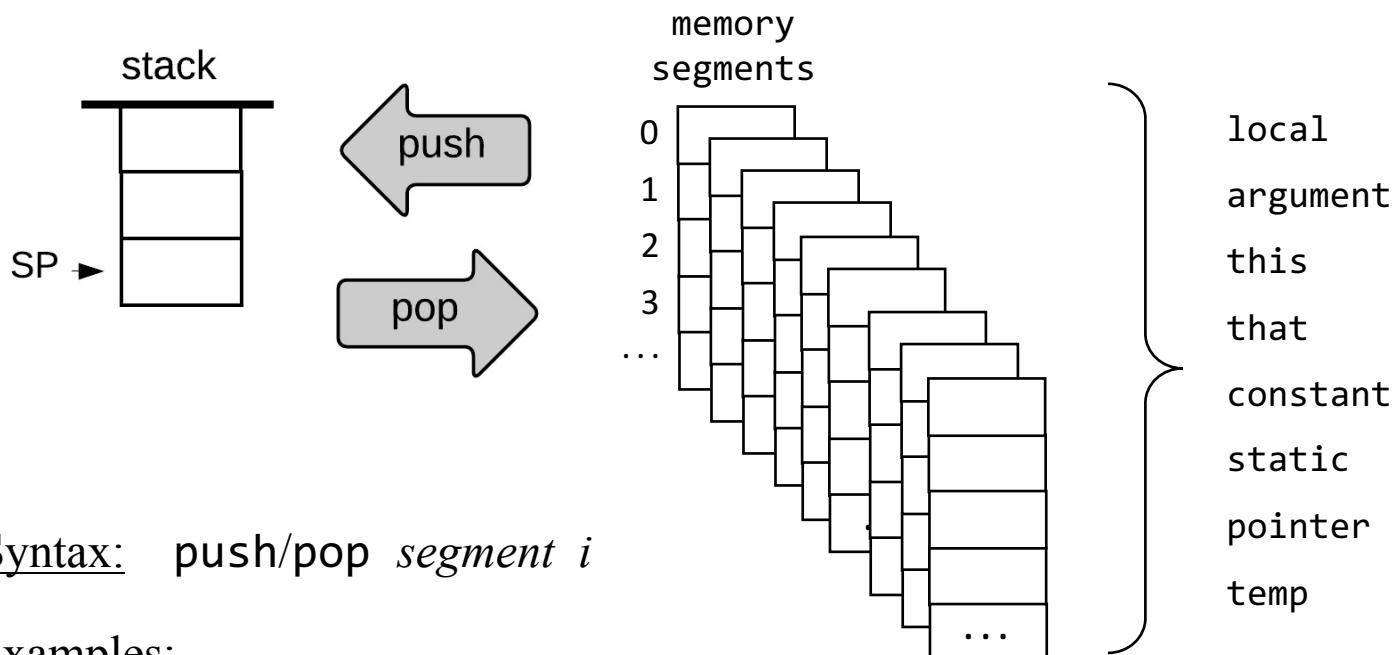
VM implementation

- ✓ the stack
- ➡ • memory segments

Memory segments (abstraction)



Memory segments (abstraction)

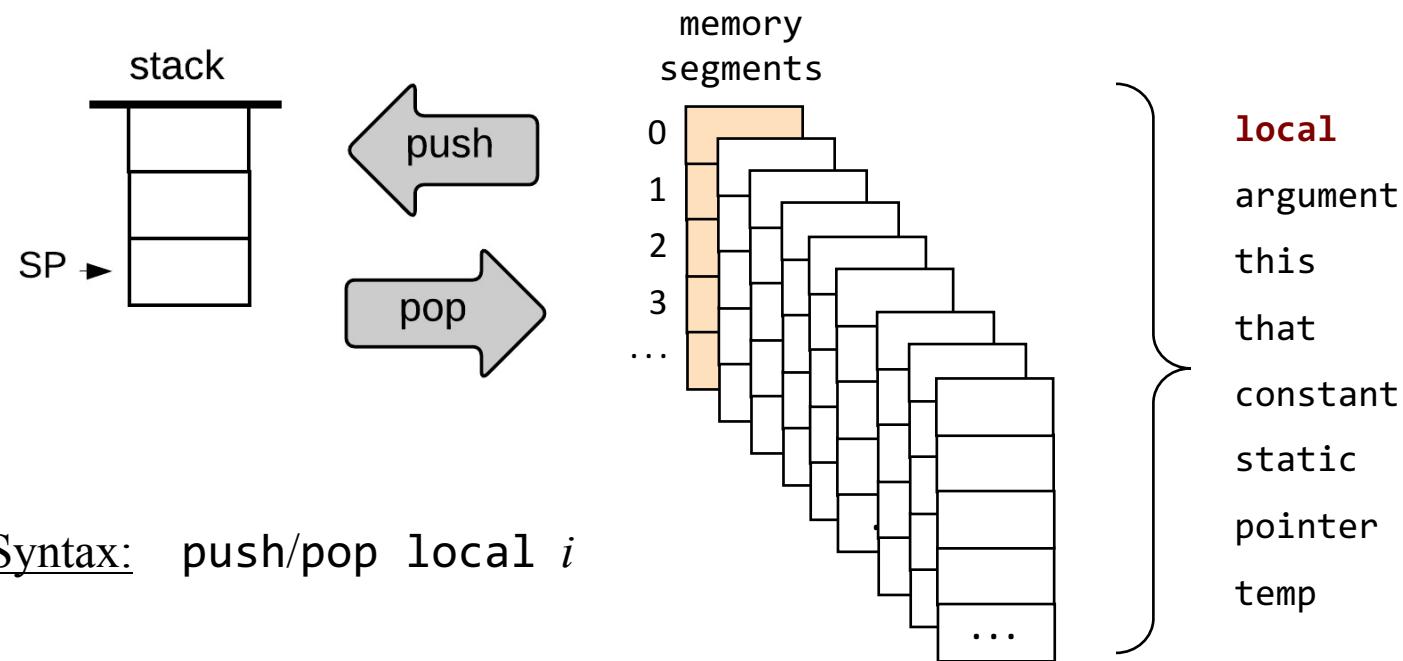


Syntax: `push/pop segment i`

Examples:

- `push constant 17`
- `pop local 2`
- `pop static 5`
- `push argument 3`
- `pop this 2`
- `...`

Implementing push/pop local *i*



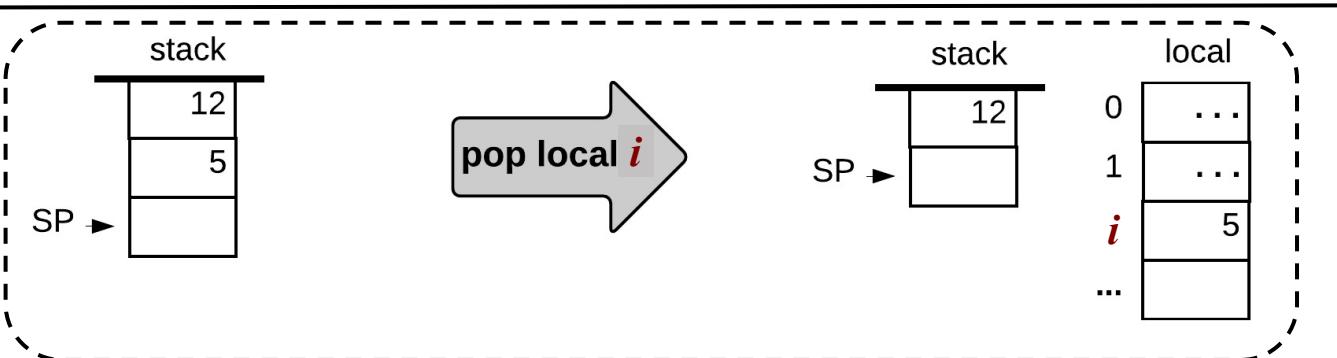
Why do we need a local segment?

When the compiler translates high-level code into VM code...

- high-level operations on *local variables* are translated into VM operations on the entries of the segment **local**
- We now turn to describe how the **local** segment can be realized on the host platform.

Implementing pop local i

Abstraction:

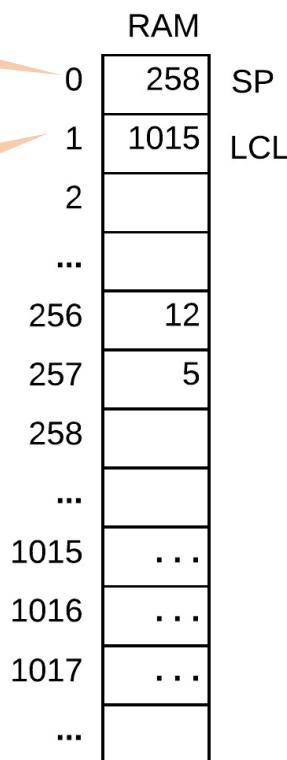


stack pointer

base address of
the local segment

Implementation:

the local segment
is stored some-
where in the RAM

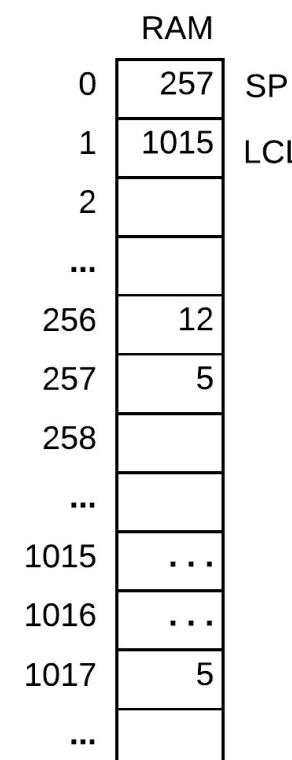


Implementation:

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

Hack assembly:

You write it!



Implementing push/pop local i

VM code:

pop local i

push local i

VM Translator

Assembly pseudo code:

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

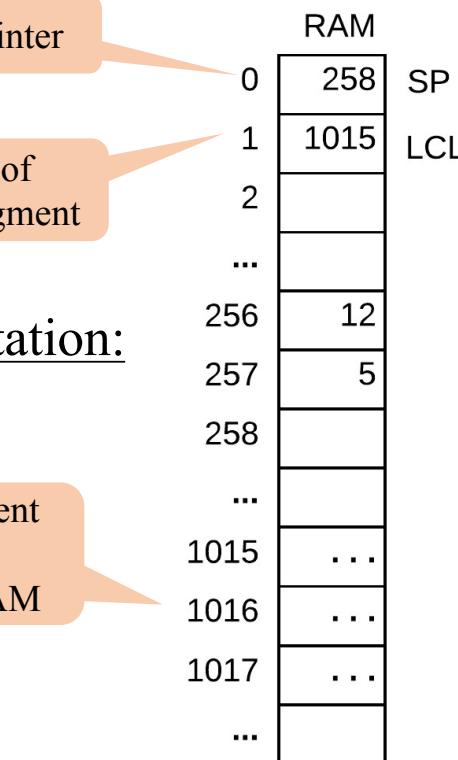
addr = LCL+ i , *SP = *addr, SP++

stack pointer

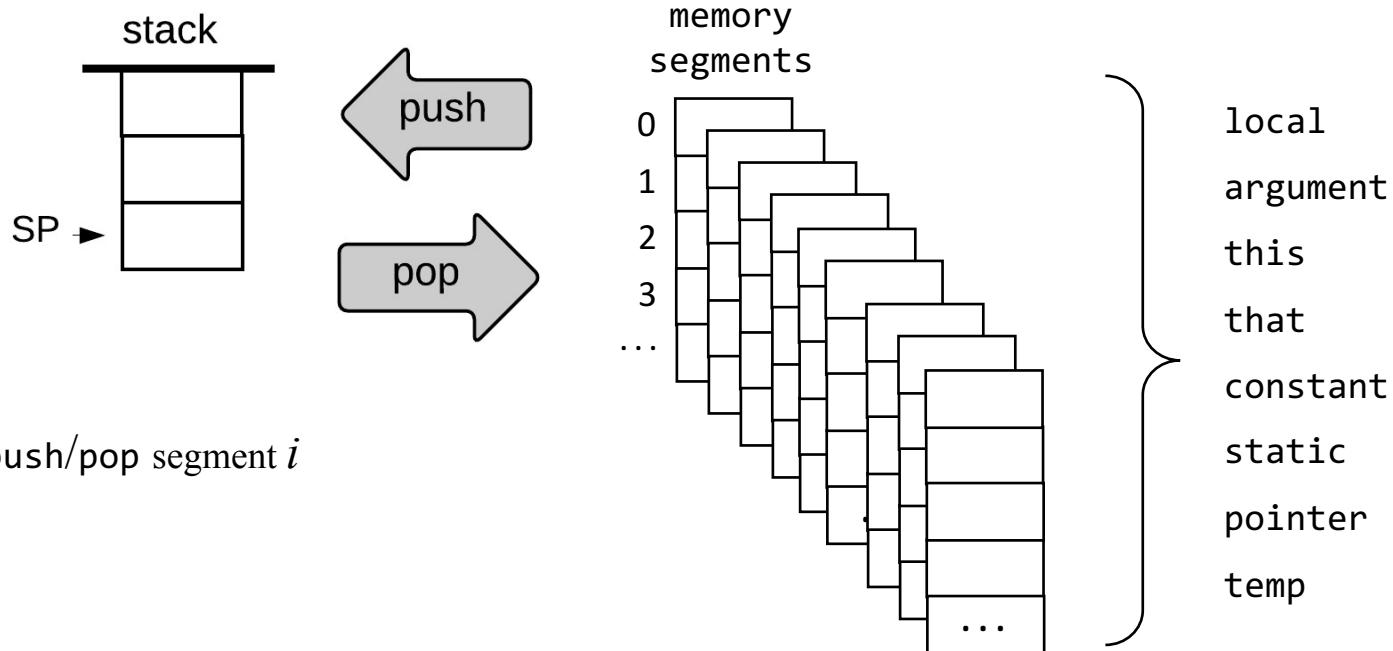
base address of
the local segment

Implementation:

the local segment
is stored some-
where in the RAM



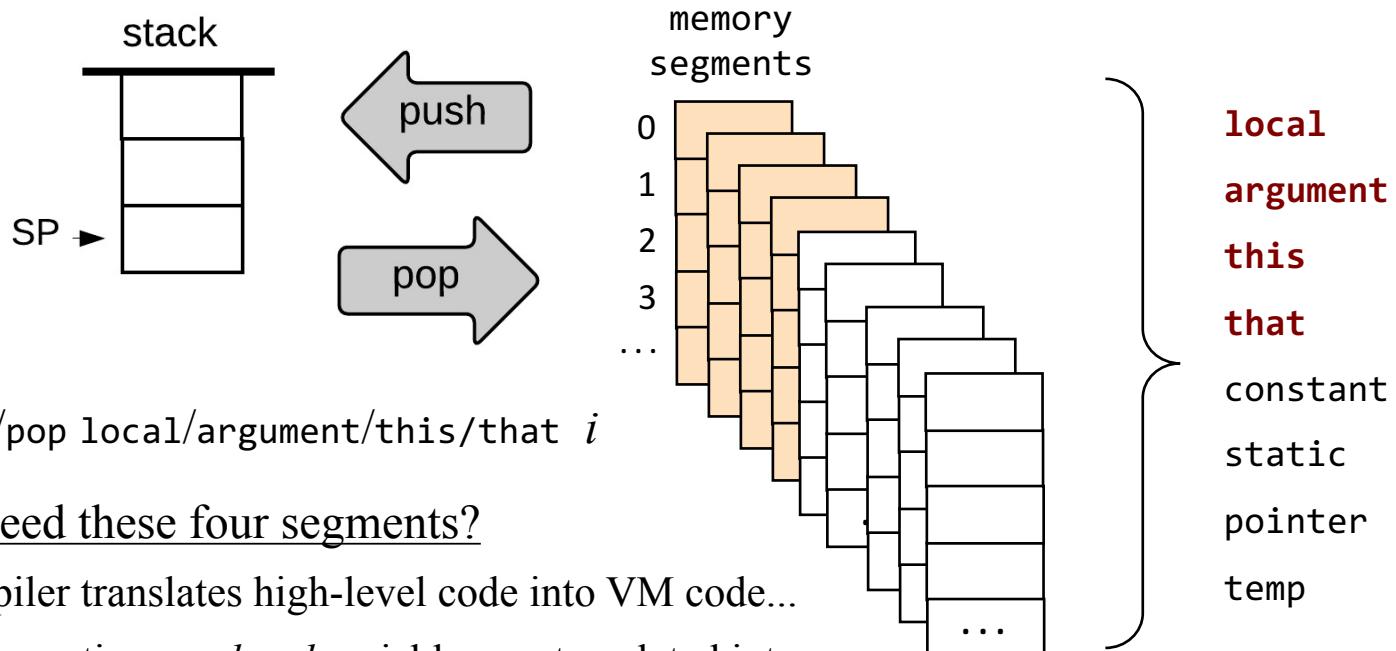
Memory segments



Syntax: push/pop segment i

- We know how to implement push/pop local i
- We now turn to implementing push/pop operations on the segments argument, this, and that.

Implementing push/pop local/argument/this/that *i*



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

Why do we need these four segments?

When the compiler translates high-level code into VM code...

- high-level operations on *local* variables are translated into VM operations on the entries of the segment *local*
- high-level operations on *argument* variables are translated into VM operations on the entries of the segment *argument*
- high-level operations on the *field* variables of the current object are translated into VM operations on the entries of the segment *this*
- high-level operations on *array entries* are translated into VM operations on the entries of the segment *that*

We now turn to describe how these four segments can be realized on the host platform.

Implementing push/pop local/argument/this/that *i*

VM code:

```
push segment i
```

```
pop segment i
```

VM translator

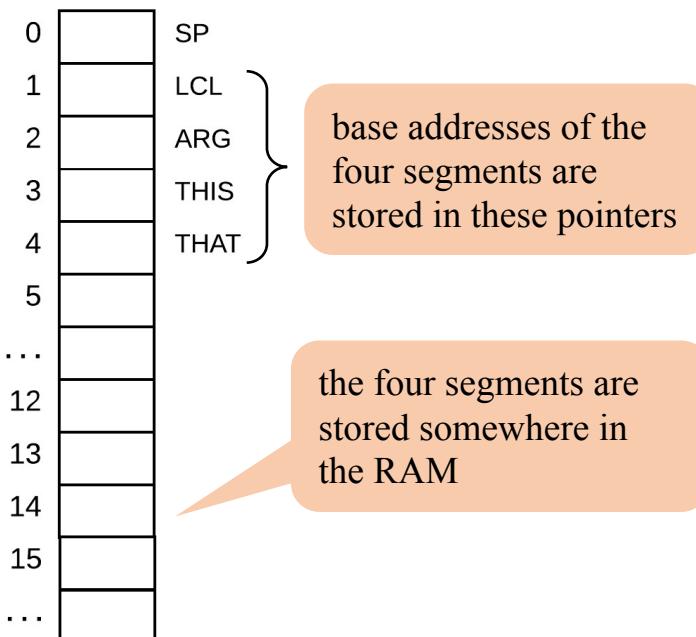
Assembly pseudo code:

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

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

segment = {local, argument, this, that}

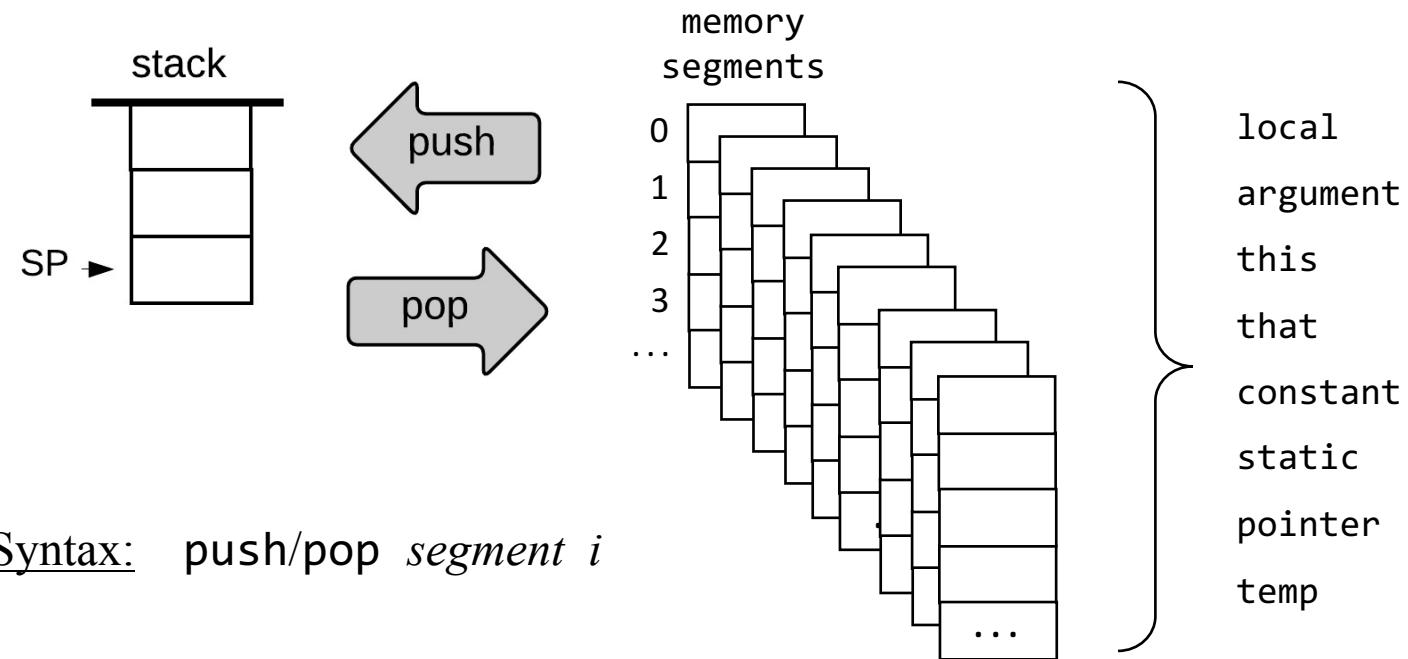
Host RAM



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

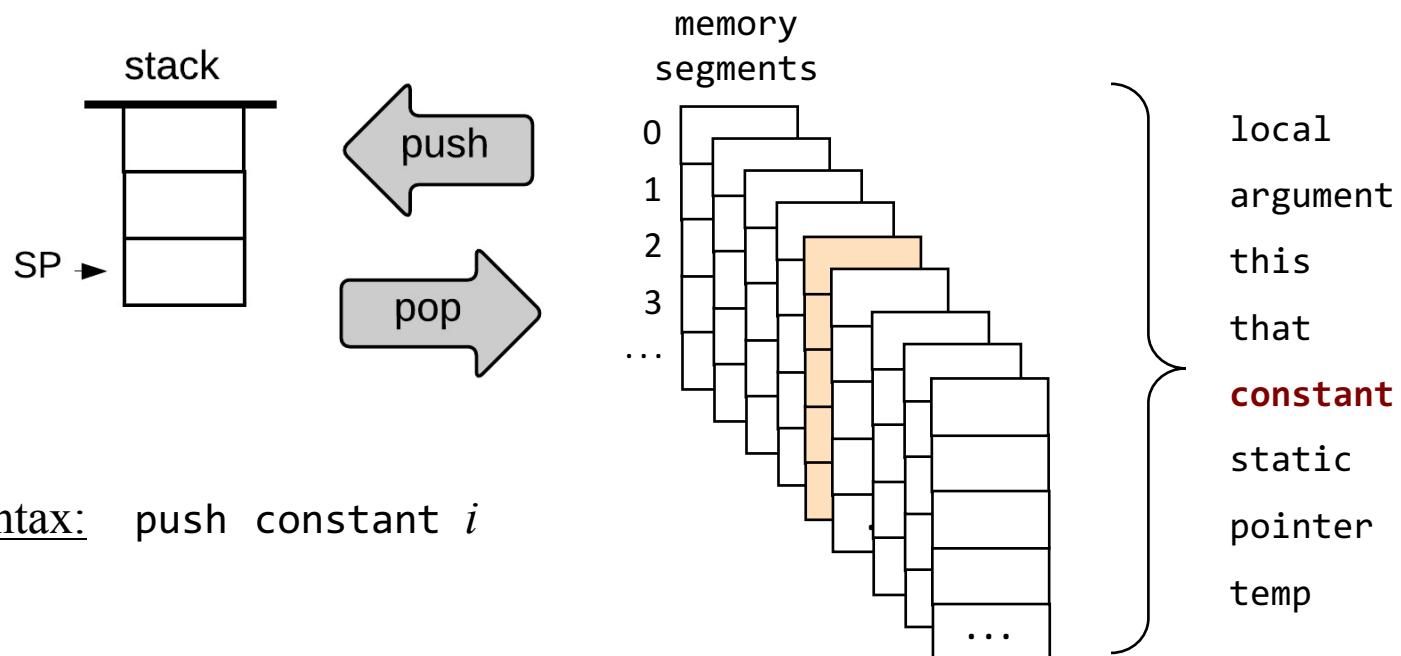
are implemented precisely the same way

Memory segments



Syntax: push/pop segment i

Implementing push constant i



Syntax: push constant i

Why do we need a constant segment?

Because we need to represent constants somehow in the VM level.

When the compiler translates high-level code into VM code...

- high-level operations on the $constant i$ are translated into VM operations on the segment entry $constant i$
- This syntactical convention will make sense when we write the compiler.

Implementing push constant i

VM code:

```
push constant i
```

VM Translator

Assembly psuedo code:

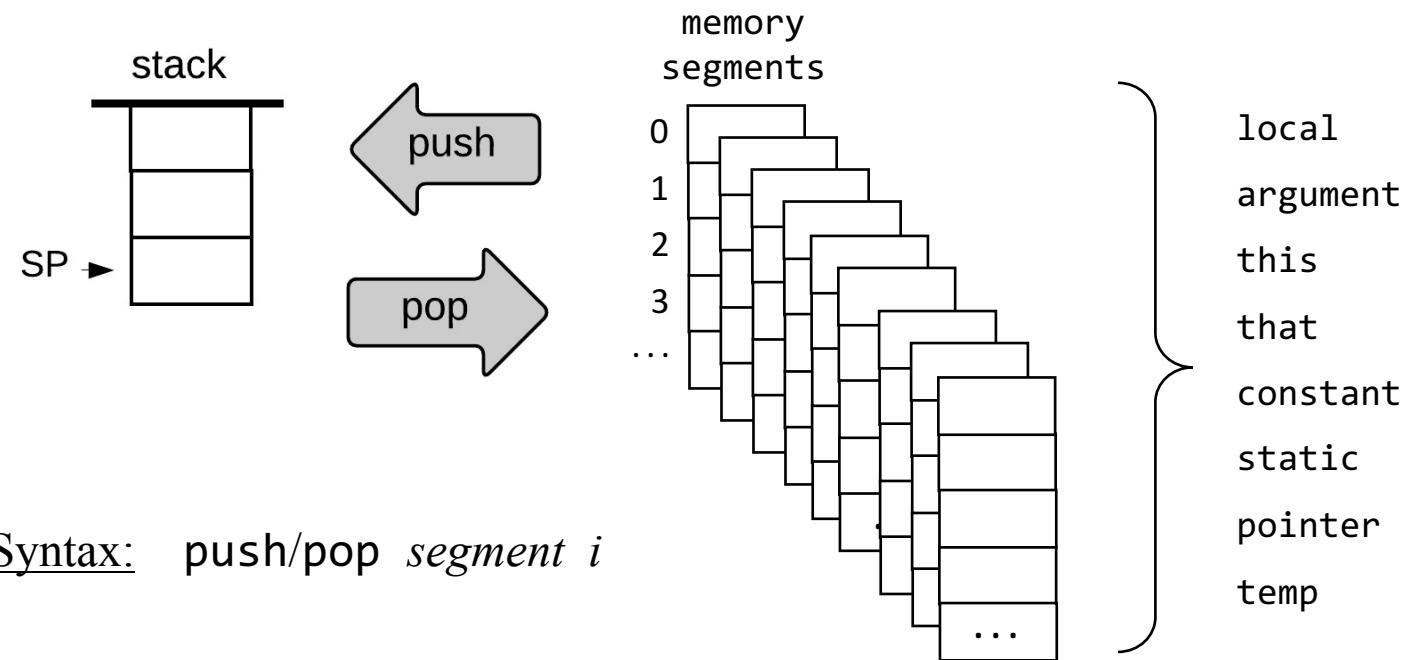
```
*SP = i, SP++
```

(no pop constant operation)

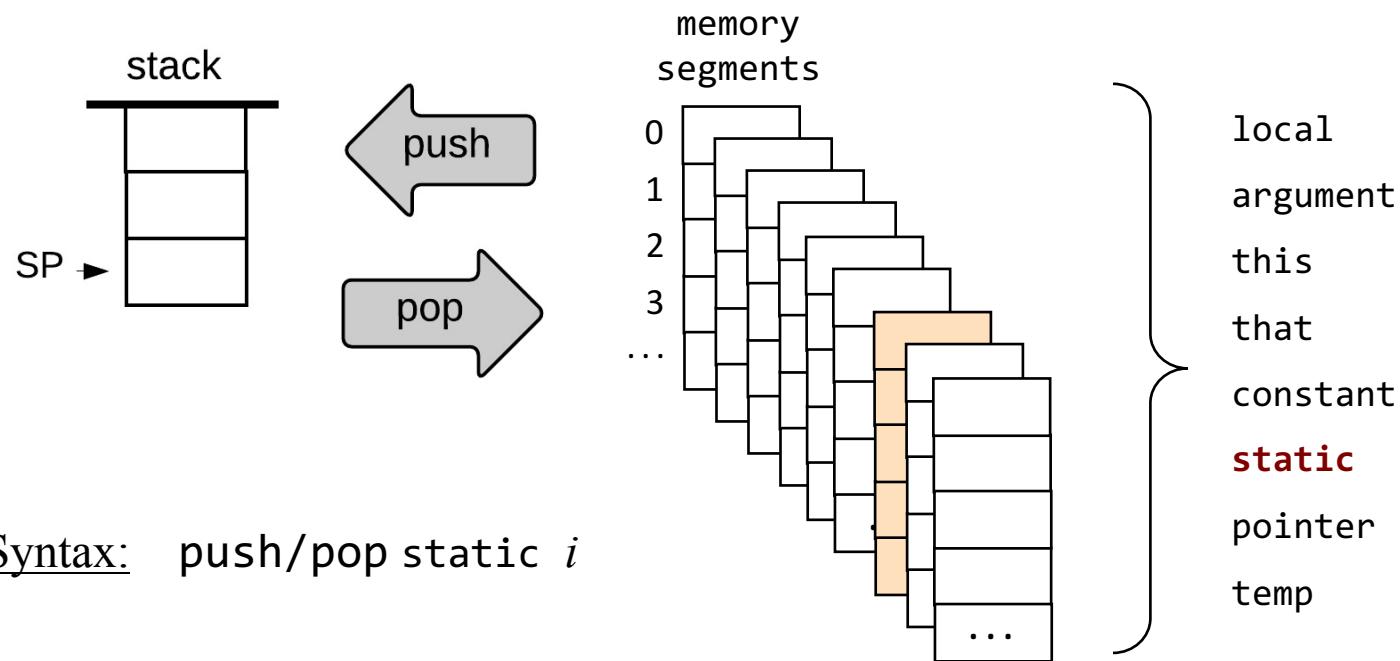
Implementation:

Supplies the specified constant

Memory segments



Implementing push/pop static *i*



Why do we need a **static** segment?

When translating high-level code into VM code, the compiler...

- high-level operations on *static* variables are translates into VM operations on entries of the segment **static**
- We now turn to discuss how the **static** segment is realized on the host platform.

Implementing push/pop static *i*

VM code:

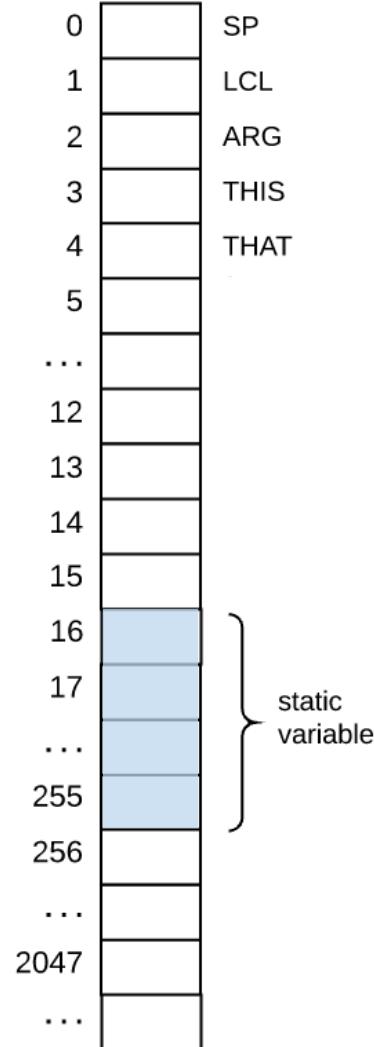
```
// File Foo.vm  
...  
pop static 5  
...  
pop static 2  
...
```

VM translator

Generated assembly code:

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

Hack RAM



The challenge:

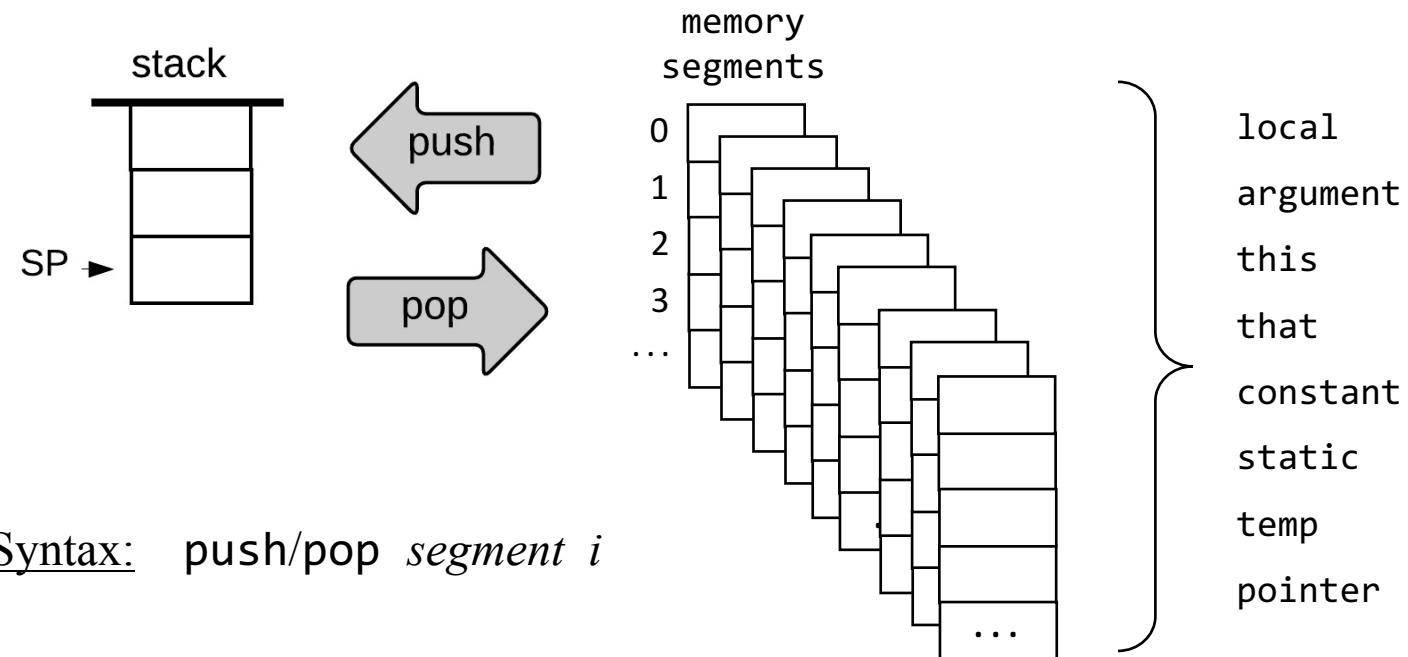
static variables should be seen
by all the methods in a program

Solution:

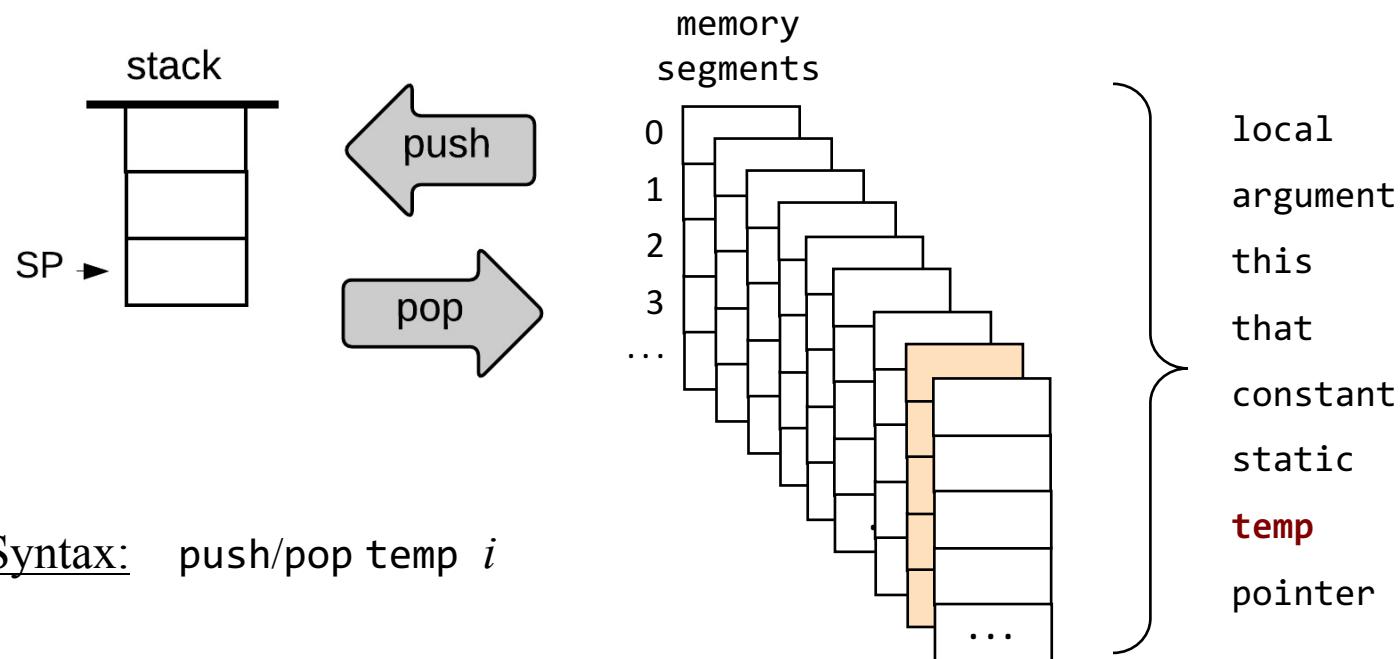
Store them in some “global space”:

- 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.

Memory segments



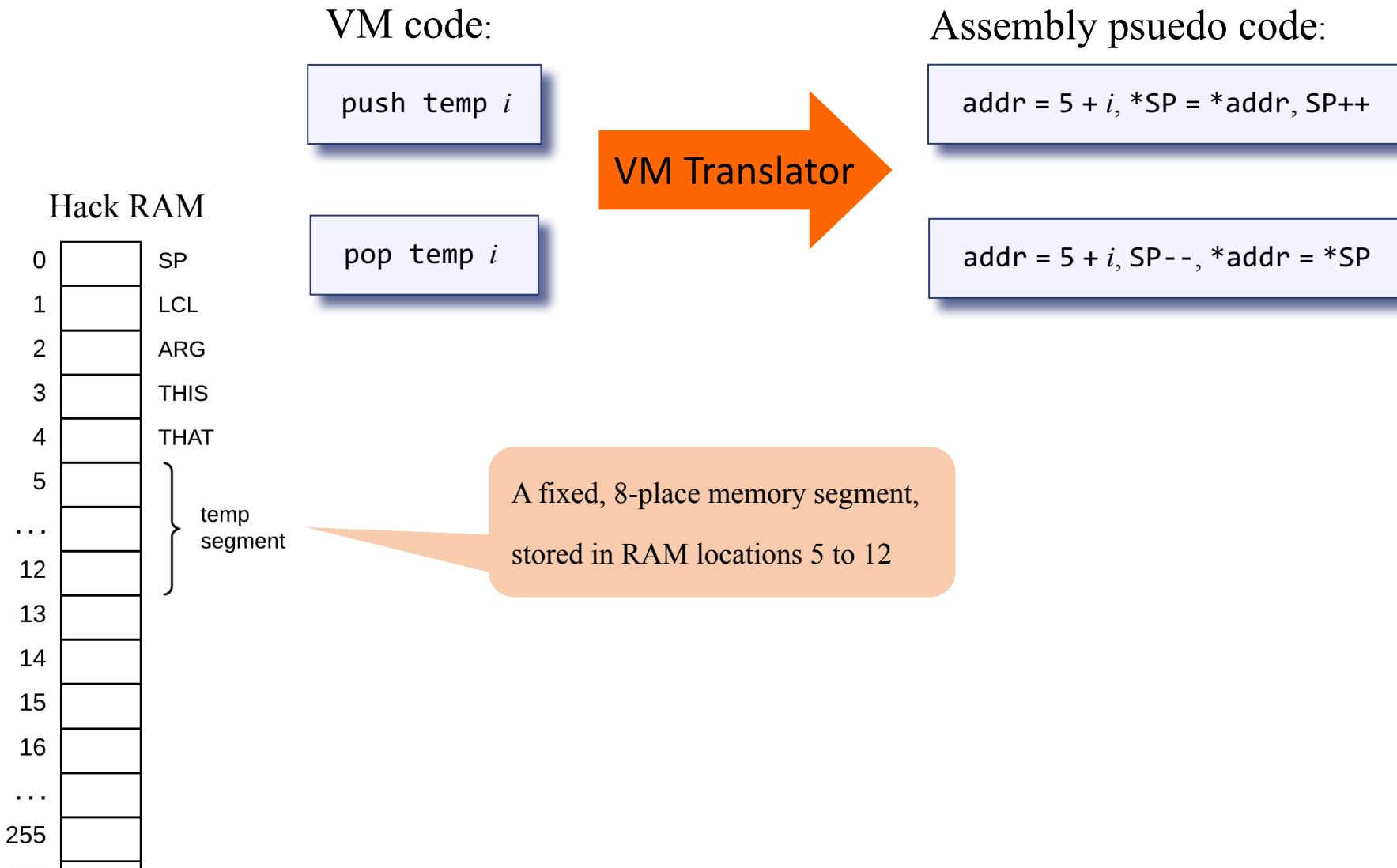
Implementing push/pop temp *i*



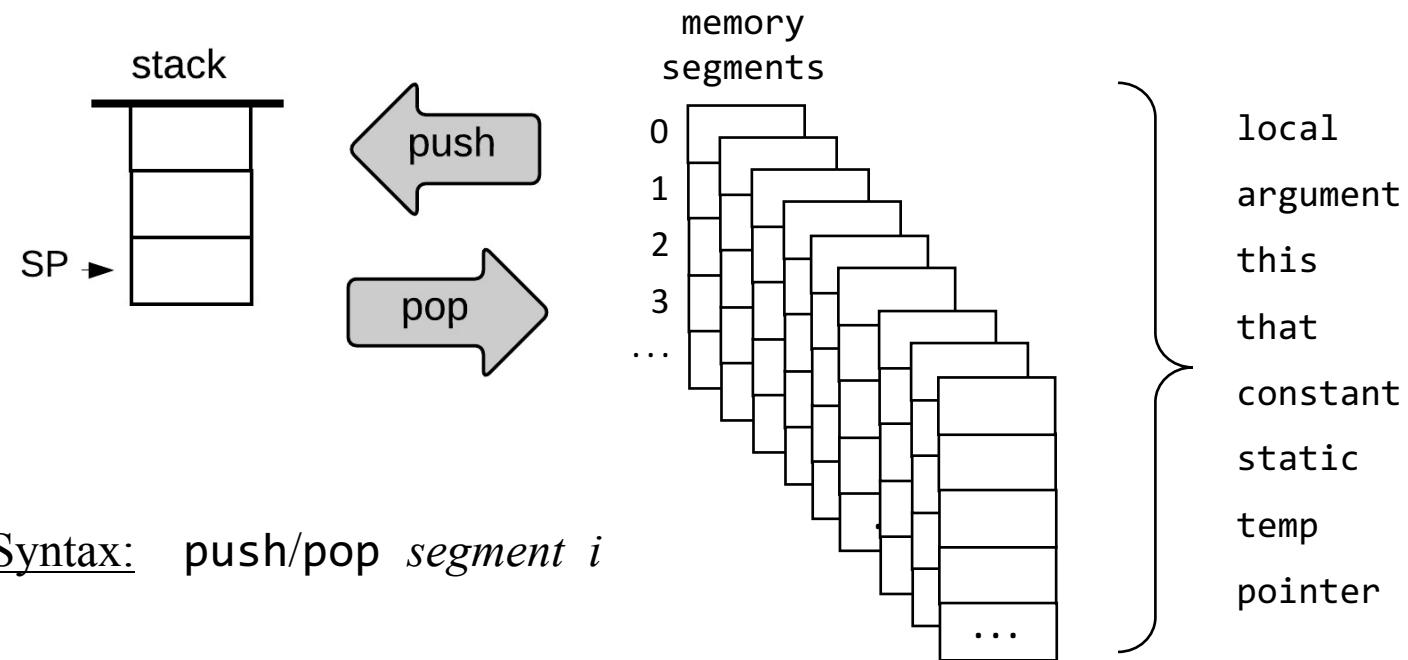
Why do we need the temp segment?

- 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**.

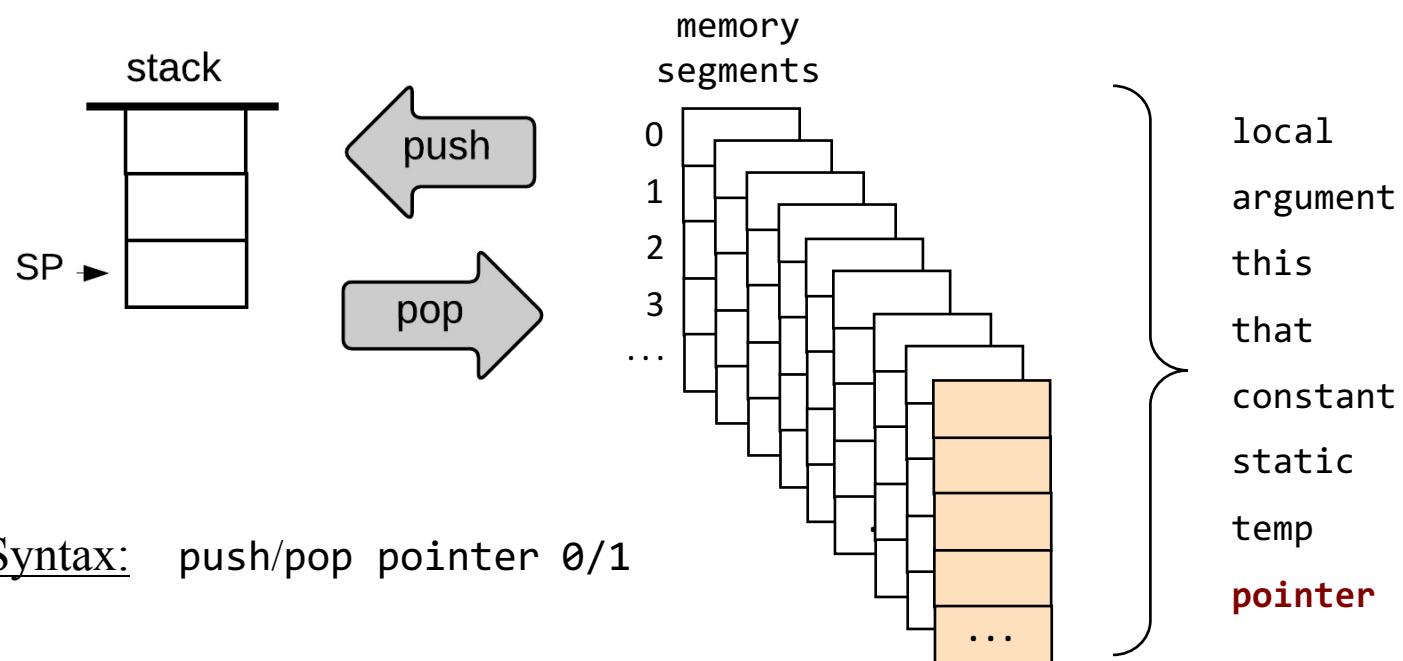
Implementing push/pop temp *i*



Memory segments



Implementing push/pop pointer 0/1



Syntax: push/pop pointer 0/1

Why do we need the pointer segment?

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

Implementing 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).

VM language

Arithmetic / Logical commands

add

sub

neg

eq

get

lt

and

or

not



Memory access commands

pop *segment i*



push *segment i*

Branching commands

label *label*

goto *label*

if-goto *label*

Function commands

function *functionName nVars*

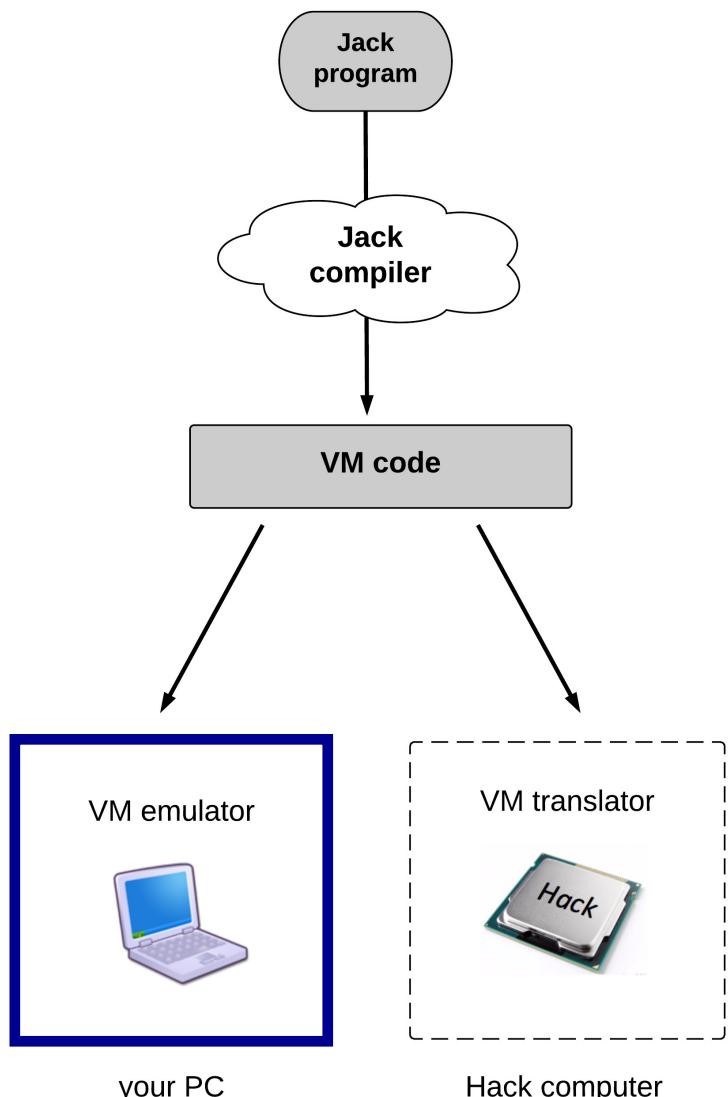
call *functionName nArgs*

return

Virtual machine: lecture plan

- ✓ The road ahead
 - ✓ Program compilation overview
 - ✓ VM abstraction:
 - ✓ the stack
 - ✓ memory segments
 - ✓ VM implementation:
 - ✓ the stack
 - ✓ memory segments
- 
- The VM emulator
 - VM implementation on the Hack platform
 - The VM translator: proposed implementation
 - Building the VM translator, Part I

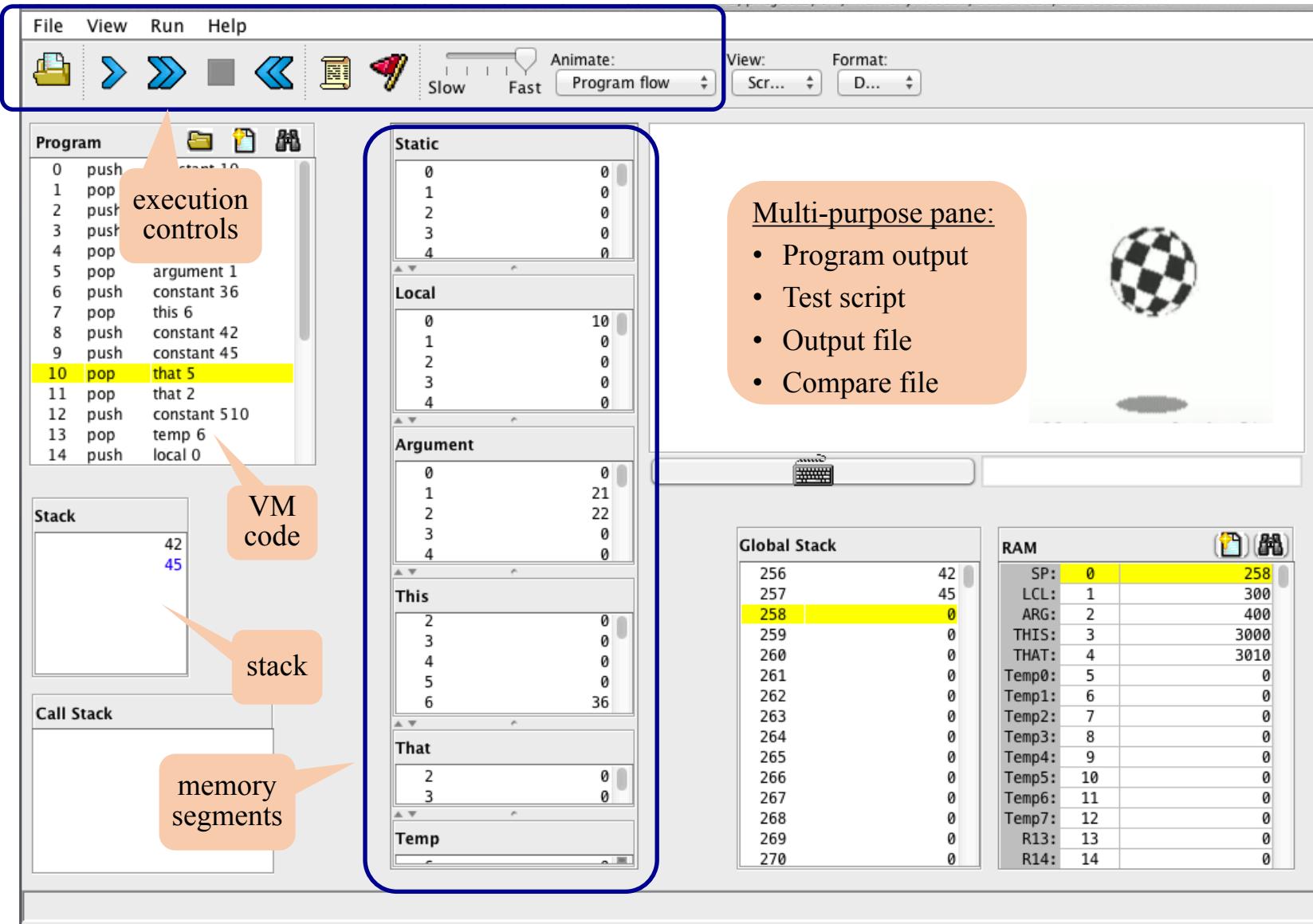
The VM Emulator



Typical uses of the VM emulator:

- Running (compiled) Jack programs
- Experimenting with VM commands
- Observing the VM internals (stack, memory segments)
- Observing how the VM is realized on the host platform.

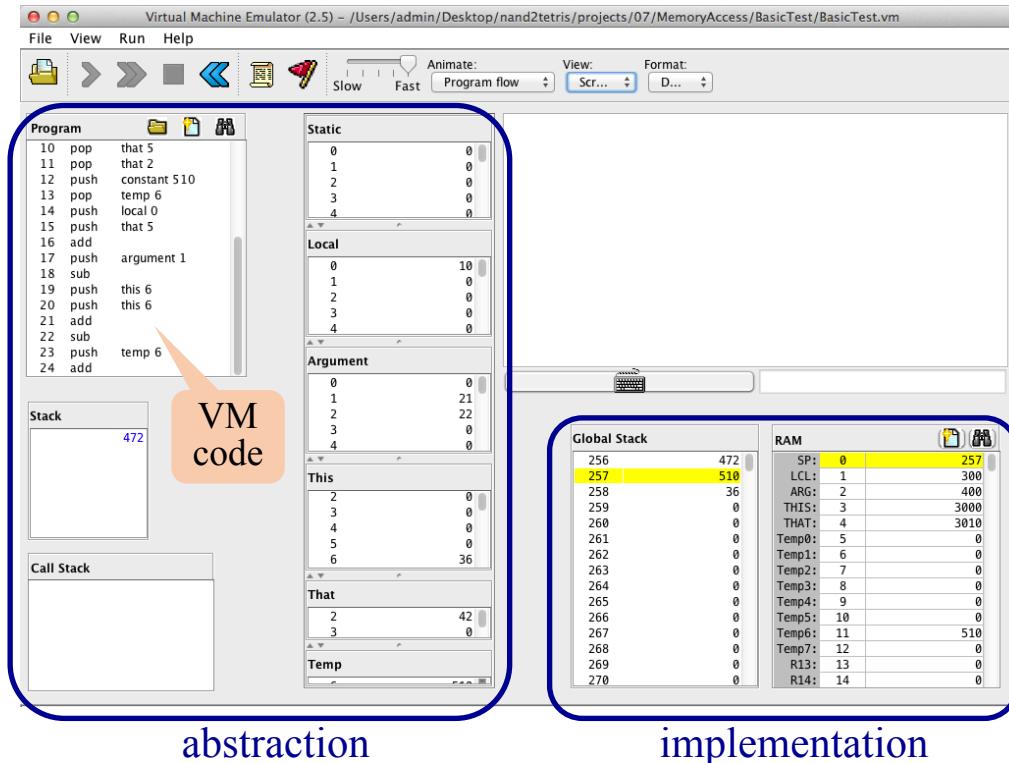
The VM Emulator



Example

BasicTest.vm

```
...  
push constant 10  
pop local 0  
push constant 21  
push constant 22  
pop argument 2  
pop argument 1  
push constant 36  
pop this 6
```



Things to watch for: (during the code's execution)

- Stack state
 - Memory segments states

How the stack and memory segments are realized on the host platform

Test script

BasicTest.vm

```
...  
push constant 10  
pop local 0  
push constant 21  
push constant 22  
pop argument 2  
pop argument 1  
push constant 36  
pop this 6  
...
```

BasicTestVME.tst

```
load BasicTest.vm,  
output-file BasicTest.out,  
compare-to BasicTest.cmp,  
output-list RAM[256]%D1.6.1 RAM[300]%D1.6.1 ...  
  
repeat 25 {           // BasicTest.vm has 25 instructions  
    vmstep;  
}  
  
// Outputs some values, as specified by the output-list  
// (stack base + selected values from the tested mem. segments)  
output;
```

There's no need to
delve into the code
of test scripts

if (.out == .cmp)
the test is
successful
else
error

BasicTest.out

RAM[256]	RAM[300]	RAM[401]	RAM[402]	RAM[3006]	RAM[3012]	RAM[3015]	RAM[11]	
472	10	21	22	36	42	45	510	

BasicTest.cmp

RAM[256]	RAM[300]	RAM[401]	RAM[402]	RAM[3006]	RAM[3012]	RAM[3015]	RAM[11]	
472	10	21	22	36	42	45	510	

Some missing elements

BasicTest.vm

```
...
push constant 10
pop local 0
push constant 21
push constant 22
pop argument 2
pop argument 1
push constant 36
pop this 6
...
```

BasicTestVME.tst

```
load BasicTest.vm,
output-file BasicTest.out,
compare-to BasicTest.cmp,
output-list RAM[256]%D1.6.1 RAM[300]%D1.6.1 ...

repeat 25 {           // BasicTest.vm has 25 instructions
    vmstep;
}

// Outputs some values, as specified by the output-list
// (stack base + selected values from the tested mem. segments)
output;
```

There's no need to
delve into the code
of test scripts

Some missing elements

BasicTest.vm

```
function Foo.bar
...
push constant 10
pop local 0
push constant 21
push constant 22
pop argument 2
pop argument 1
push constant 36
pop this 6
...
return
```

BasicTestVME.tst

```
load BasicTest.vm,
output-file BasicTest.out,
compare-to BasicTest.cmp,
output-list RAM[256]%D1.6.1 RAM[300]%D1.6.1 ...

set sp 256,      // stack pointer
set local 300,   // base address of the local segment
set argument 400, // base address of the argument segment
set this 3000,   // base address of the this segment
set that 3010,   // base address of the that segment

repeat 25 {       // BasicTest.vm has 25 instructions
    vmstep;
}

// Outputs some values, as specified by the output list
// (stack base + selected values from the tested memory segments)
output;
```

There's no need to
delve into the code
of test scripts

Initialization is handled
manually by the supplied
test script

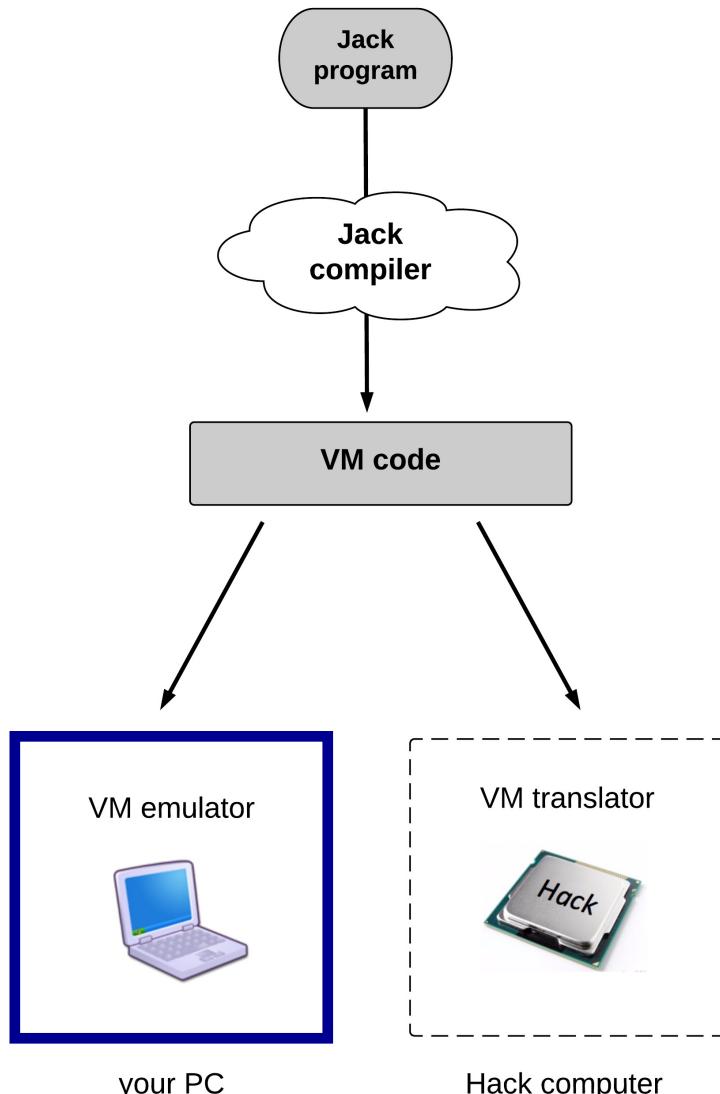
Some missing elements

- function / return “envelope”
- Initializing the stack and the memory segments on the host RAM
(both will be added in project 8)

Demo



Recap: the VM Emulator



The VM emulator helps us:

- Run and test high-level programs
- Understand ...
 - the VM abstraction
 - the VM implementation

Virtual machine: lecture plan

- ✓ The road ahead
- ✓ Program compilation overview
- ✓ VM abstraction:
 - ✓ the stack
 - ✓ memory segments
- ✓ VM implementation:
 - ✓ the stack
 - ✓ memory segments
- ✓ The VM emulator
 - VM implementation on the Hack platform
 - The VM translator: proposed implementation
 - Building the VM translator, Part I

VM translator

VM code

```
push constant 2
push local 0
sub
push local 1
push constant 5
add
sub
pop local 2
...
```

VM translator

Assembly code

```
// push constant 2
@2
D=A
@SP
A=M
M=D
@SP
M=M+1
// push local 0
...
```

Each VM command is translated into several assembly commands

In order to write a VM translator, we must be familiar with:

- the source language
- the target language
- the VM mapping on the target platform.

Source: VM language

Arithmetic / Logical commands

add
sub
neg
eq
gt
lt
and
or
not

Branching commands

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

Function commands

function *functionName nVars*
call *functionName nArgs*
return

Memory access commands

pop *segment i*
push *segment i*

Target: symbolic Hack code

A instruction:

`@value`

where *value* is either a non-negative decimal constant or a symbol referring to such a constant

Semantics:

- ❑ sets the A register to *value*;
- ❑ makes M the RAM location whose address is *value*.
(M stands for RAM[A])

C instruction:

`dest = comp ; jump`

(*dest* and *jump* are optional)

where:

comp =

0, 1, -1, D, A, !D, !A, -D, -A, D+1, A+1, D-1, A-1, D+A, D-A, A-D, D&A, D|A,
M, !M, -M, M+1, M-1, D+M, D-M, M-D, D&M, D|M

dest =

null, M, D, MD, A, AM, AD, AMD

(M stands for RAM[A])

jump =

null, JGT, JEQ, JGE, JLT, JNE, JLE, JMP

Semantics:

- ❑ computes the value of *comp* and stores the result in *dest*;
- ❑ if (*comp* jump 0) is true, jumps to execute the instruction in ROM[A].

Standard VM mapping on the Hack platform

VM mapping decisions:

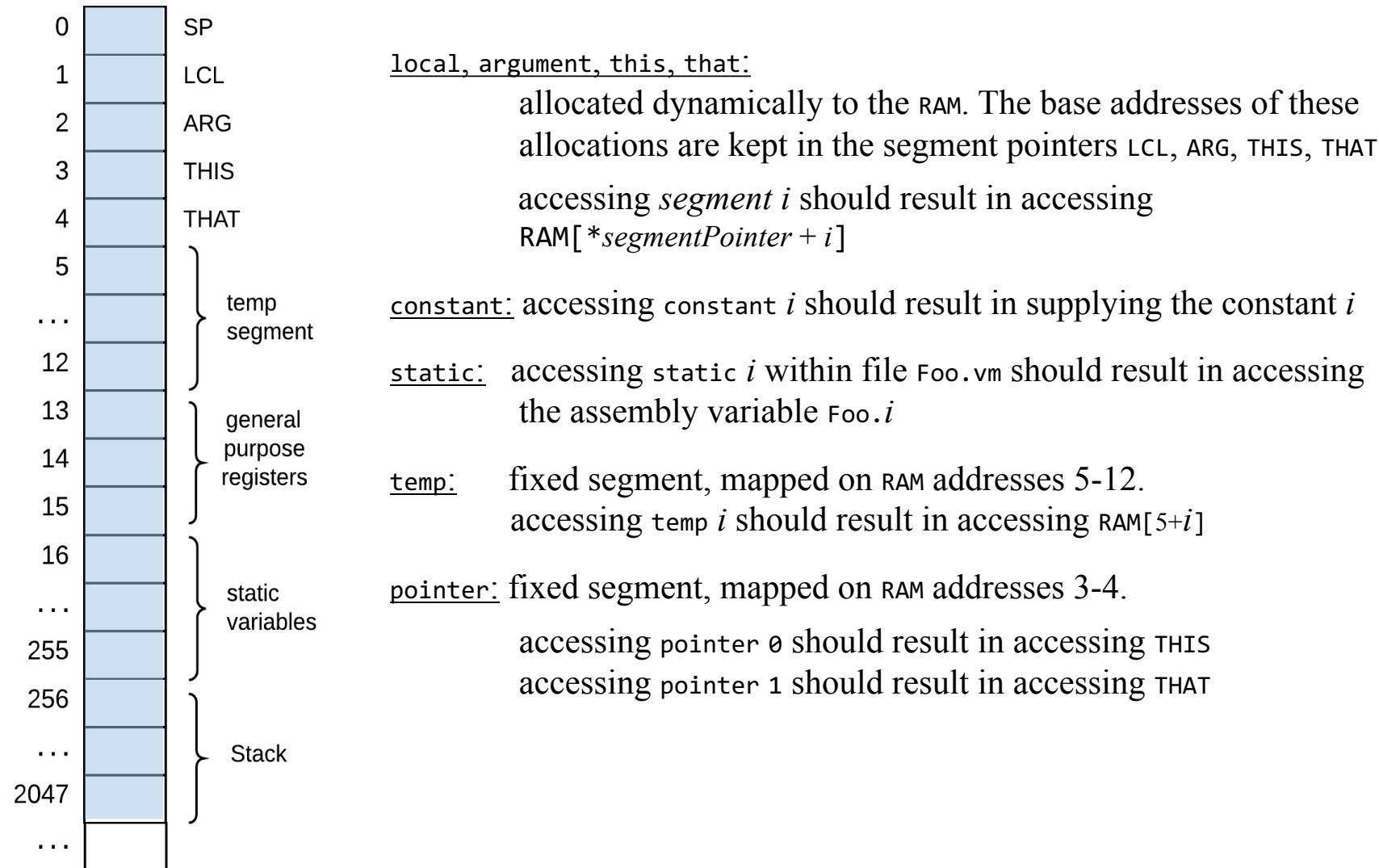
- How to map the VM's data structures using the host hardware platform
- How to express the VM's commands using the host machine language

Standard mapping:

- Specifies how to do the mapping in an agreed-upon way
- Benefits:
 - Compatibility with other software systems
 - Standard testing.

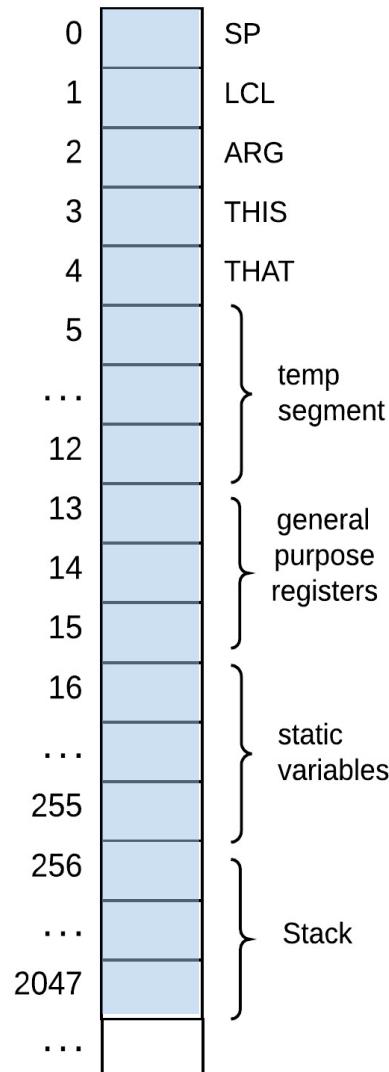
Standard VM mapping on the Hack platform

Hack RAM



Standard VM mapping on the Hack platform

Hack RAM



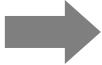
In order to realize this mapping, the VM translator should use some special variables / symbols:

<i>Symbol</i>	<i>Usage</i>
SP	This predefined symbol points to the memory address within the host RAM just following the address containing the topmost stack value.
LCL, ARG, THIS, THAT	These predefined symbols point, respectively, to the base addresses within the host RAM of the virtual segments local , argument , this , and that of the currently running VM function.
R13–R15	These predefined symbols can be used for any purpose.
Xxx.i symbols	The static segment is implemented as follows: each static variable <i>i</i> in file Xxx.vm is translated into the assembly symbol Xxx.i . In the subsequent assembly process, these symbolic variables will be allocated to the RAM by the Hack assembler.

Implementation note:

The standard mapping will be extended in project 8, when we'll complete the VM translator's implementation.

Virtual machine: lecture plan

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 - ✓ VM implementation:
 - ✓ the stack
 - ✓ memory segments
 - ✓ The VM emulator
 - ✓ VM implementation on the Hack platform
- 
- The VM translator:
proposed implementation
 - Building the VM translator,
Part I

The VM translator

VM code (*fileName.vm*)

```
...
push constant 17
push local 2
add
pop argument 1
...
```

VM
translator

Generated assembly code (*fileName.asm*)

```
...
// push constant 17
@17
D=A
... additional assembly commands that complete the
implementation of push constant 17
```

The VM translator

VM code (*fileName.vm*)

```
...
push constant 17
push local 2
add
pop argument 1
...
```

VM
translator

Generated assembly code (*fileName.asm*)

```
...
// push constant 17
@17
D=A
... additional assembly commands that complete the
implementation of push constant 17
// push local 2
... generated assembly code that implements push local 2
```

The VM translator

VM code (*fileName.vm*)

```
...
push constant 17
push local 2
add
pop argument 1
...
```

VM
translator

Generated assembly code (*fileName.asm*)

```
...
// push constant 17
@17
D=A
... additional assembly commands that complete the
implementation of push constant 17
// push local 2
... generated assembly code that implements push local 2
```

The VM translator

VM code (*fileName.vm*)

```
...
push constant 17
push local 2
add
pop argument 1
...
```

VM
translator

Generated assembly code (*fileName.asm*)

```
...
// push constant 17
@17
D=A
... additional assembly commands that complete the
implementation of push constant 17

// push local 2
... generated assembly code that implements push local 2

// add
... generated assembly code that implements add
```

The VM translator

VM code (*fileName.vm*)

```
...
push constant 17
push local 2
add
pop argument 1
...
```

VM
translator

Generated assembly code (*fileName.asm*)

```
...
// push constant 17
@17
D=A
... additional assembly commands that complete the
implementation of push constant 17

// push local 2
... generated assembly code that implements push local 2

// add
... generated assembly code that implements add
```

The VM translator

VM code (*fileName.vm*)

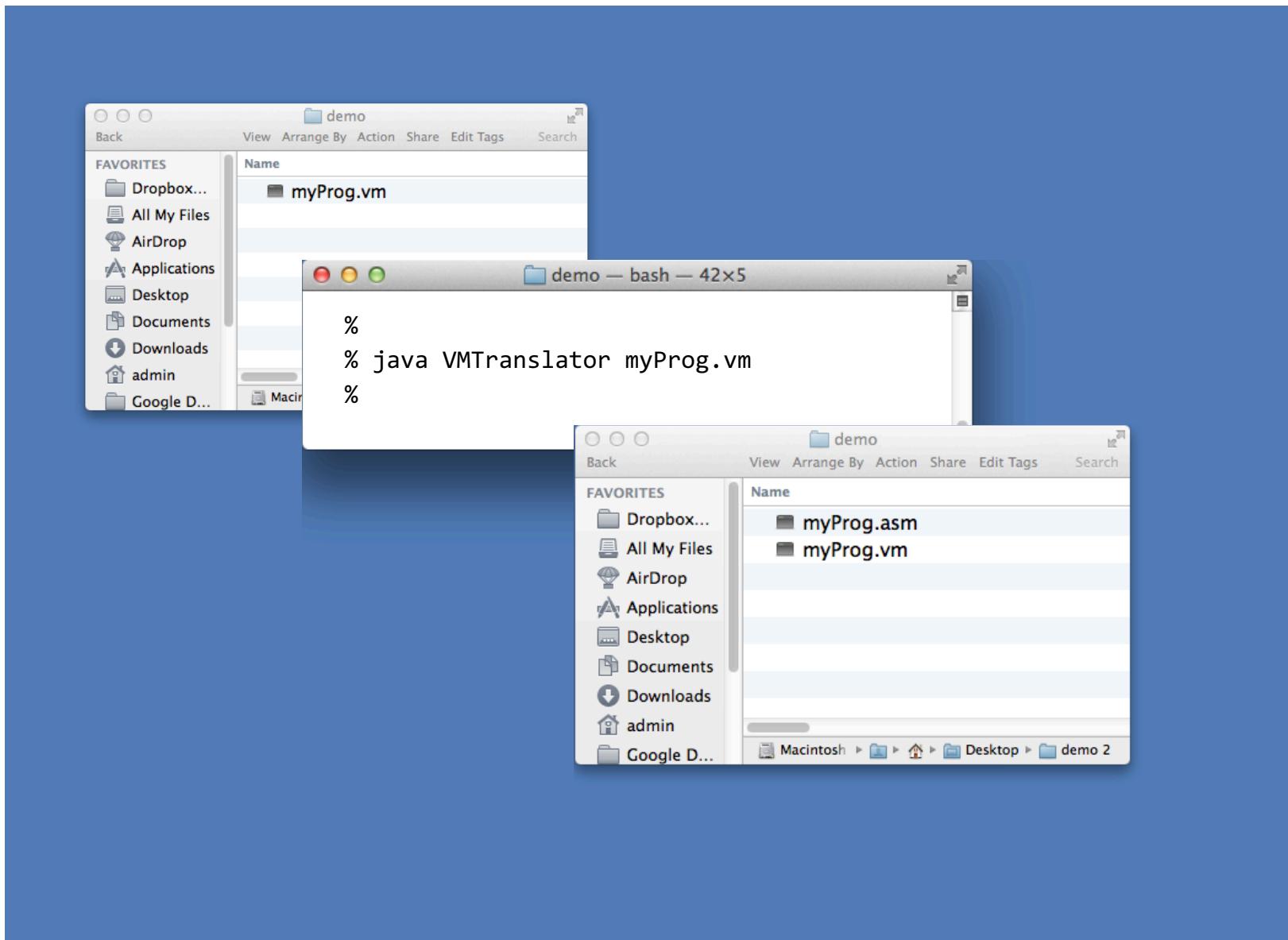
```
...  
push constant 17  
push local 2  
add  
pop argument 1  
...
```

VM
translator

Generated assembly code (*fileName.asm*)

```
...  
// push constant 17  
@17  
D=A  
... additional assembly commands that complete the  
implementation of push constant 17  
  
// push local 2  
... generated assembly code that implements push local 2  
  
// add  
... generated assembly code that implements add  
  
// pop argument 1  
... generated assembly code that implements push argument 1  
...
```

The VM translator: usage



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:

- Constructs a `Parser` to handle the input file
- Constructs a `CodeWriter` to handle the output file
- Marches through the input file, parsing each line and generating code from it

Parser

- Handles the parsing of a single .vm file
- Reads a VM command, parses the command into its lexical components, and provides convenient access to these components
- Ignores 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 <code>hasMoreCommands()</code> is true. Initially there is no current command.

Parser

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

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

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.

More routines will be added to this module in Project 8,
when we complete the implementation of the VM translator.

The big picture

VM language:

Arithmetic / Logical commands:

`add`
`sub`
`neg`
`eq`
`gt`
`lt`
`and`
`or`
`not`

Memory access commands:

`pop segment i`
`push segment i`

Branching commands:

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

Function commands:

`function functionName nVars`
`call functionName nArgs`
`return`

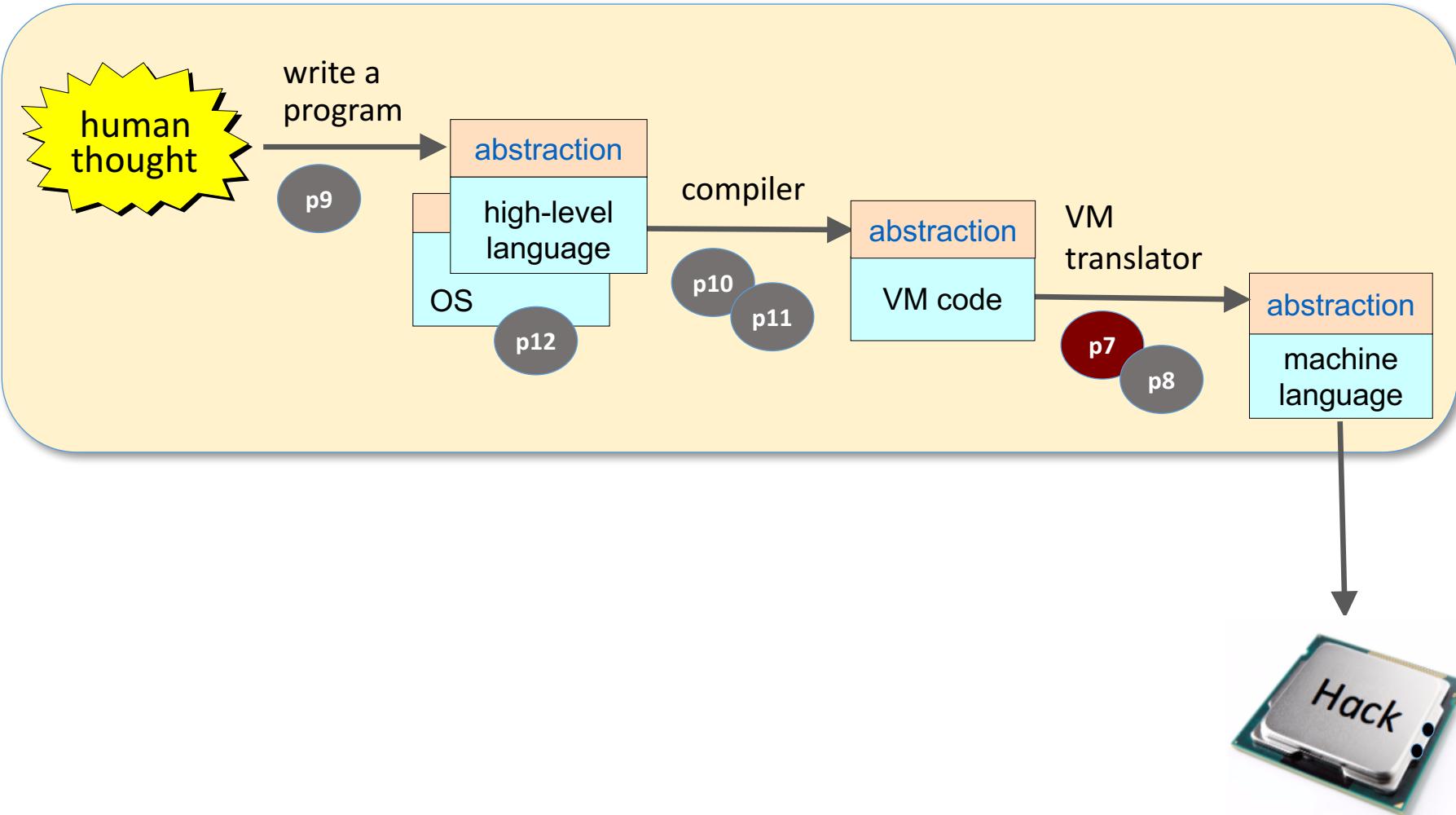
Project 7

Project 8

Virtual machine: lecture plan

- ✓ The road ahead
 - ✓ Program compilation overview
 - ✓ VM abstraction:
 - ✓ the stack
 - ✓ memory segments
 - ✓ VM implementation:
 - ✓ the stack
 - ✓ memory segments
 - ✓ The VM emulator
 - ✓ VM implementation on the Hack platform
 - ✓ The VM translator:
proposed implementation
- 
- Building the VM translator,
Part I

The big picture



The VM language

VM language:

Arithmetic / Logical commands:

add
sub
neg
eq
gt
lt
and
or
not

Memory access commands:

pop segment i
push segment i

Branching commands:

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

Function commands:

function *functionName nVars*
call *functionName nArgs*
return

Project 7

Objective: build a basic VM translator that handles a subset of the VM language: stack arithmetic and memory access (push/pop) commands

VM language:

Arithmetic / Logical commands:

```
add  
sub  
neg  
eq  
gt  
lt  
and  
or  
not
```

Memory access commands:

```
pop segment i  
push segment i
```

Branching commands:

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

Function commands:

```
function functionName nVars  
call functionName nArgs  
return
```

Project 7

Objective: build a basic VM translator that handles a subset of the VM language: stack arithmetic and memory access (push/pop) commands

fileName.vm

```
...
push constant 17
push local 2
add
pop argument 1
...
```

fileName.asm

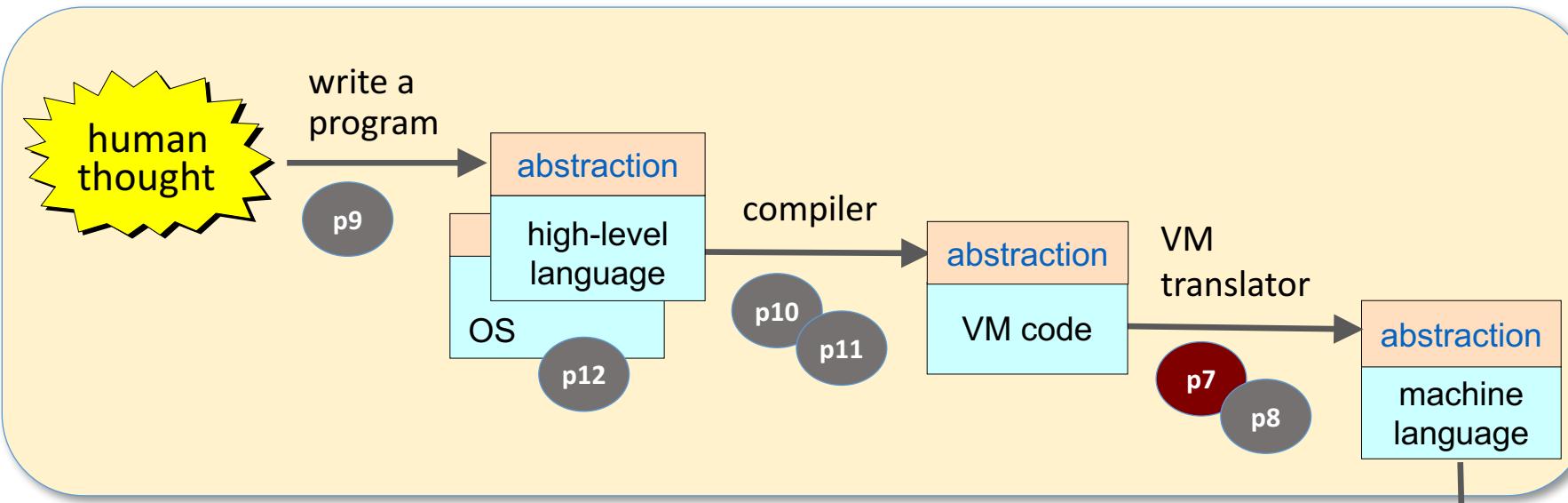
```
...
// push constant 17
@17
D=A
...
// push local 2
... generated assembly code that implements push local 2
// add
... generated assembly code that implements add
// pop argument 1
... generated assembly code that implements push argument 1
...
```



To test the translation:

Run the generated code on the target platform

Project 7: testing

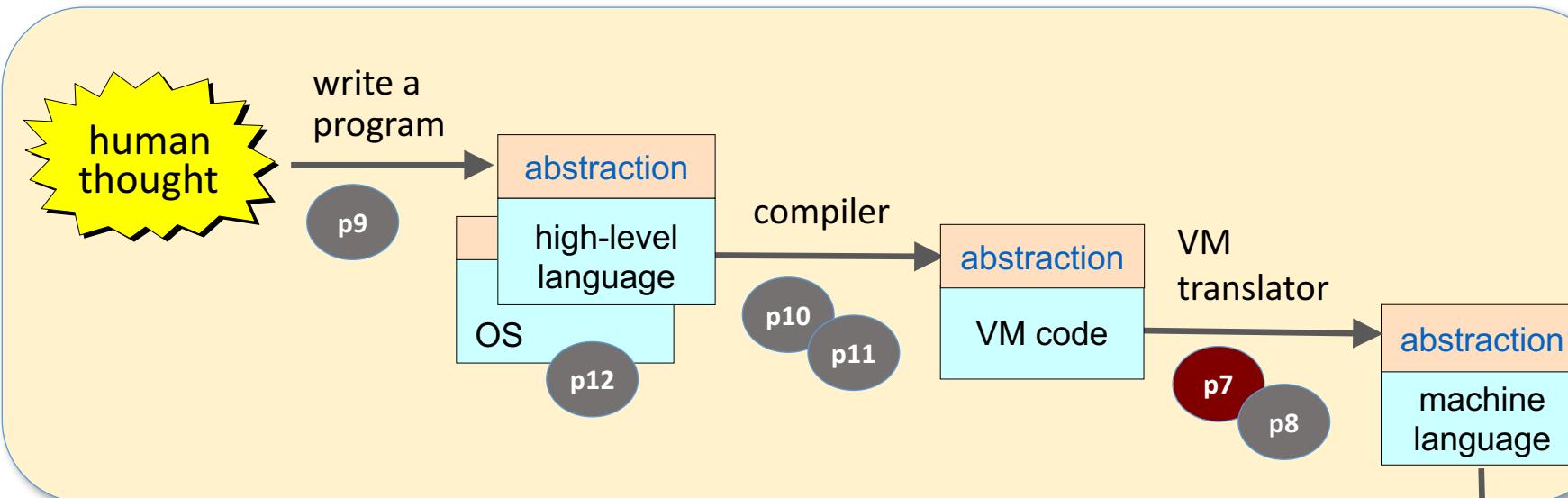


Testing option 1:

- Translate the generated assembly code into machine language,
- Run the binary code of the Hack computer



Project 7: testing



Testing option 2 (simpler):

- Run the generated assembly code on the CPU emulator.



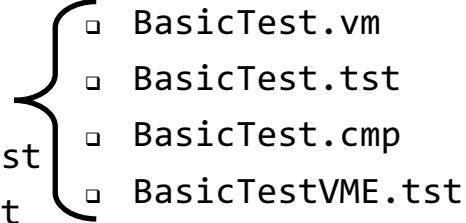
Development Plan

Objective: build a basic VM translator that handles the VM language
stack arithmetic and *memory access* (push/pop) commands

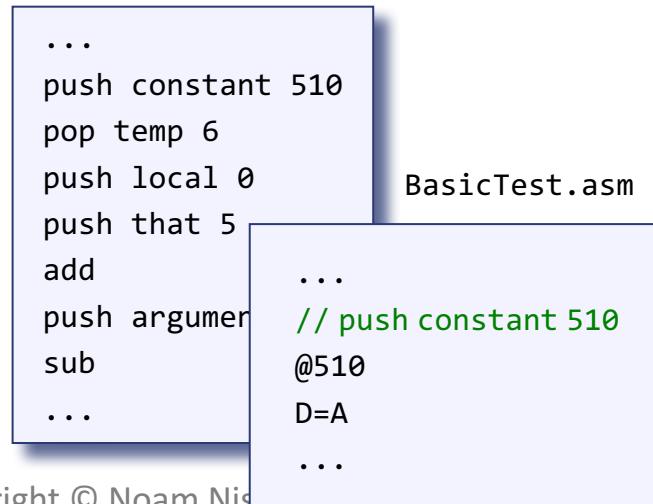
Contract

- Write a VM-to-Hack translator, conforming to the *Standard VM-on-Hack Mapping*
- Use your VM translator to translate and test the supplied .vm programs, yielding corresponding .asm programs
- When executed on the supplied CPU emulator, the generated .asm programs should deliver the same results mandated by the supplied test scripts and compare files.

Test programs

- SimpleAdd
 - StackTest
 - BasicTest
 - PointerTest
 - StaticTest
- 
- BasicTest.vm
 - BasicTest.tst
 - BasicTest.cmp
 - BasicTestVME.tst

BasicTest.vm (example)



```
...  
push constant 510  
pop temp 6  
push local 0  
push that 5  
add  
push argument  
sub  
...  
...  
// push constant 510  
@510  
D=A  
...
```

Development Plan

Objective: build a basic VM translator that handles the VM language
stack arithmetic and *memory access* (push/pop) commands

For each test `xxx.vm` program:

0. (optional) load `xxxVME.tst` into the VM emulator; run the test script and inspect the program's operation
1. use your translator to translate `xxx.vm`; The result will be a file named `xxx.asm`
2. inspect the generated code;
If there's a problem, fix your translator and go to stage 1
3. Load `xxx.tst` into the CPU emulator
4. Run the test script, inspect the results
5. If there's a problem, fix your translator and go to stage 1.

Test programs

- SimpleAdd
- StackTest
- BasicTest
- PointerTest
- StaticTest
- BasicTest.vm
- BasicTest.tst
- BasicTest.cmp
- BasicTestVME.tst

`BasicTest.vm` (example)

```
...  
push constant 510  
pop temp 6  
push local 0  
push that 5  
add  
push argument  
sub  
...  
...  
// push constant 510  
@510  
D=A  
...
```

BasicTest.asm

Tools and resources

Objective: build a basic VM translator that handles the VM language
stack arithmetic and *memory access* (push/pop) commands

Tools and resources:

- Test programs and compare files: `nand2tetris/projects/07`
- Experimenting with the test VM programs: the supplied *VM emulator*
- Translating the test VM programs into assembly: your *VM translator*
- Testing the resulting assembly code: the supplied *CPU emulator*
- Programming language for implementing your VM translator: Java, Python, ...
- Tutorials: VM emulator, CPU emulator ([nand2tetris web site](#))
- Reference: chapter 7 in *The Elements of Computing Systems*

Some testing issues

Objective: build a **basic** VM translator that will be extended in project 8

BasicTest.vm

```
function Foo.bar
...
push constant 510
pop temp 6
push local 0
push that 5
add
push argument 1
sub
push this 6
...
return
```

There's no need
to delve into the
test's code

BasicTest.asm

```
...
// push constant 510
@510
D=A
...
```

BasicTest.tst (for CPU emulator)

```
load BasicTest.asm,
output-file BasicTest.out,
compare-to BasicTest.cmp,
output-list RAM[256] RAM[300] ...

set RAM[0] 256, // base of stack
set RAM[1] 300, // base of local
set RAM[2] 400, // base of argument
set RAM[3] 3000, // base of this
set RAM[4] 3010, // base of that

repeat 600 {
    ticktock;
}
output;
```

The stack and segment base
addresses are handled by the
supplied test scripts, using fixed
addresses

(In project 8 the mappings will
be handled dynamically, by the
VM implementation)

Missing elements (in project 7)

- function / return “envelope”
- Mapping of the stack and the memory segments on the host RAM

Recap



Recap

Objective: build a basic VM translator that handles the VM language
stack arithmetic and *memory access* (push/pop) commands

VM language:

Arithmetic / Logical commands:

add
sub
neg
eq
gt
lt
and
or
not

Memory access commands:

push *segment i*
pop *segment i*

Branching commands:

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

Function commands:

function *functionName nVars*
call *functionName nArgs*
return

Project 7

Project 8

Perspective

(A subset of historical notes and additional issues)

- History of VMs and two-tier compilation:
 - p-code
 - Sun
 - Cellphones
- How close is our VM to Java's JVM?
- Efficiency and optimization
- Different VM implementations:
 - Stack machine
 - Register machine
 - Other approaches.