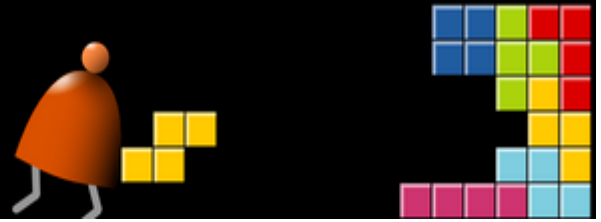

Chapter 5

Computer Architecture

These slides support chapter 5 of the book

The Elements of Computing Systems

By Noam Nisan and Shimon Schocken

MIT Press

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Happy teaching!

Noam Nisam / Shimon Schocken

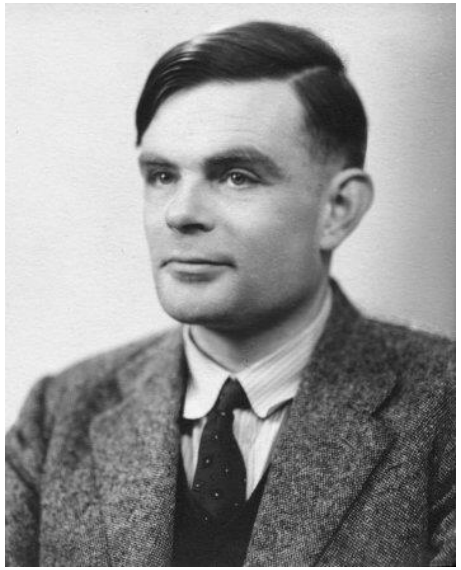
Computer Architecture: lecture plan

- Von Neumann Architecture
- Fetch-Execute Cycle
- The Hack CPU
- The Hack Computer
- Project 5 Overview

Universality

Same **hardware** can run many different **software** programs

Theory



Alan Turing:

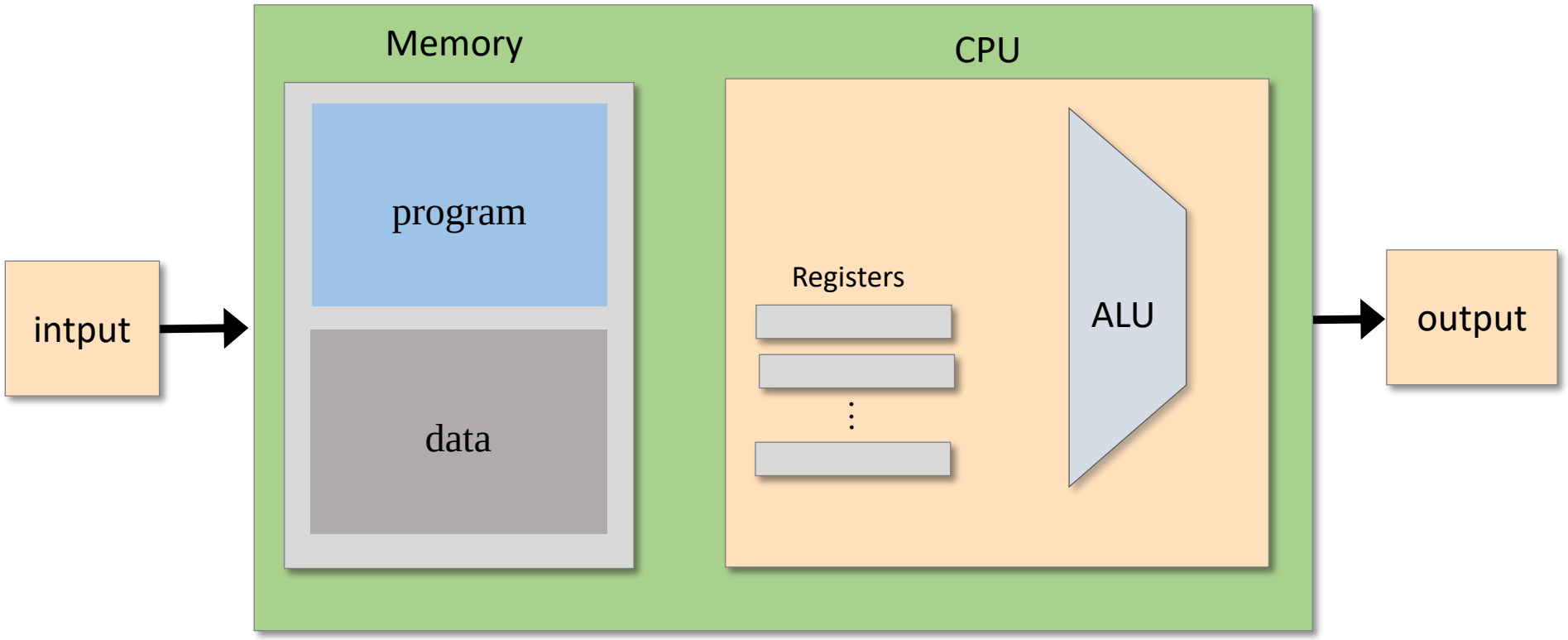
Universal Turing Machine

Practice

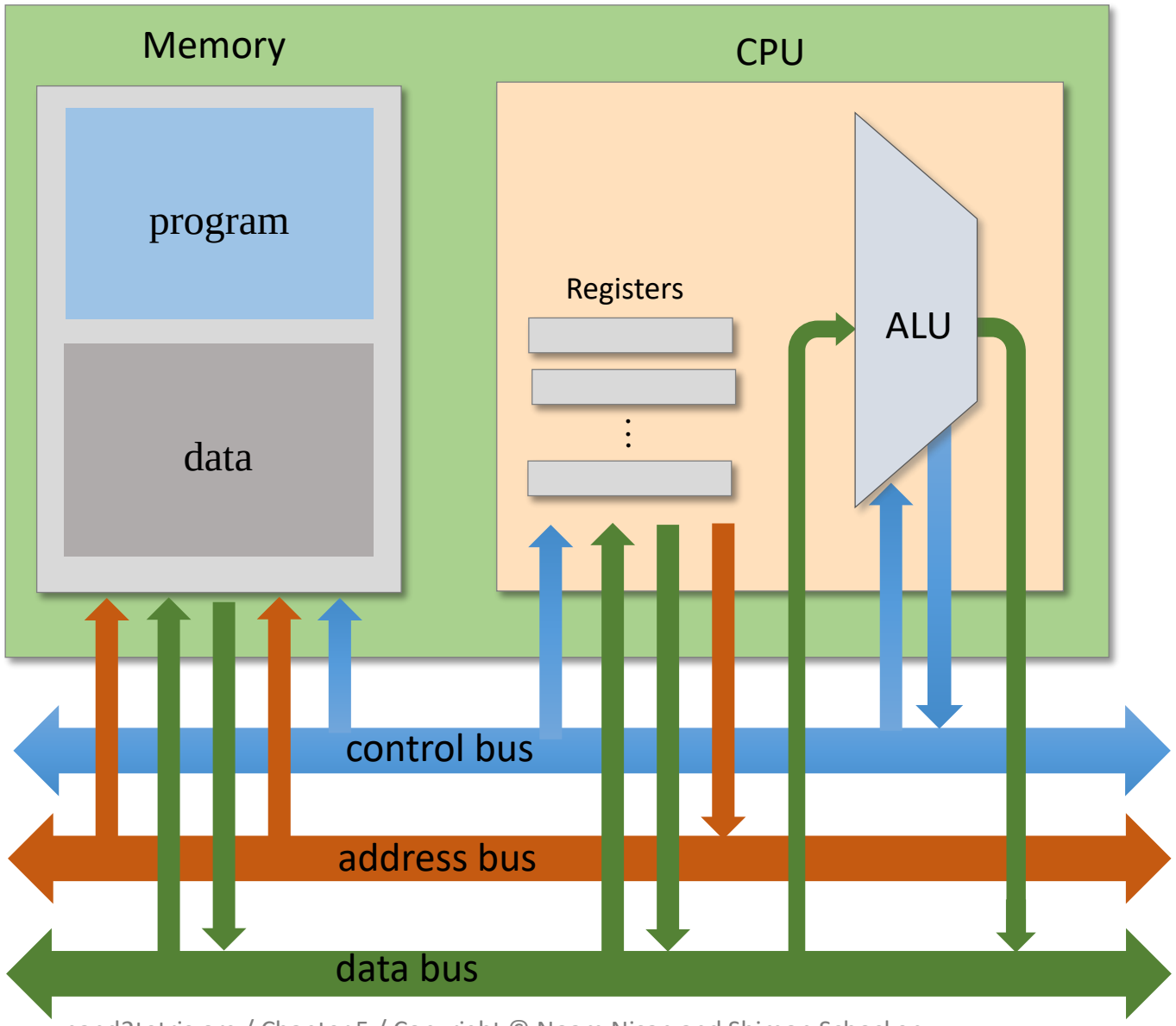
John Von Nuemann:

Stored Program Computer

Computer architecture



Computer architecture



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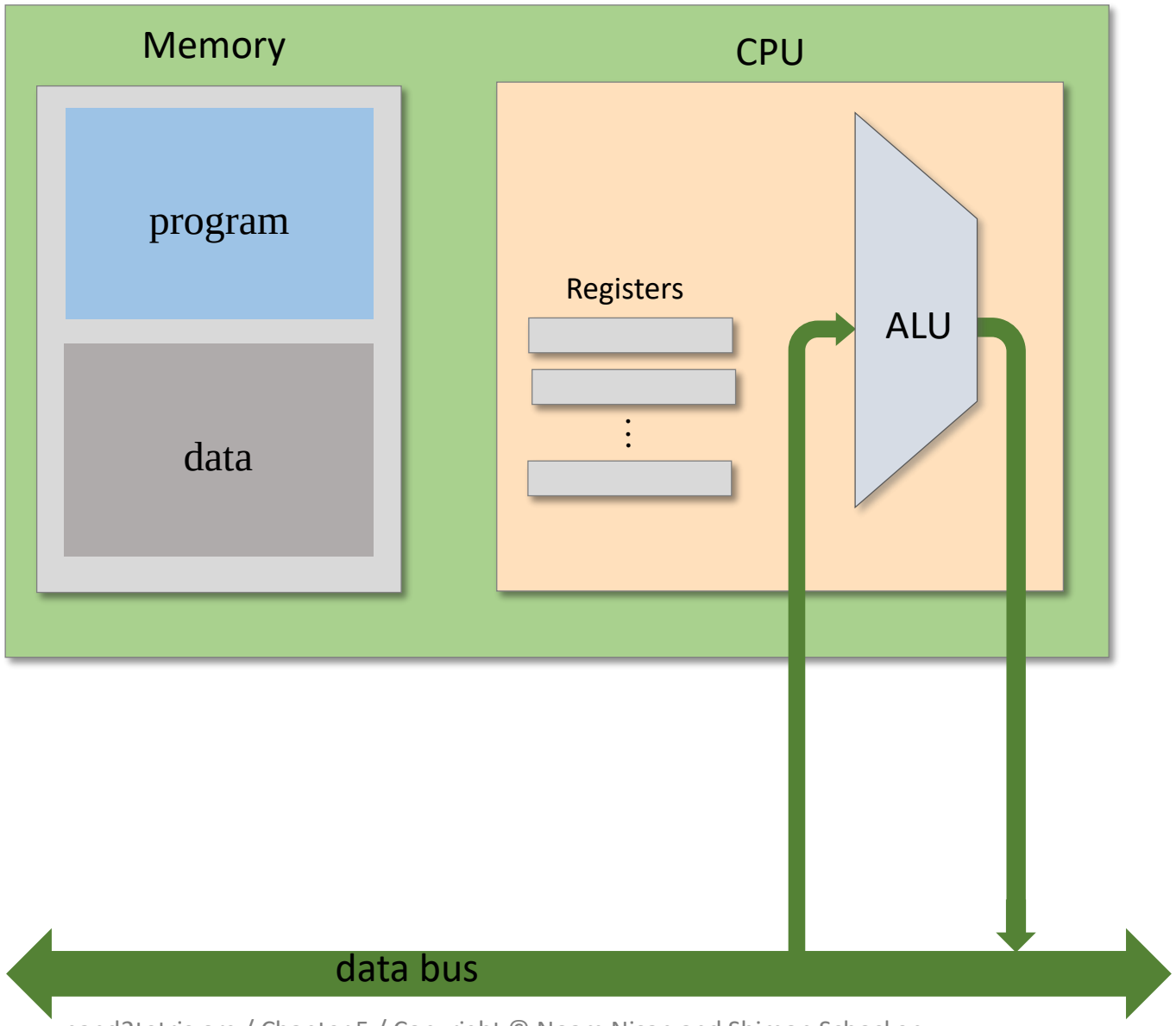
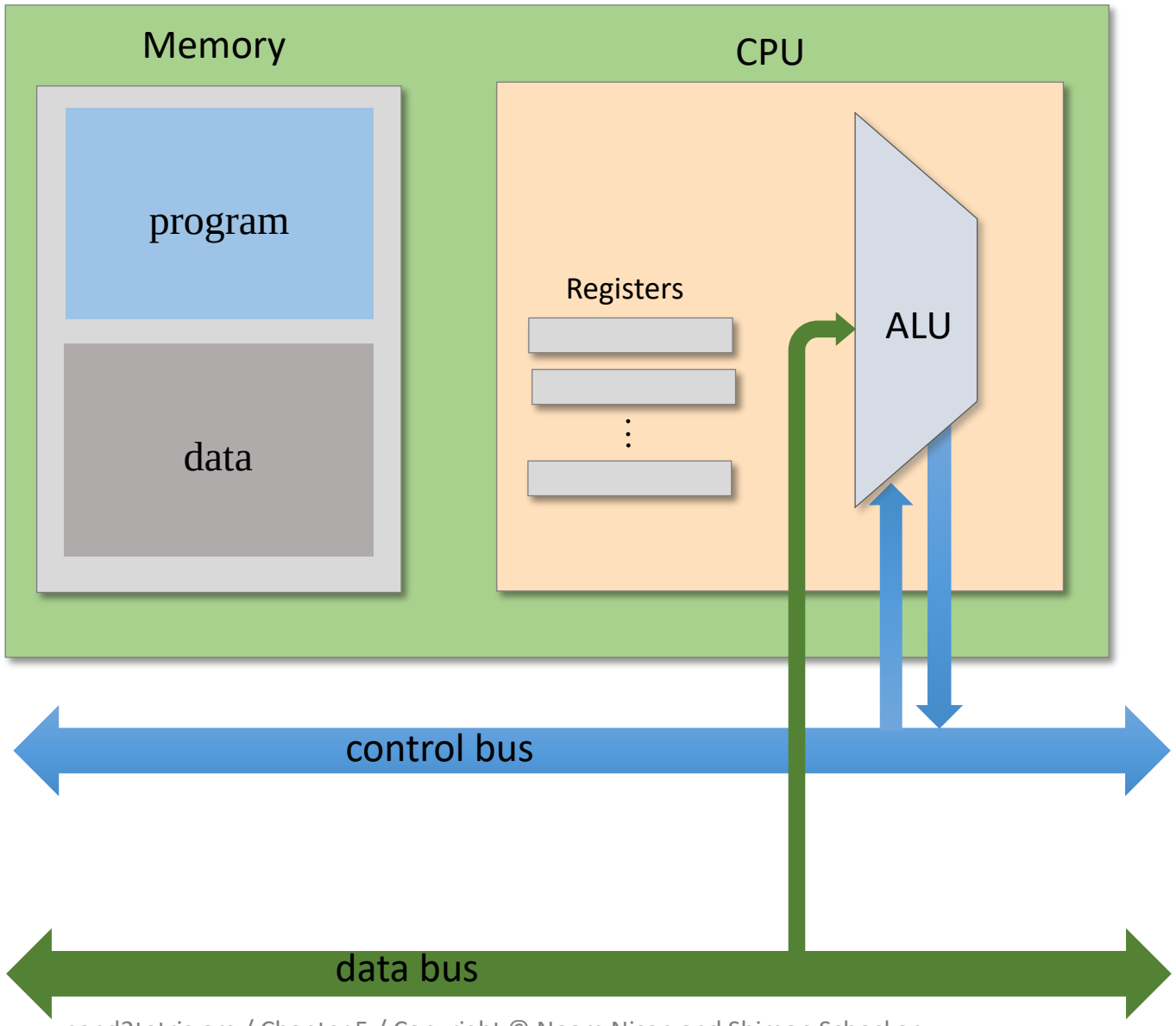


Computer architecture



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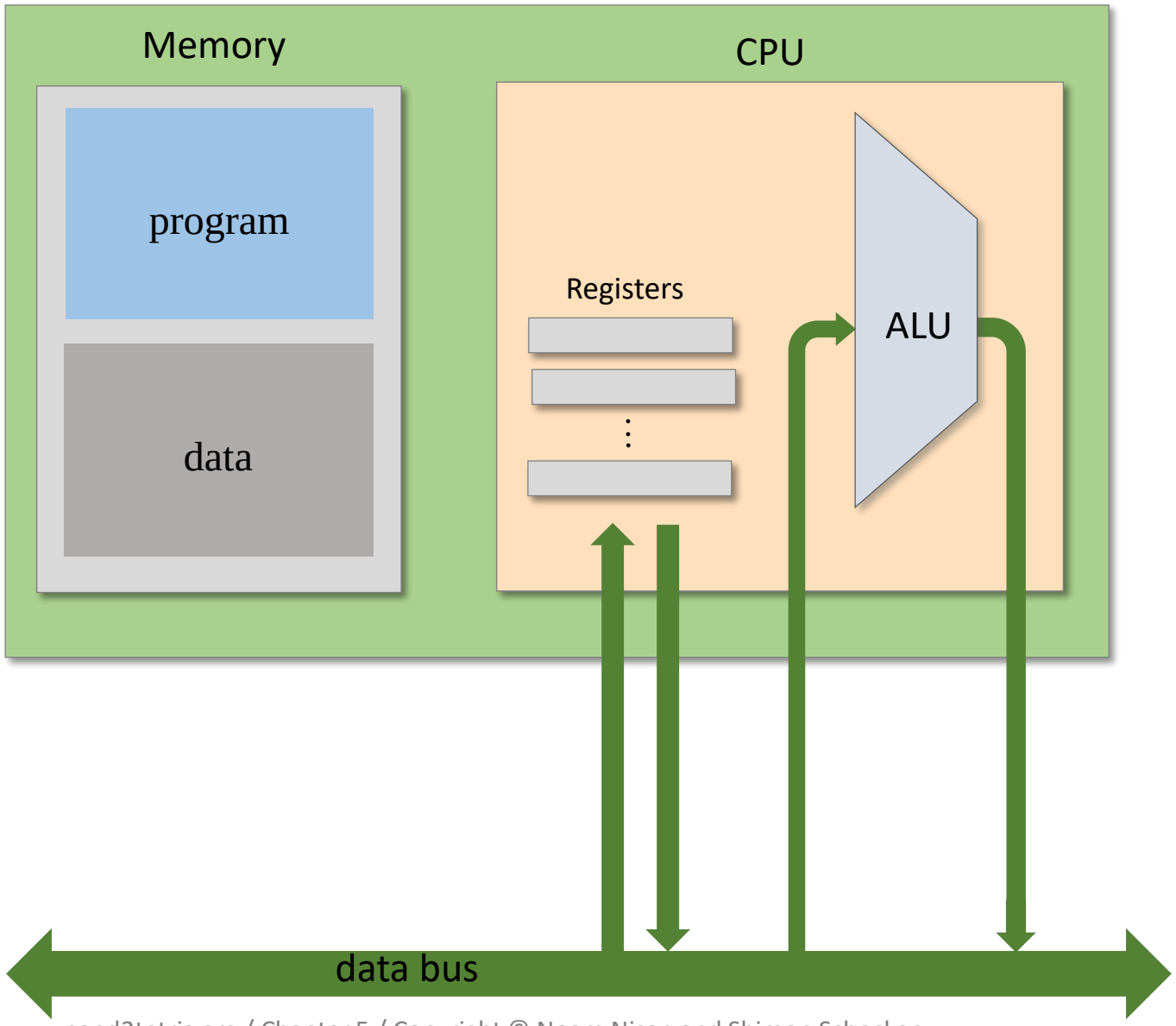
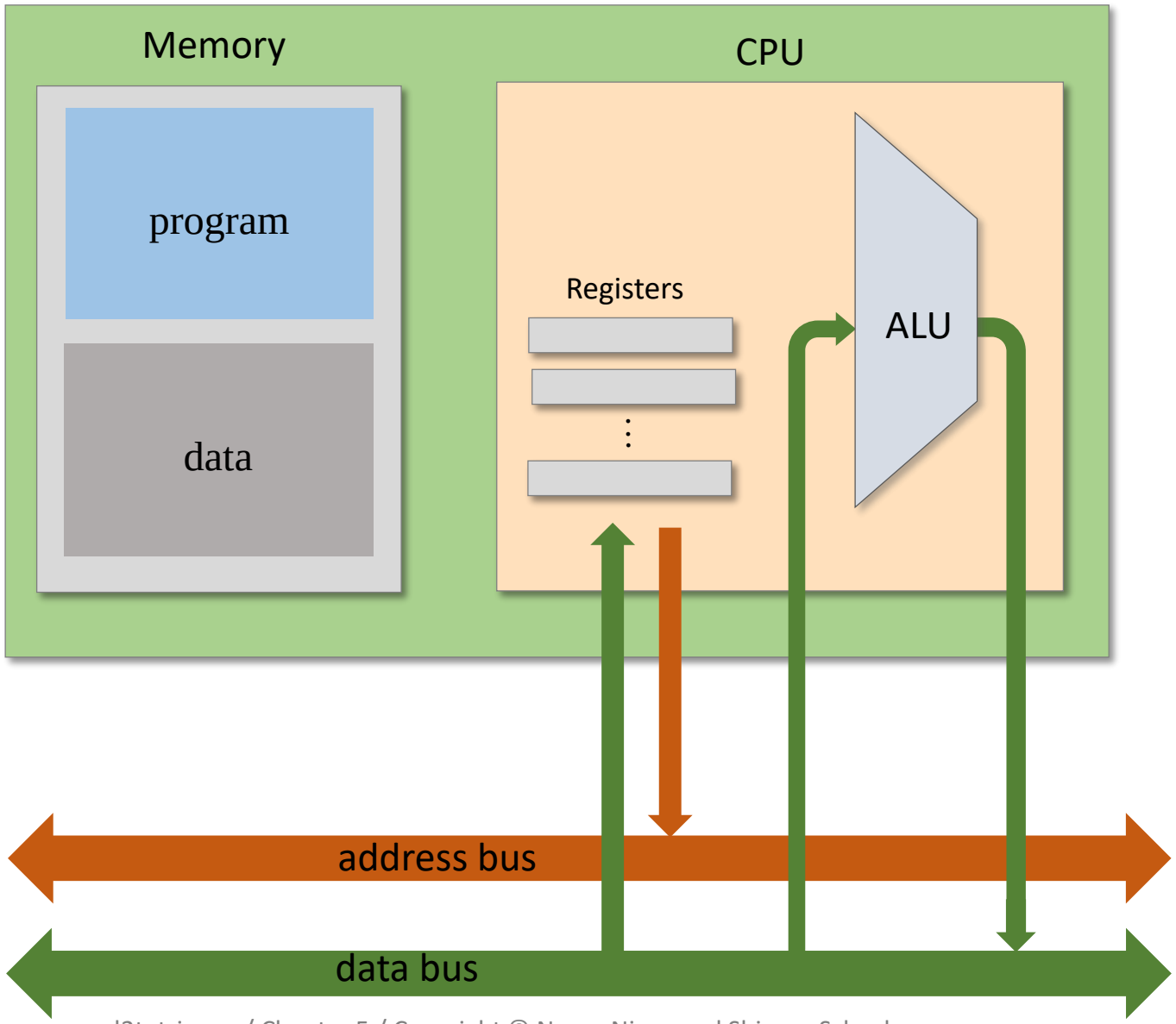
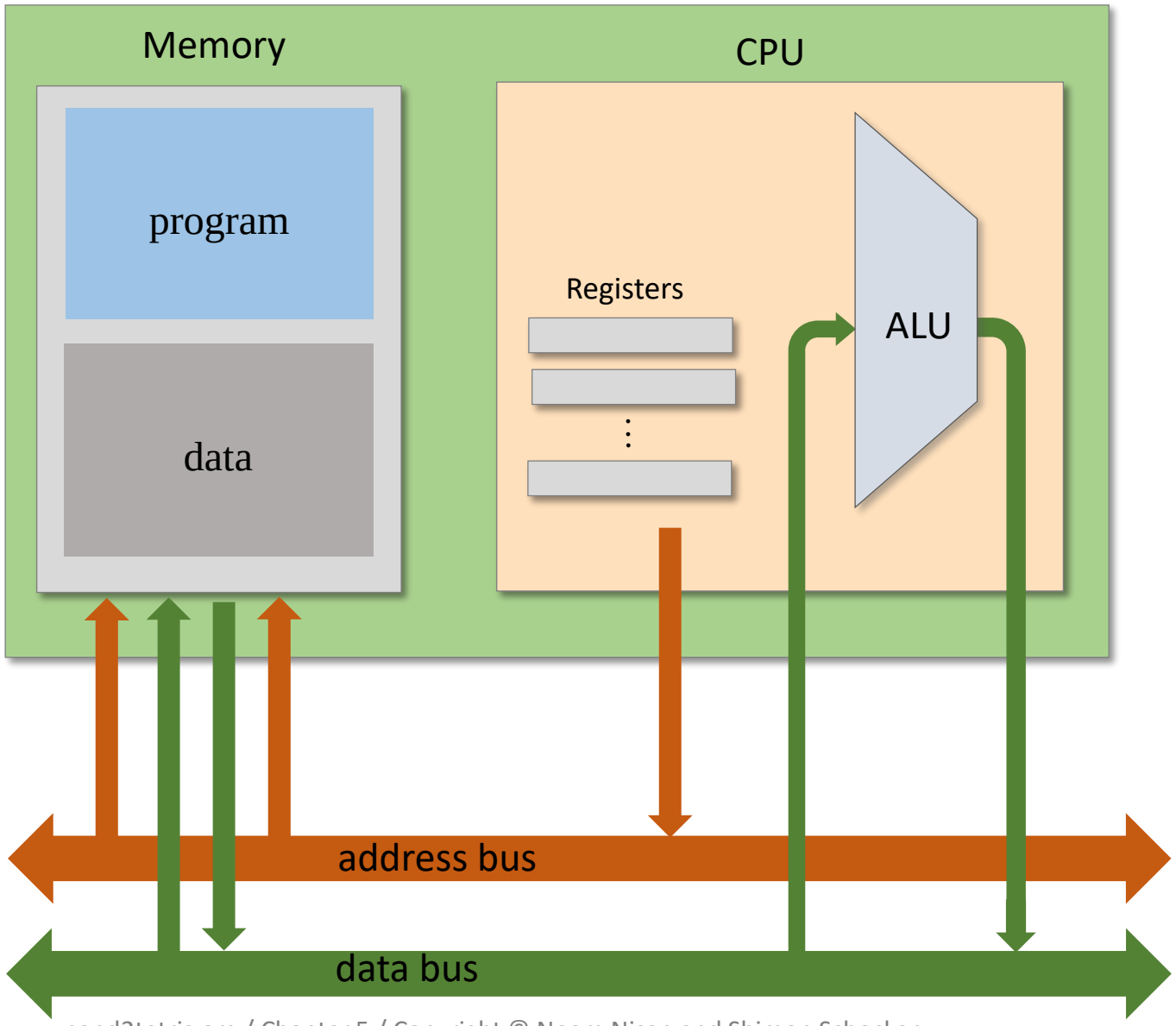


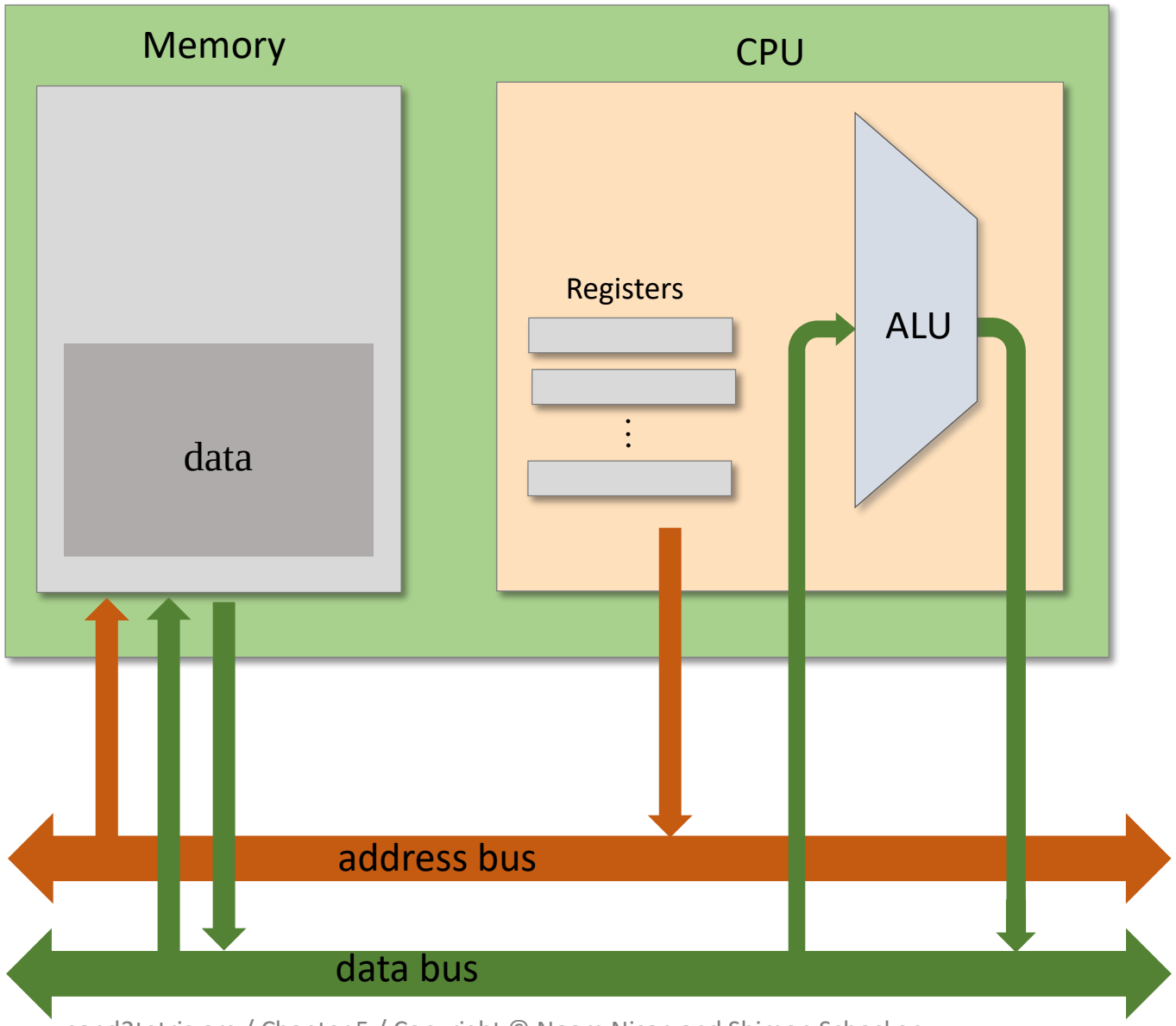
Computer architecture



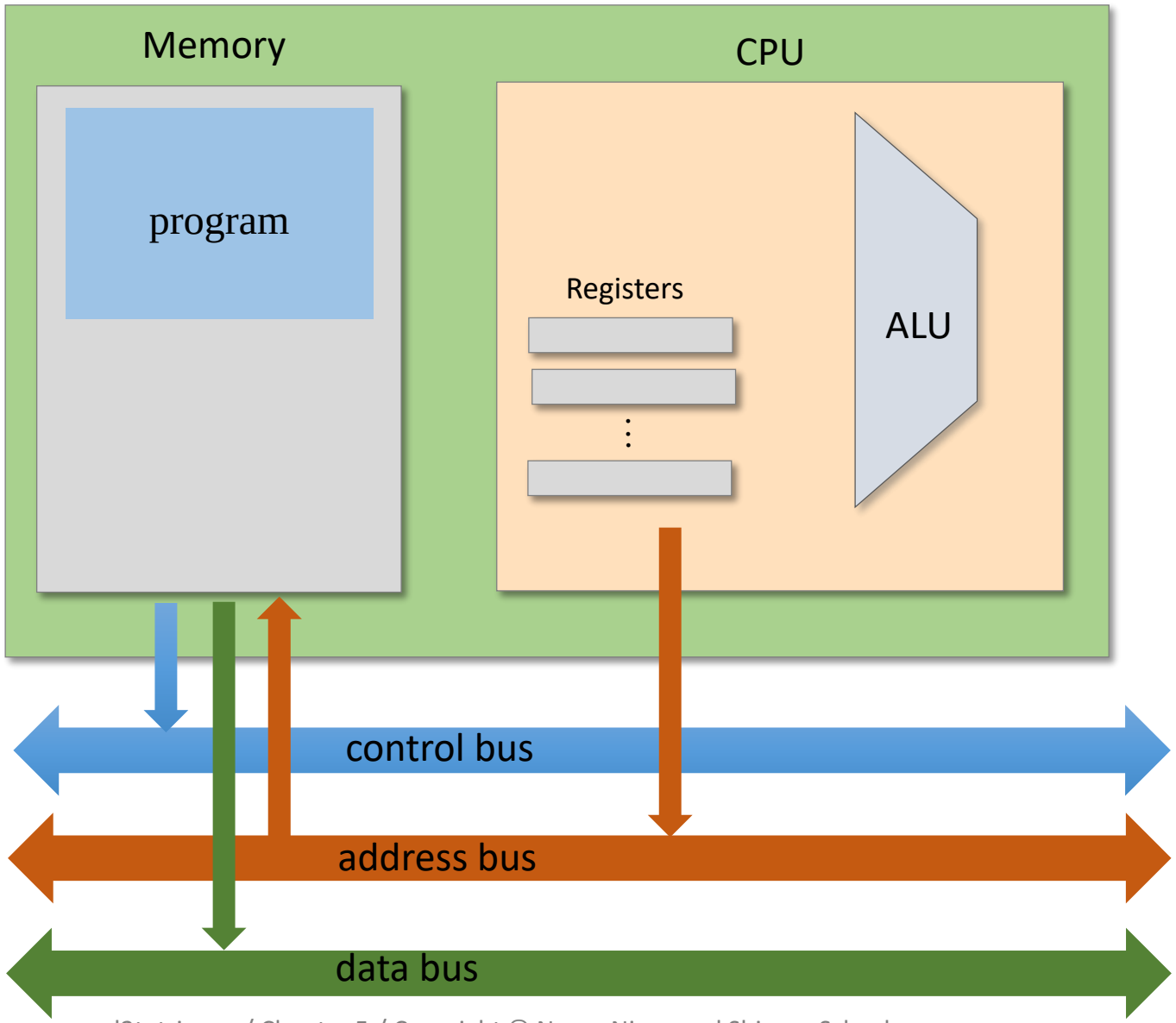
Computer architecture



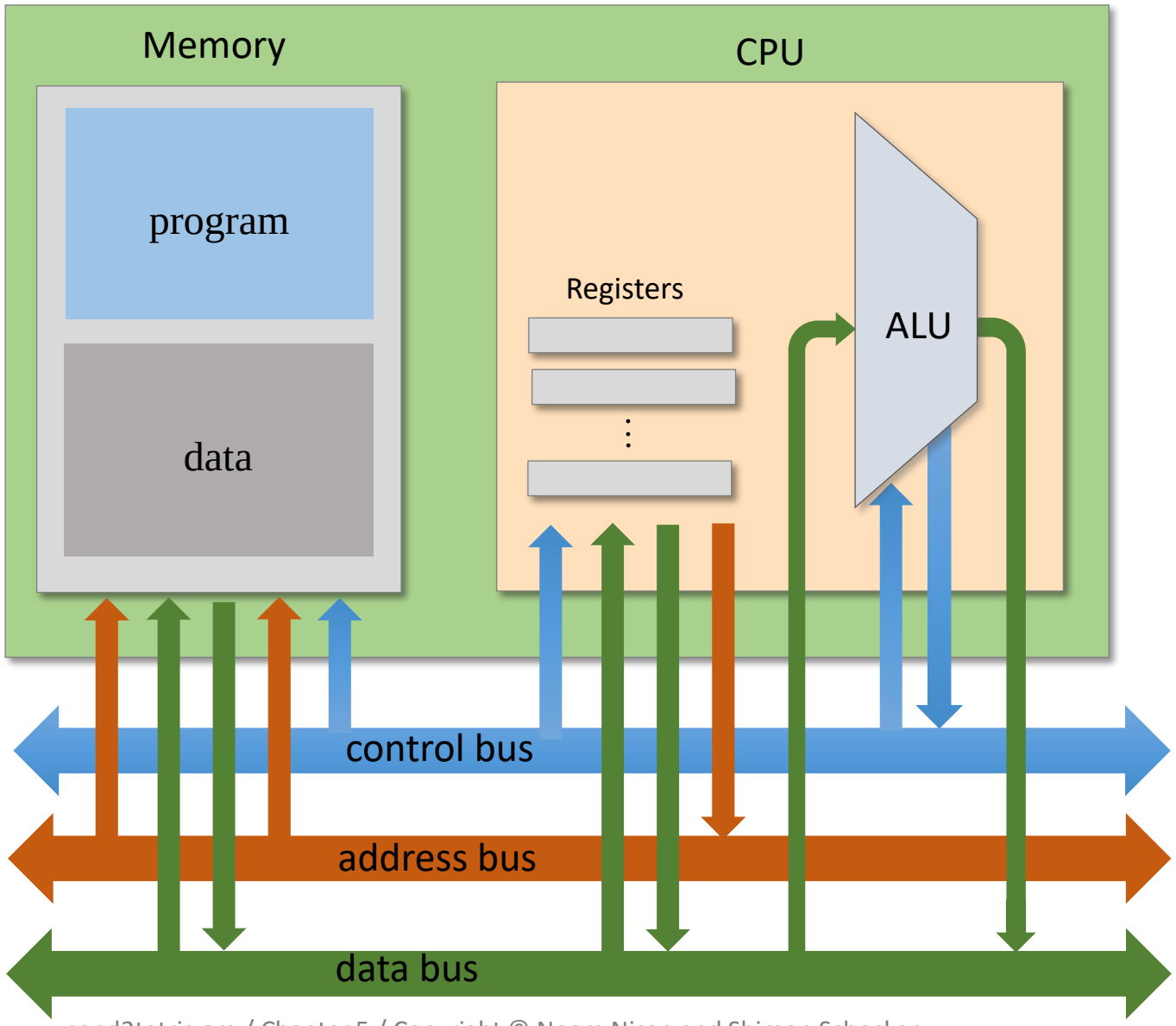
Computer architecture



Computer architecture



Computer architecture



Computer Architecture: lecture plan

Von Neumann Architecture

Fetch-Execute Cycle

- The Hack CPU
- The Hack Computer
- Project 5 Overview

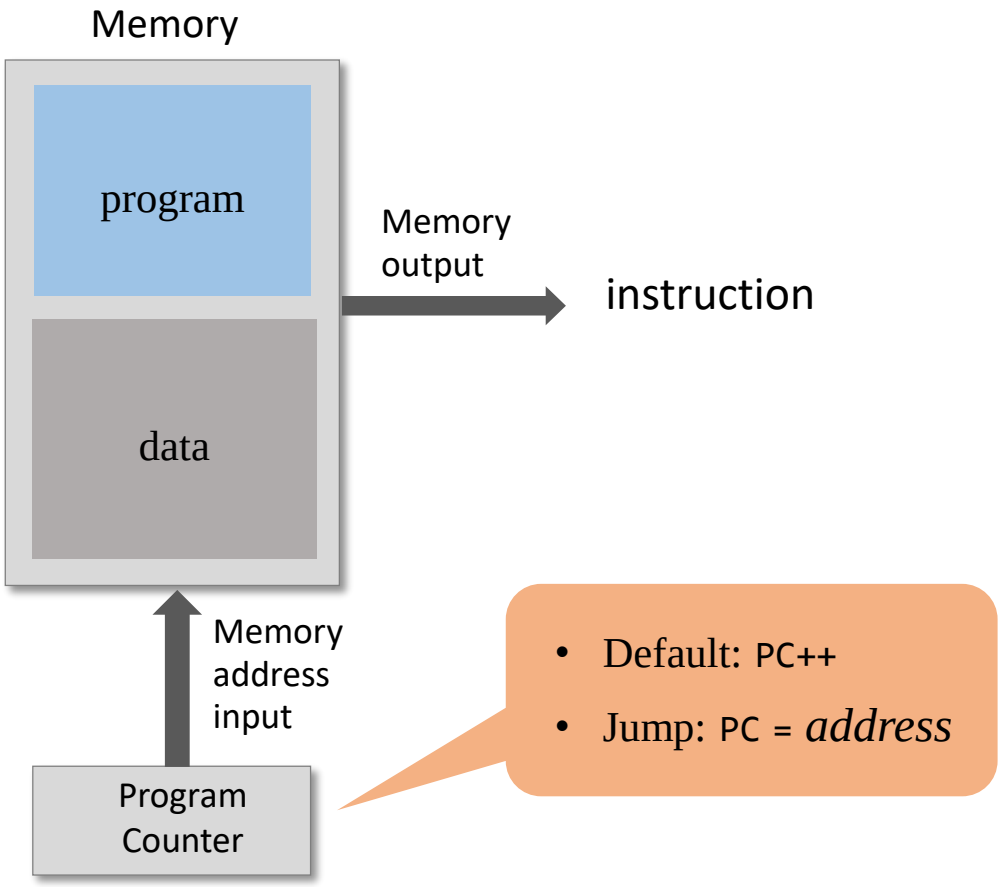
Basic CPU loop

Repeat:

- ***Fetch*** an instruction from the program memory
- ***Execute*** the instruction.

Fetching

- Put the location of the next instruction in the Memory *address* input
- Get the instruction code by reading the contents at that Memory location



Executing

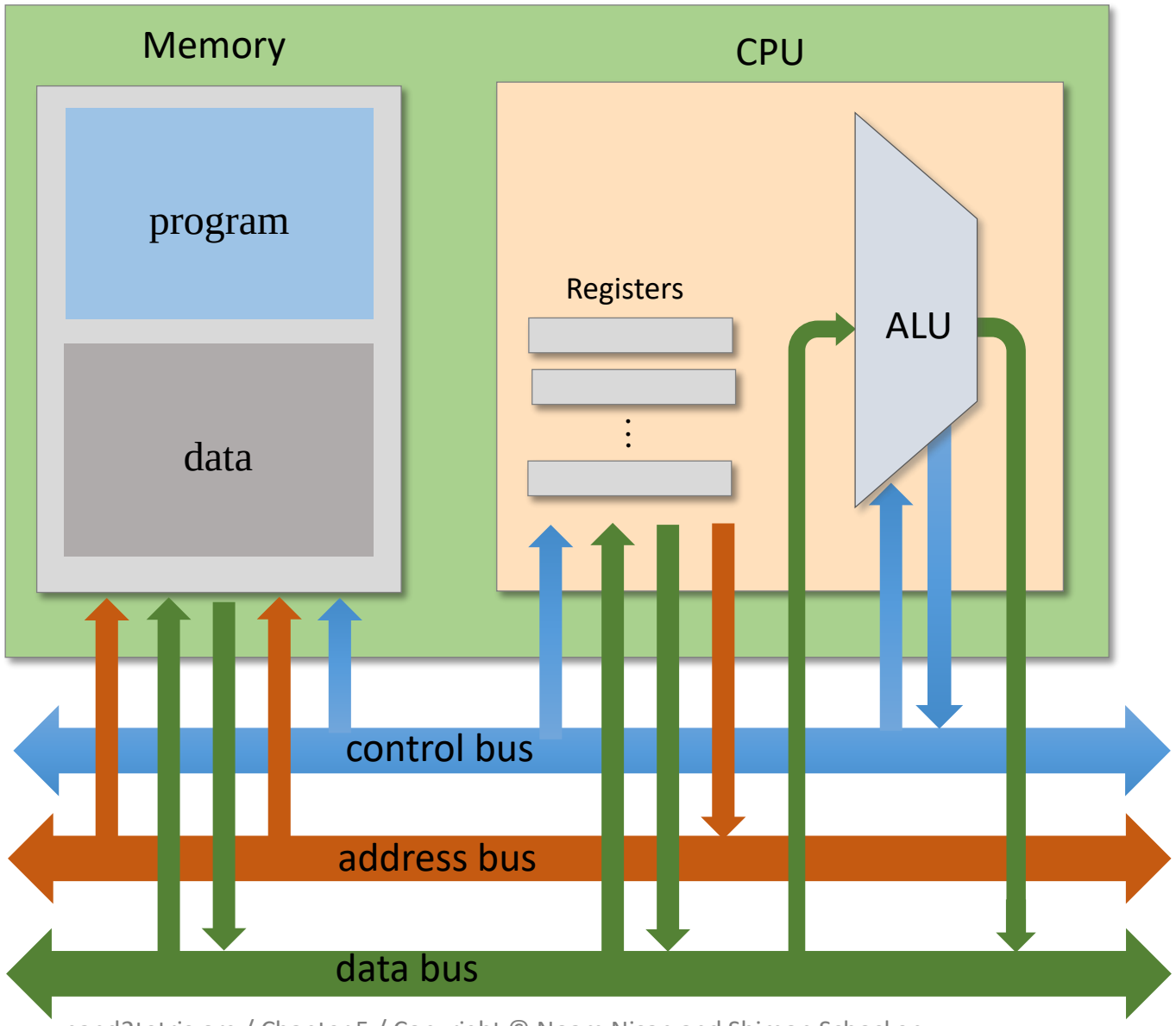
- The instruction code specifies "what to do"
  - Which arithmetic or logical instruction to execute
  - Which memory address to access (for read / write)
  - If / where to jump
  - …

different subsets of the instruction bits control different aspects of the operation

- Executing the instruction involves:
  - accessing registers

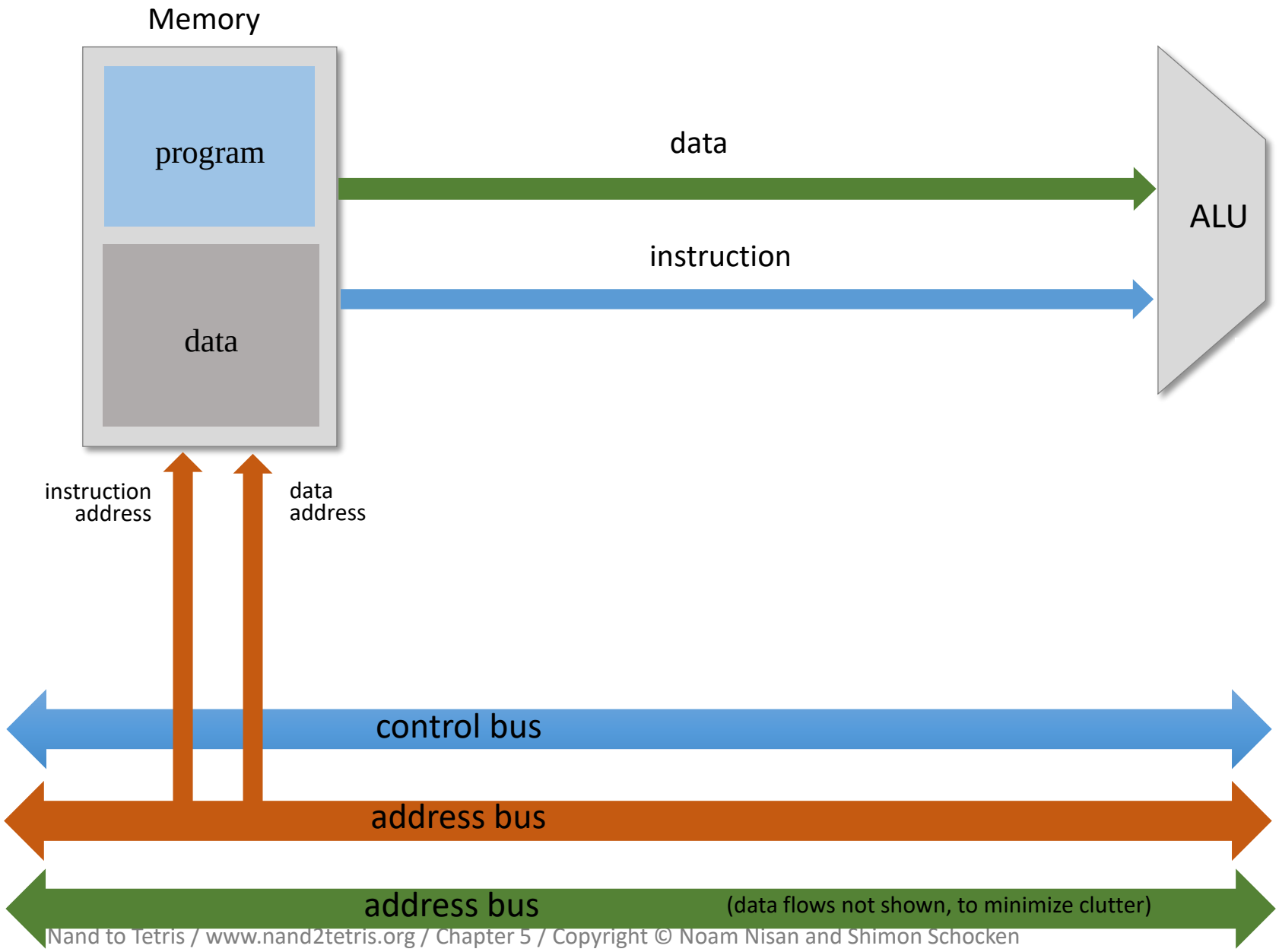
    and / or:
  - accessing the data memory.

Computer architecture

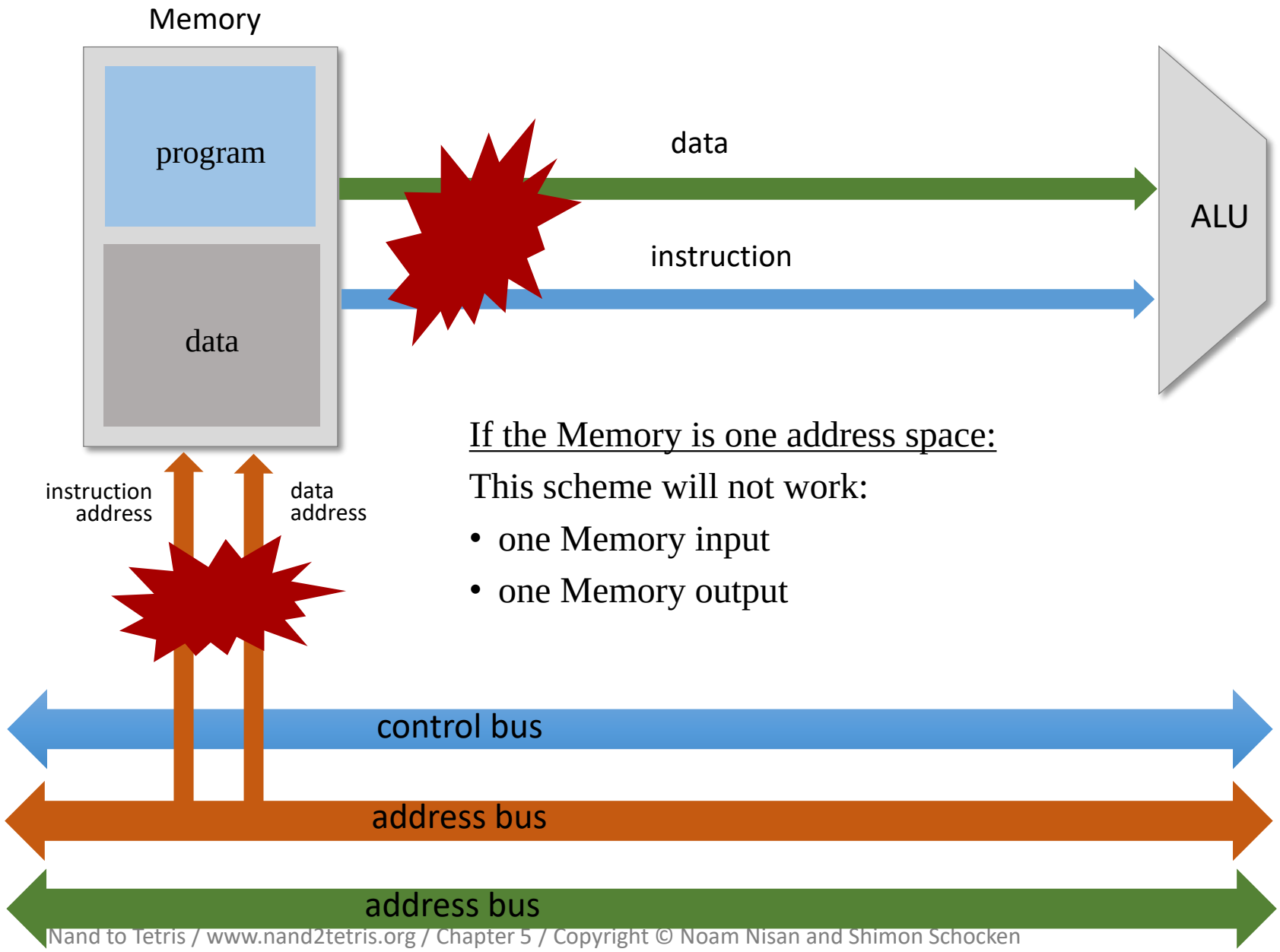


Fetch – Execute

Fetch – Execute



Fetch – Execute clash

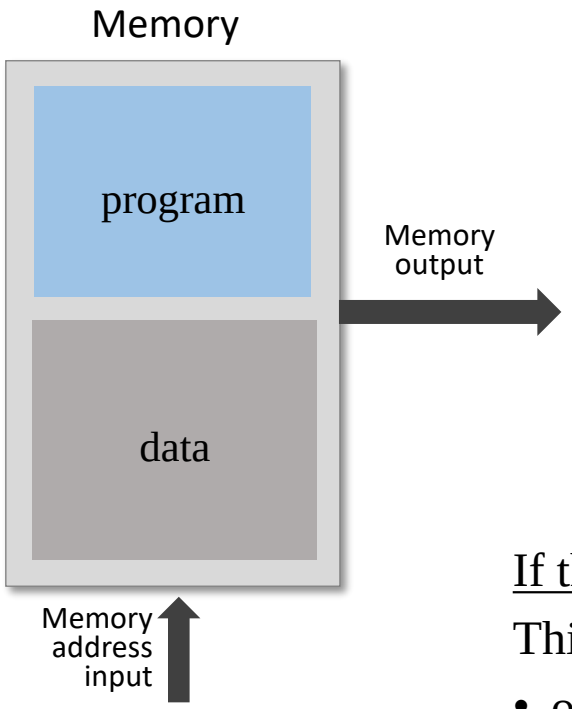


<u>If the Memory is one address space:</u>

This scheme will not work:

- one Memory input
- one Memory output

Fetch – Execute clash



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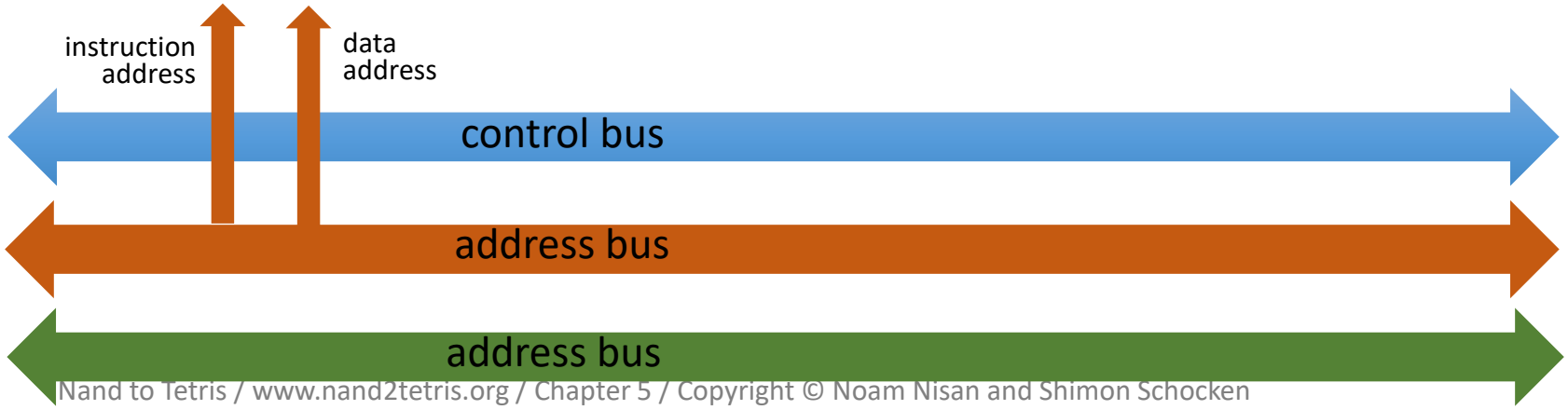
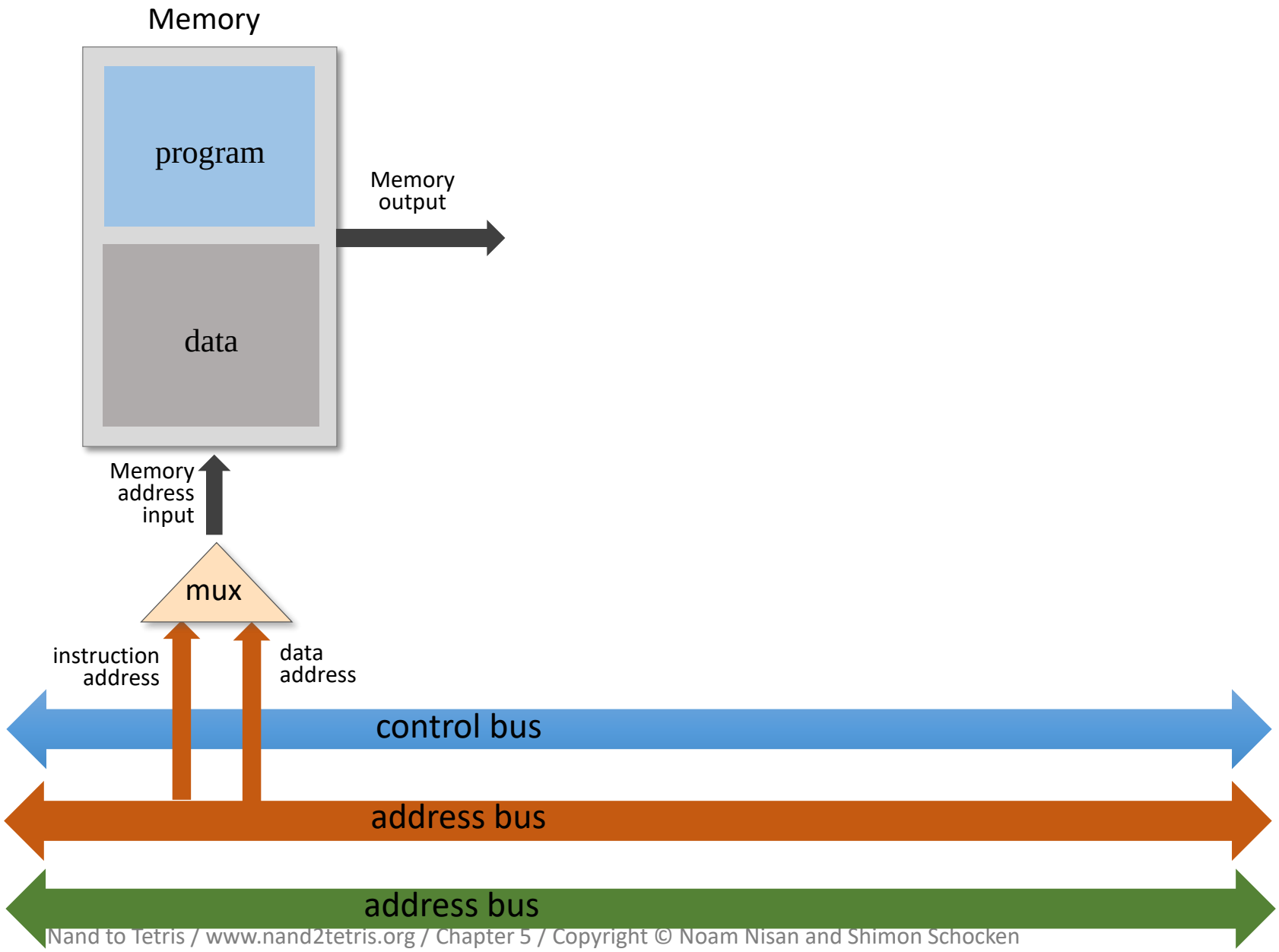
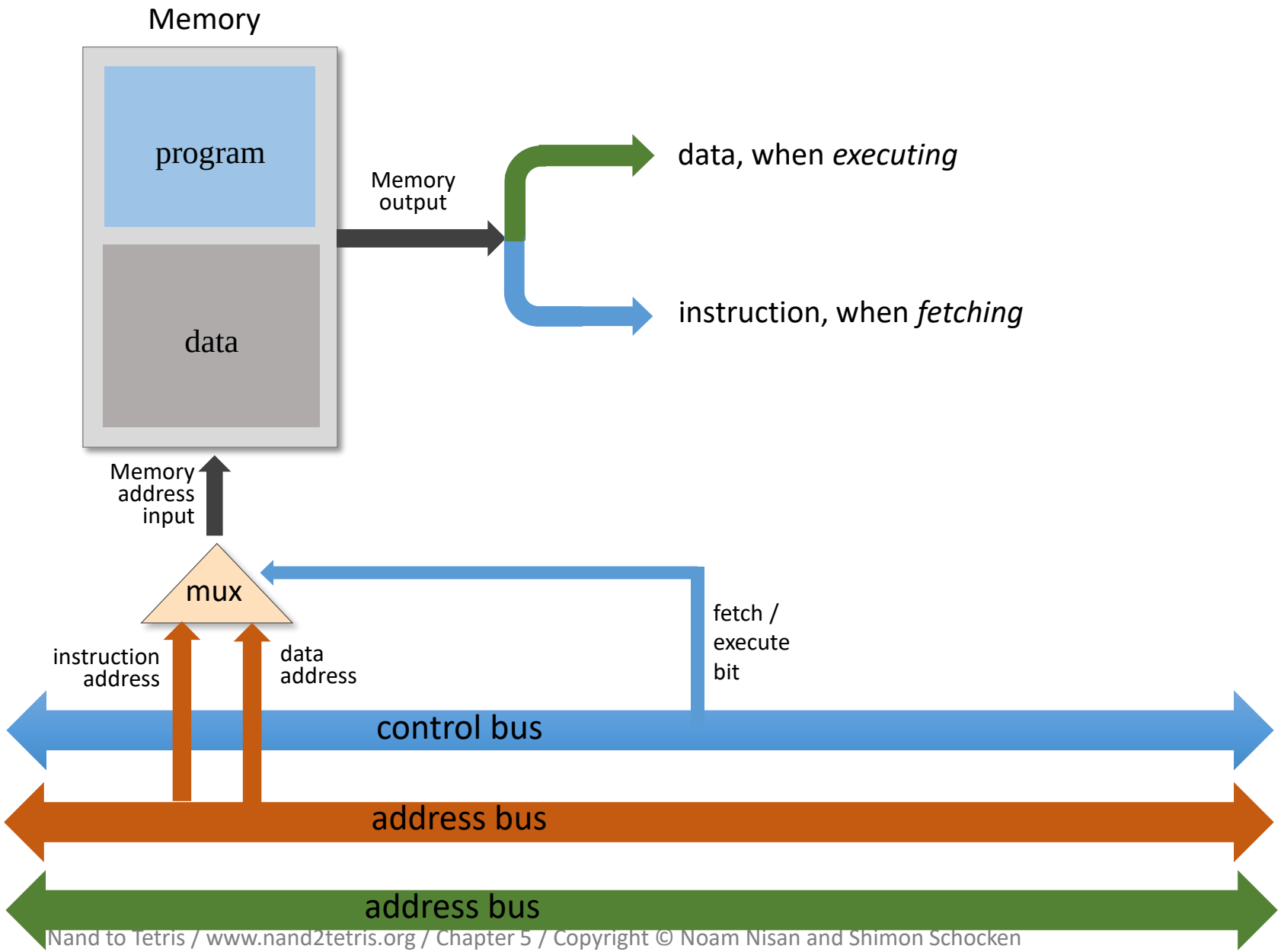


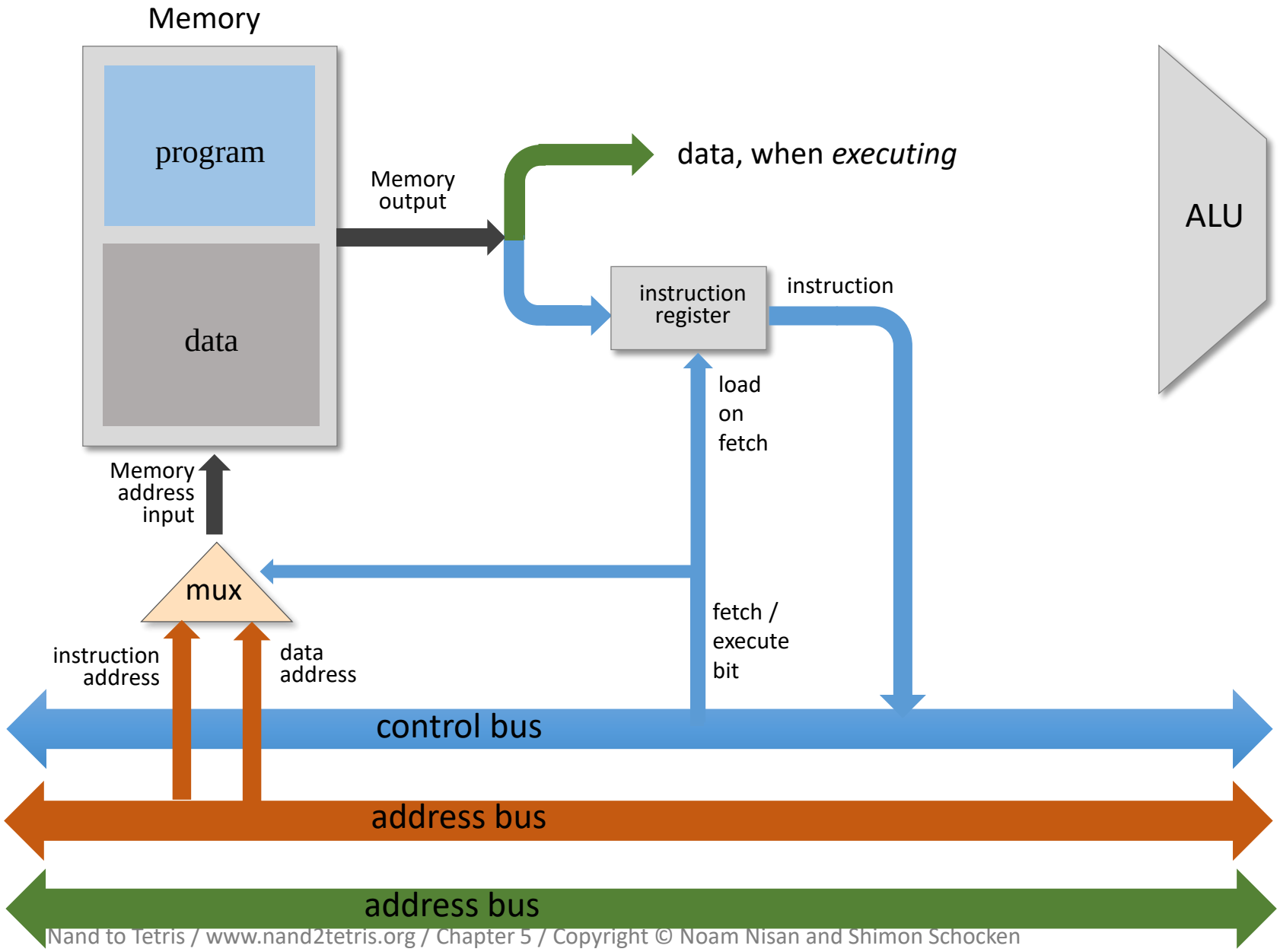
Solution: multiplex



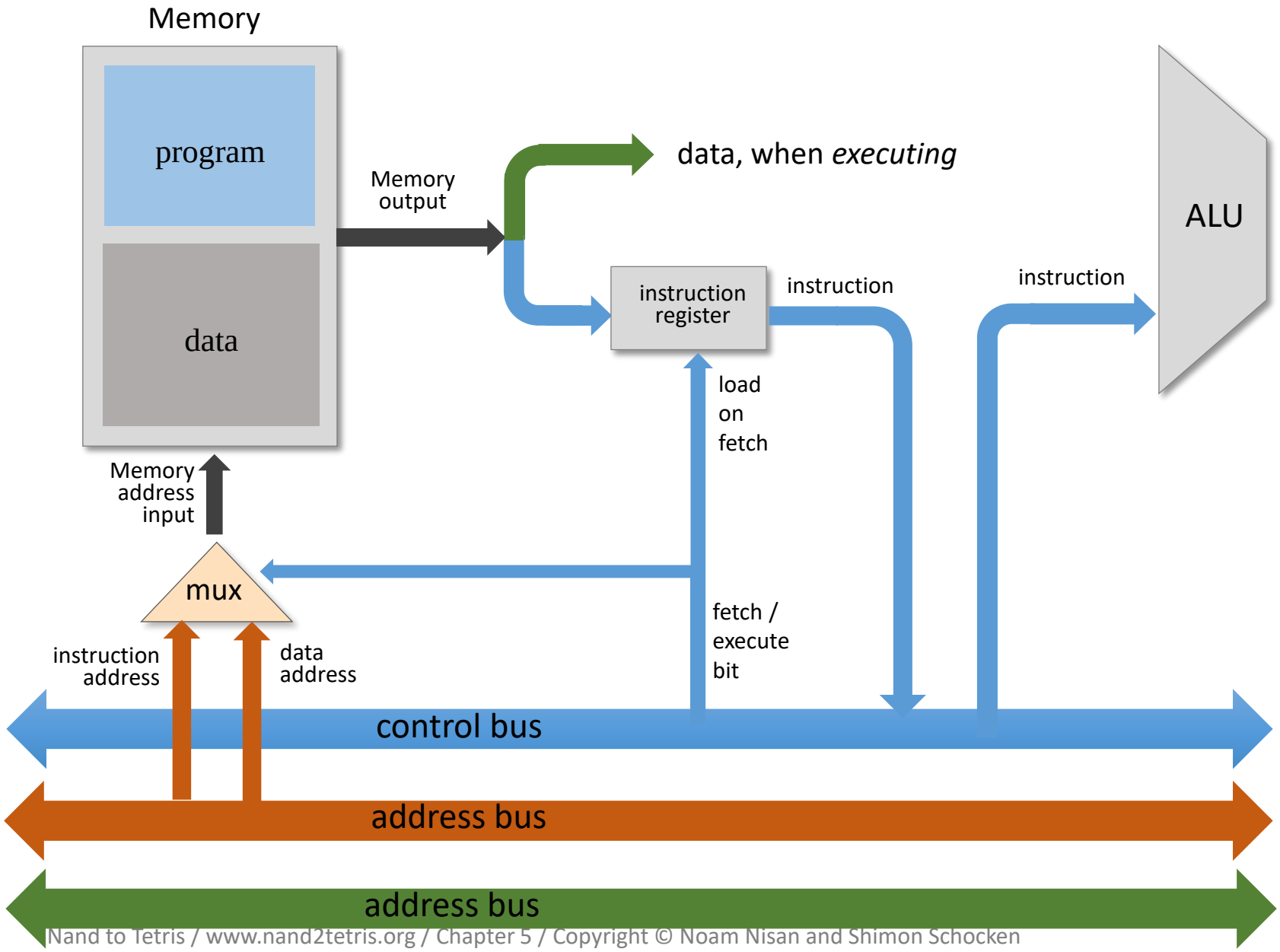
Solution: multiplex



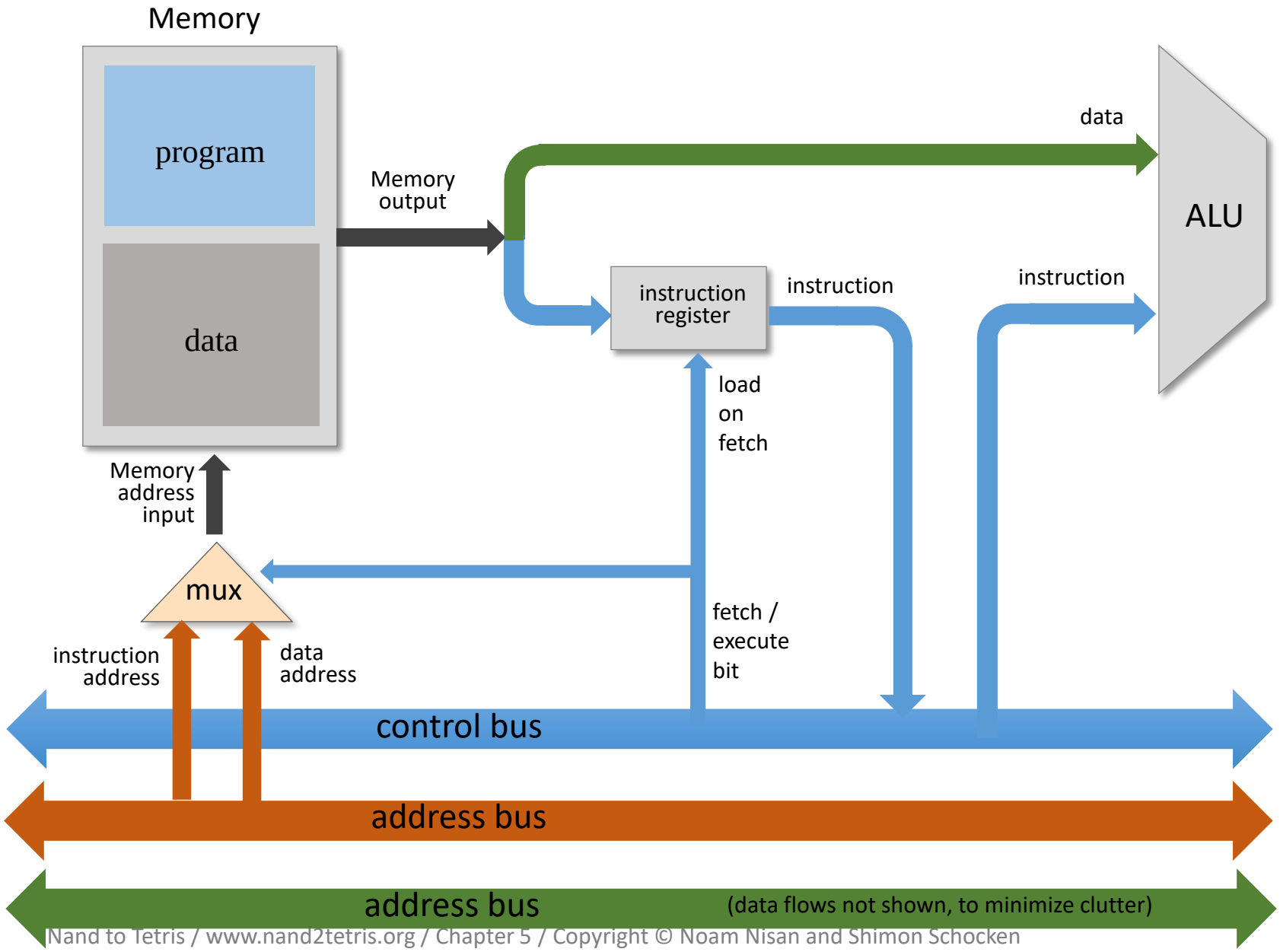
Solution: multiplex, using an instruction register



Solution: multiplex, using an instruction register



Solution: multiplex, using an instruction register



Simpler solution: separate memory units

Variant of von Neumann Architecture (used by the Hack computer):

Two physically separate memory units:

- Instruction memory
- Data memory

} Each can be addressed and manipulated seperately, and simultaneously

Simpler solution: separate memory units

Variant of von Neumann Architecture (used by the Hack computer):

Two physically separate memory units:

- Instruction memory
- Data memory

} Each can be addressed and manipulated seperately, and simultaneously

- Advantage:
  - Complication avoided
- Disadvantage:
  - Two memory chips instead of one
  - The size of the two chips is fixed.

Sometmes called "Harvard Architecture"

Computer Architecture: lecture plan

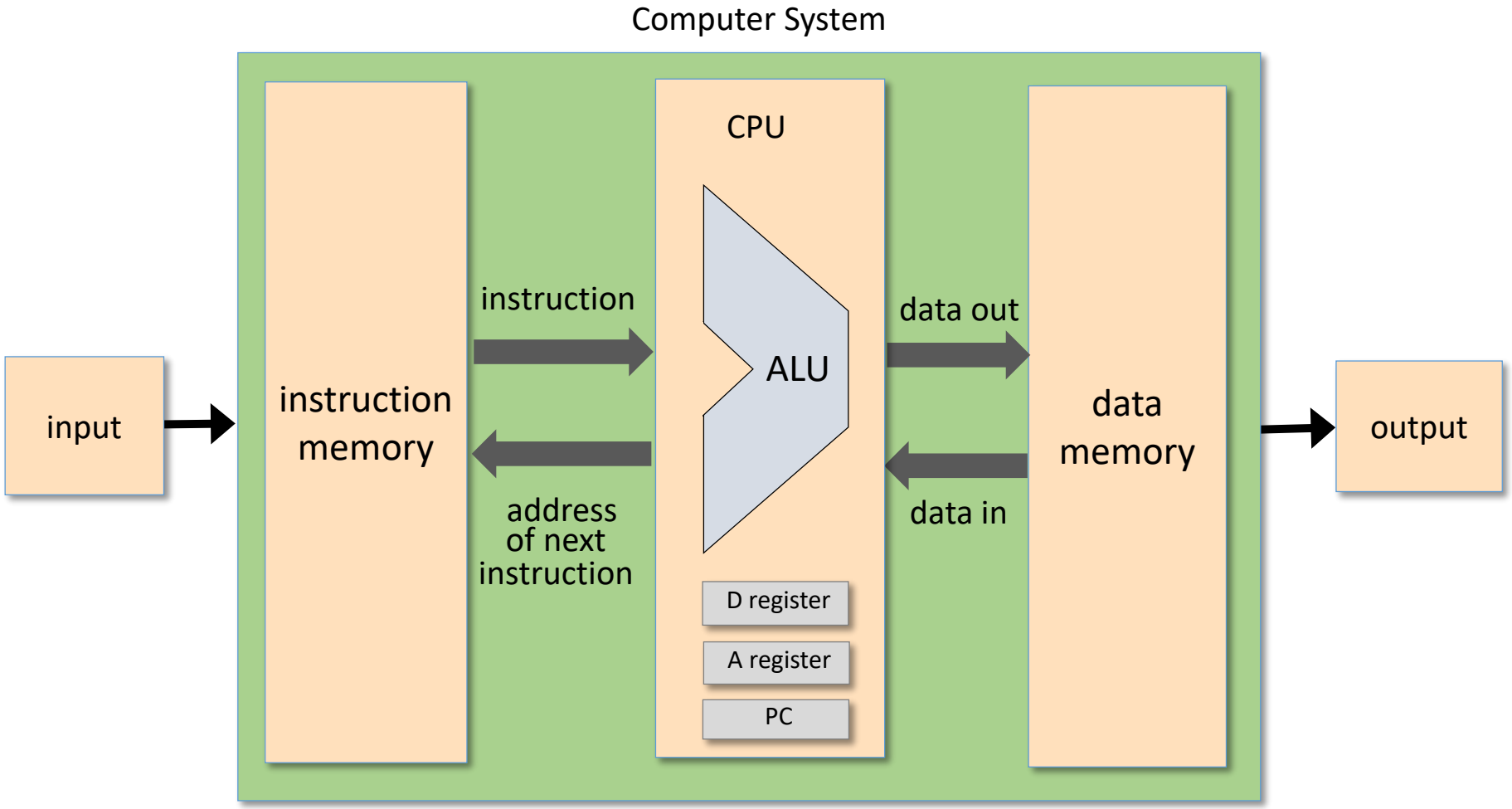

Von Neumann Architecture


Fetch-Execute Cycle

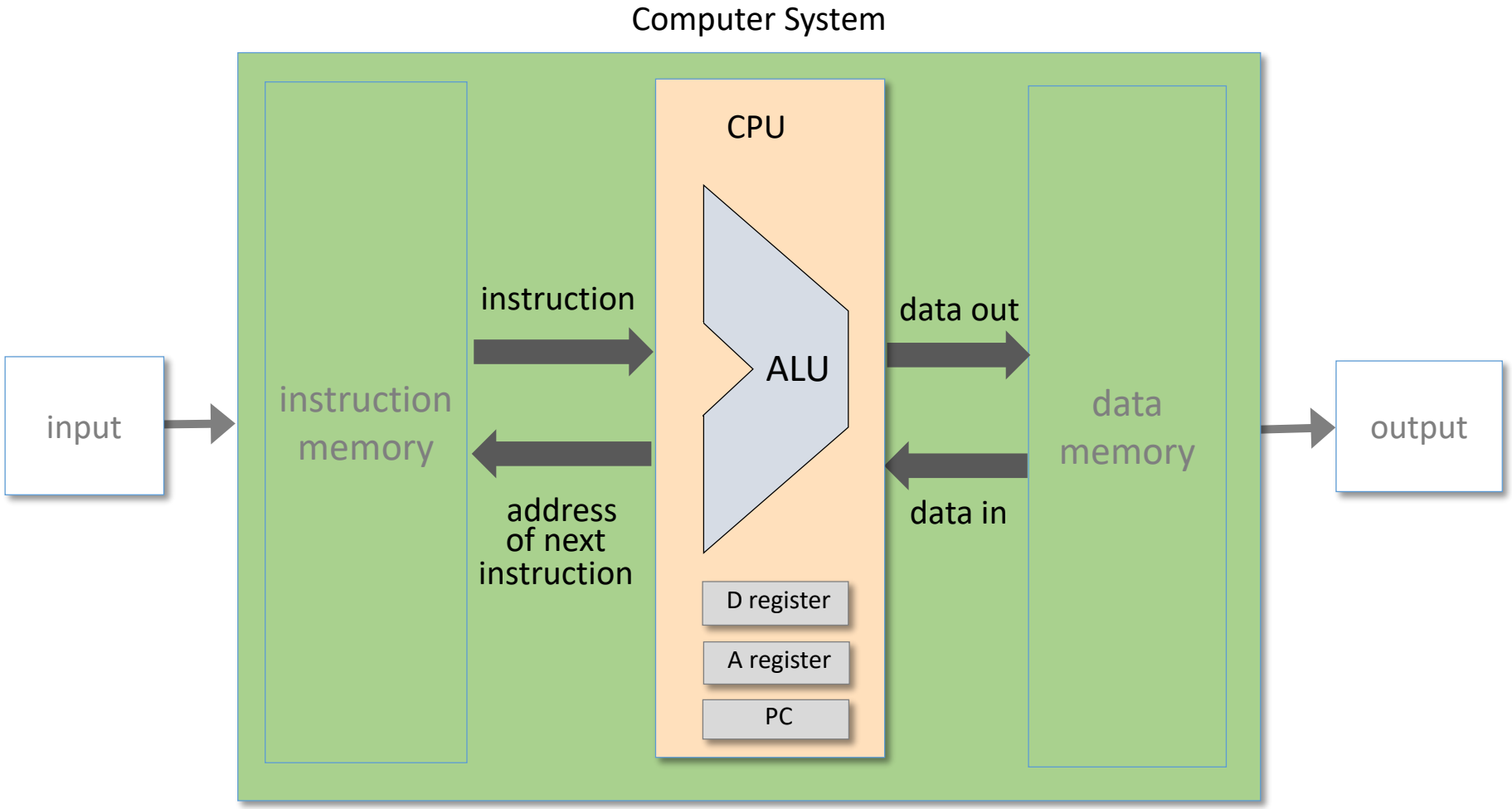

The Hack CPU

- The Hack Computer
- Project 5 Overview

Hack computer



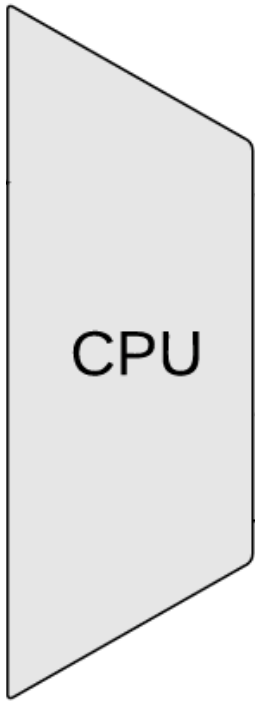
Hack CPU



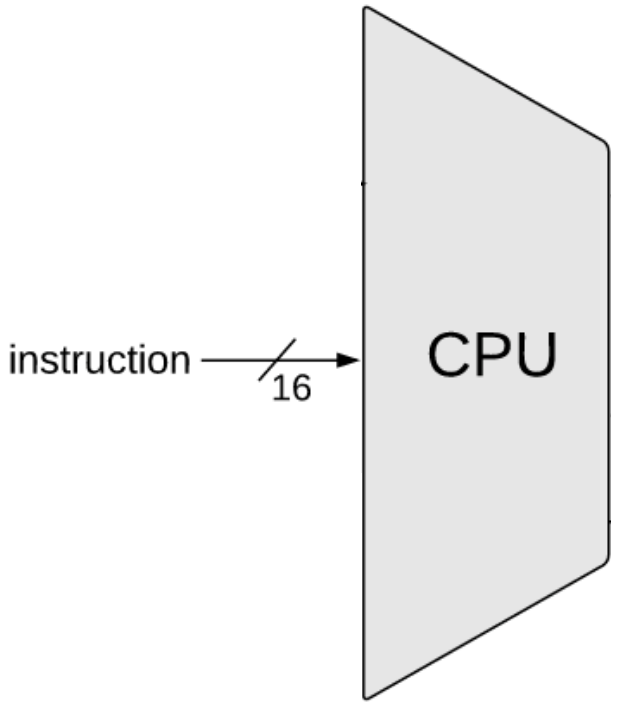
Hack CPU: A 16-bit processor, designed to:

- Execute the current instruction: dataOut = instruction(dataIn)
- Figure out which instruction to execute next.

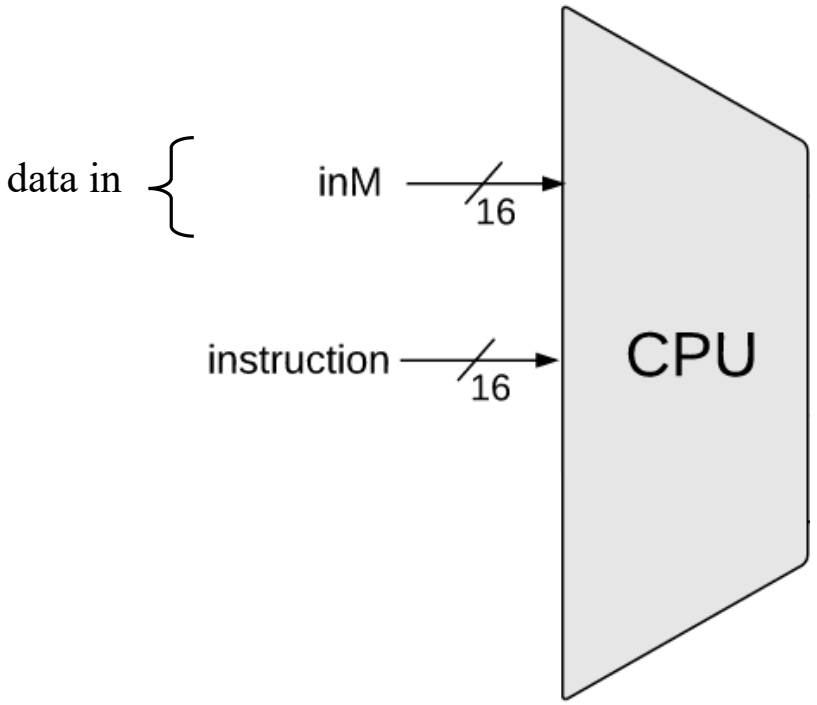
Hack CPU Interface



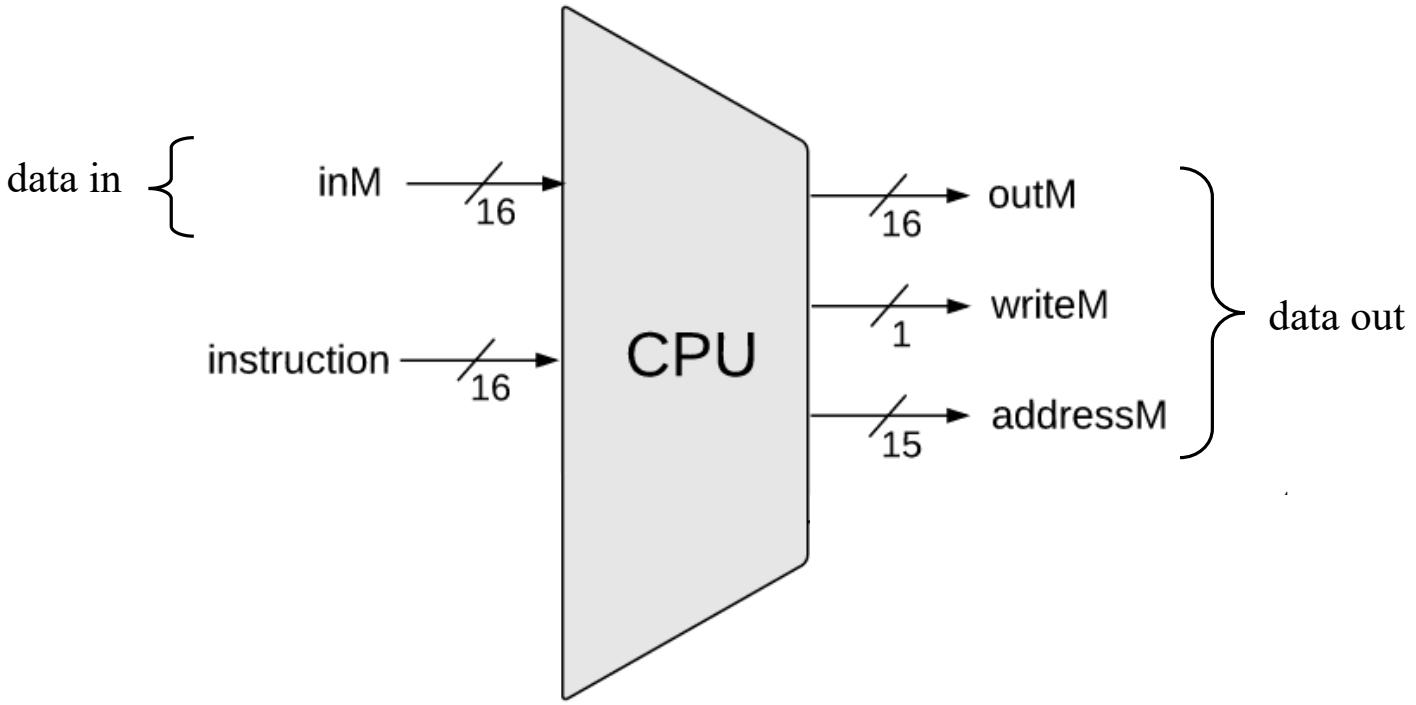
Hack CPU Interface



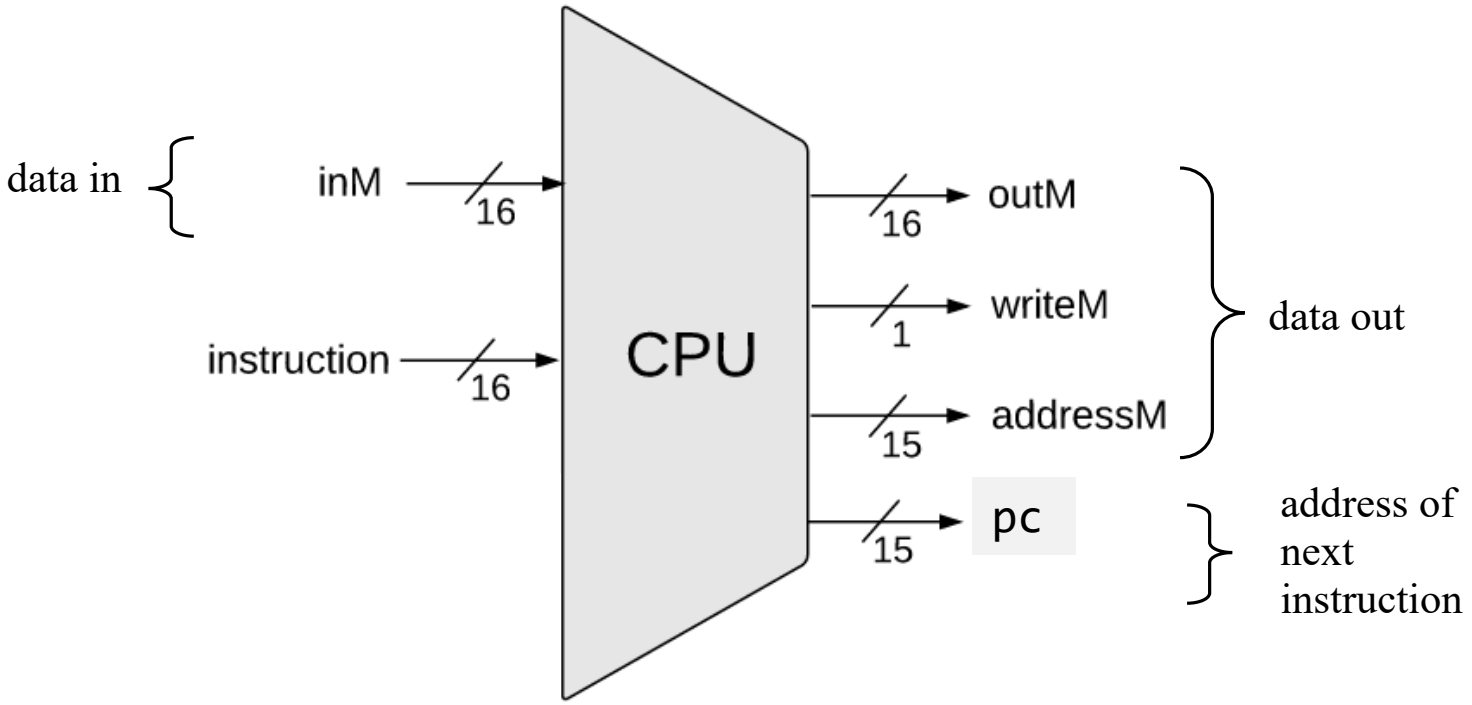
Hack CPU Interface



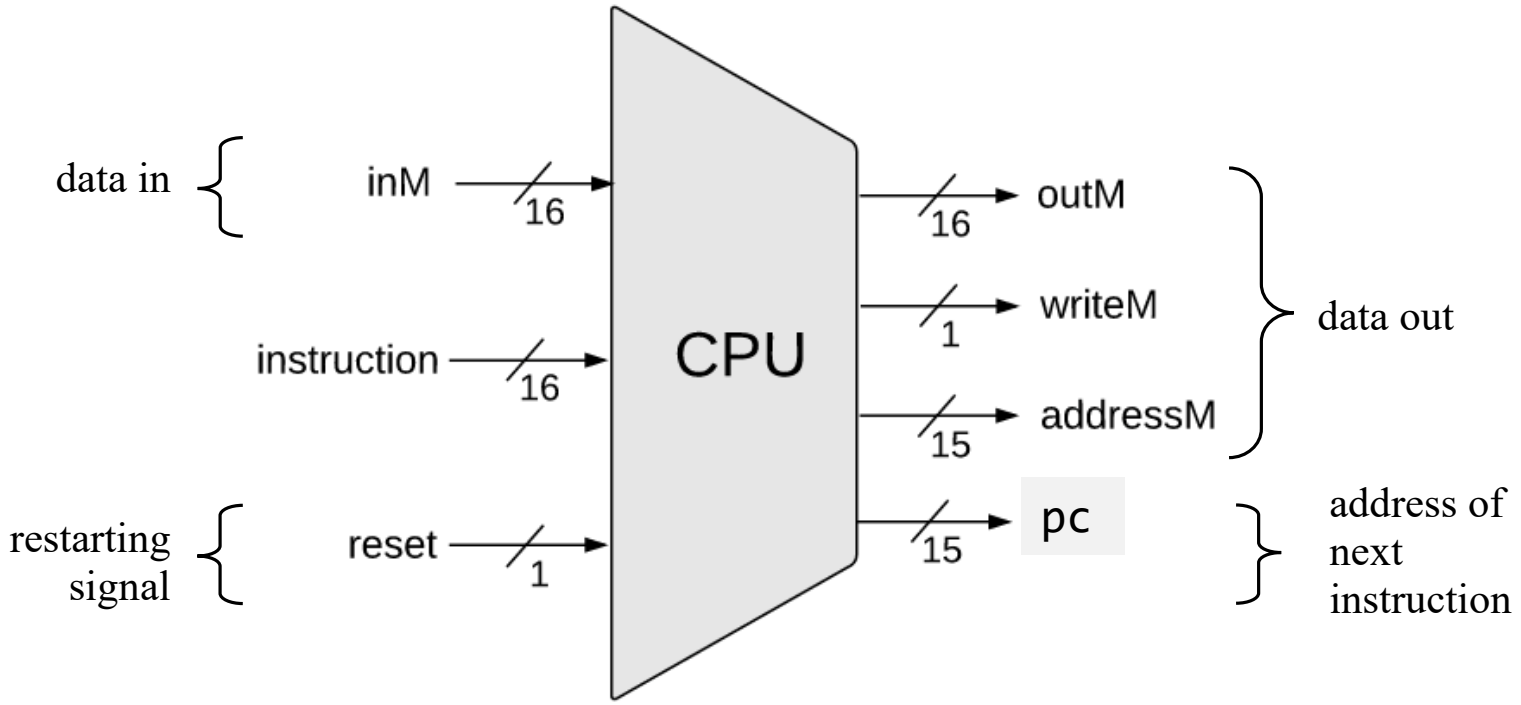
Hack CPU Interface



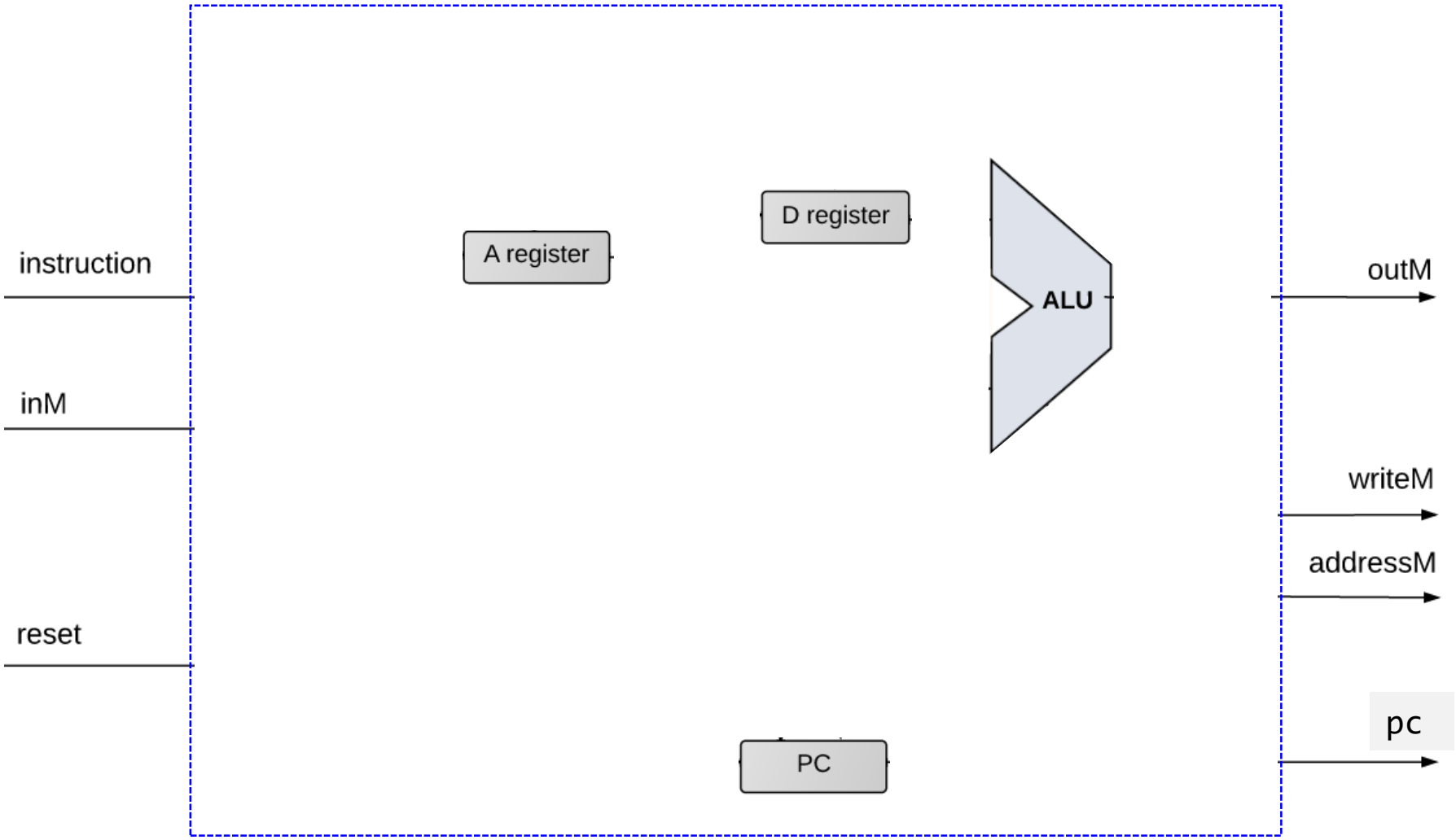
Hack CPU Interface



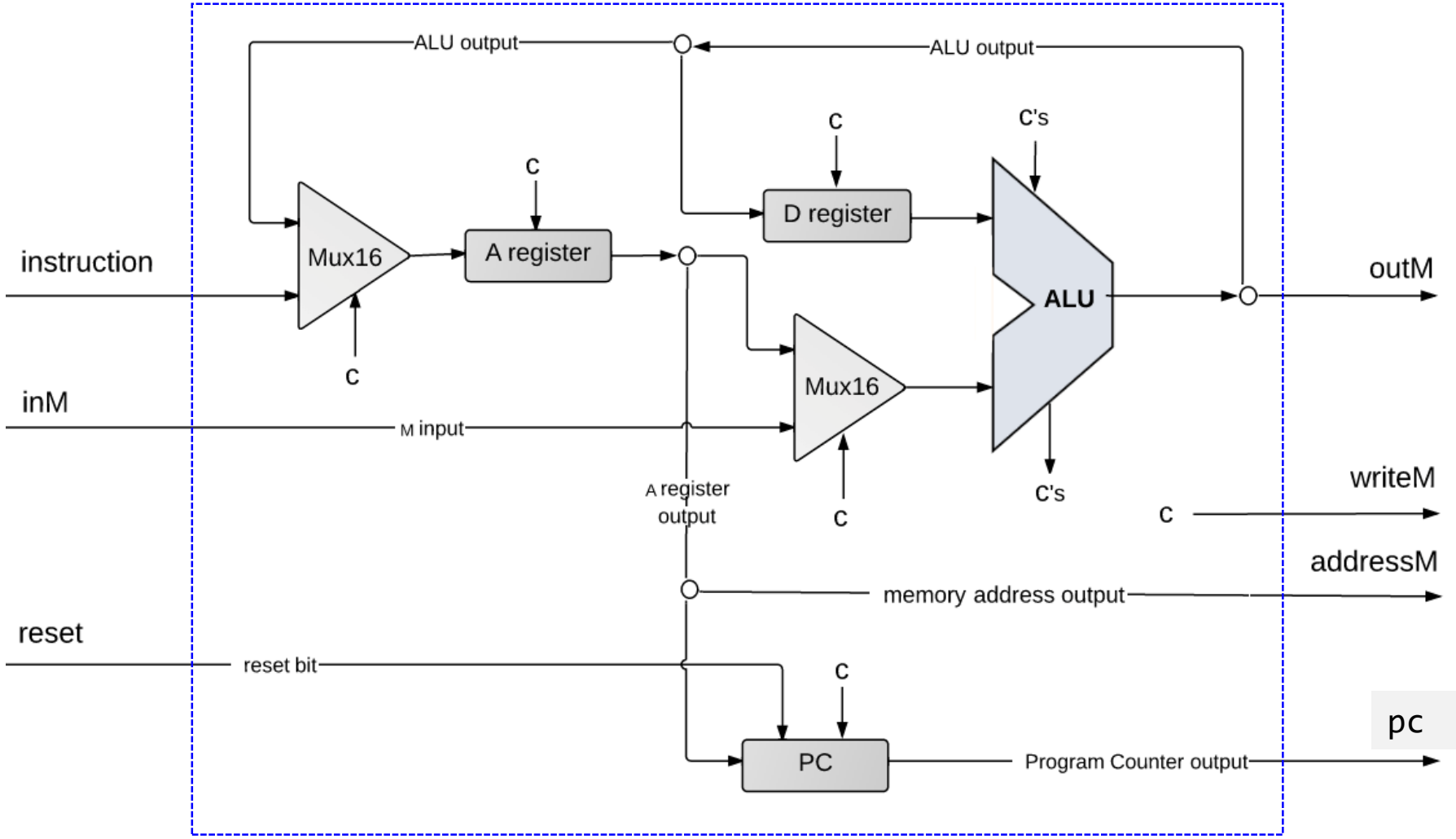
Hack CPU Interface



Hack CPU Implementation

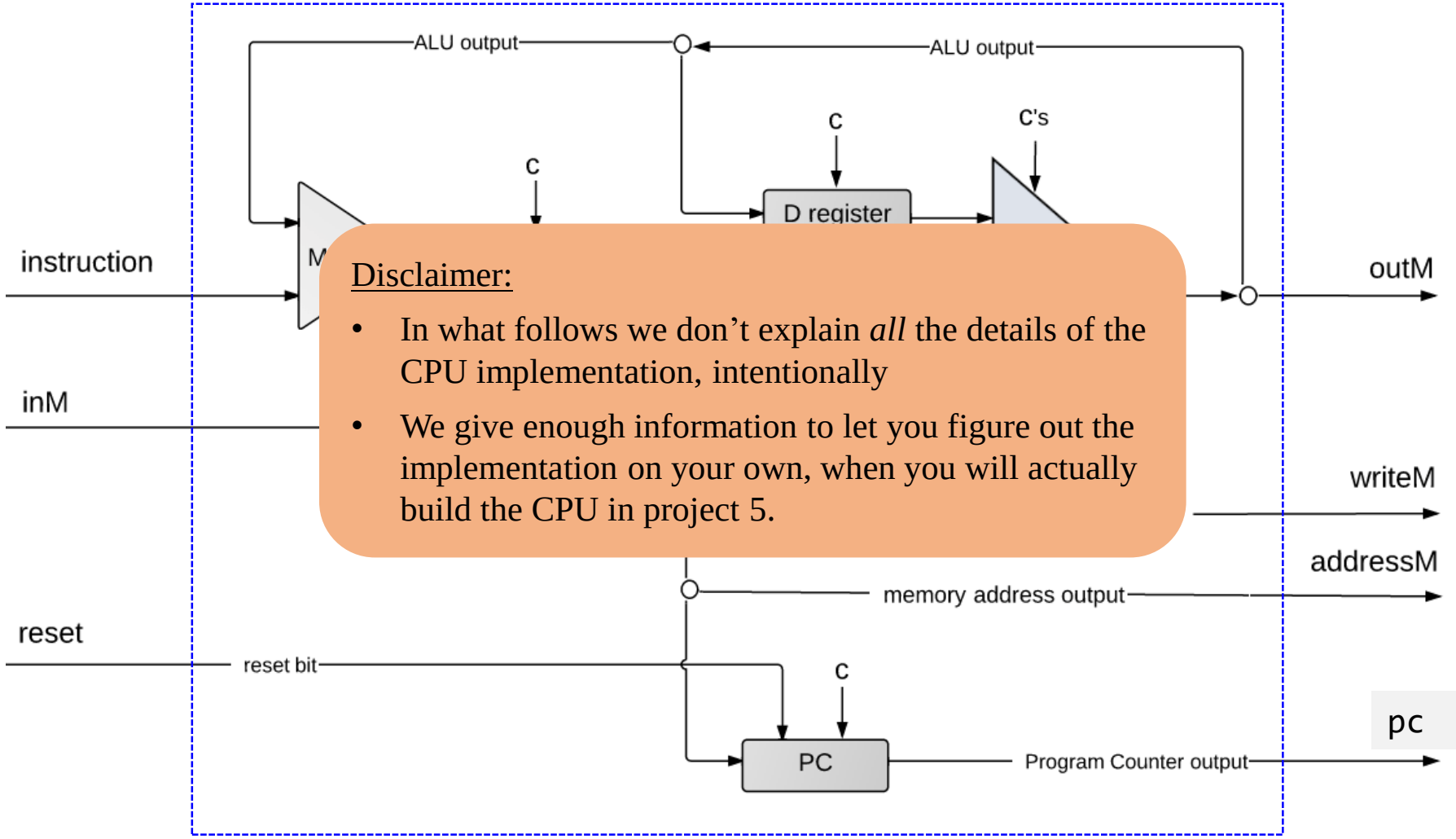


Hack CPU Implementation



(each "C" symbol represents a control bit)

Hack CPU Implementation

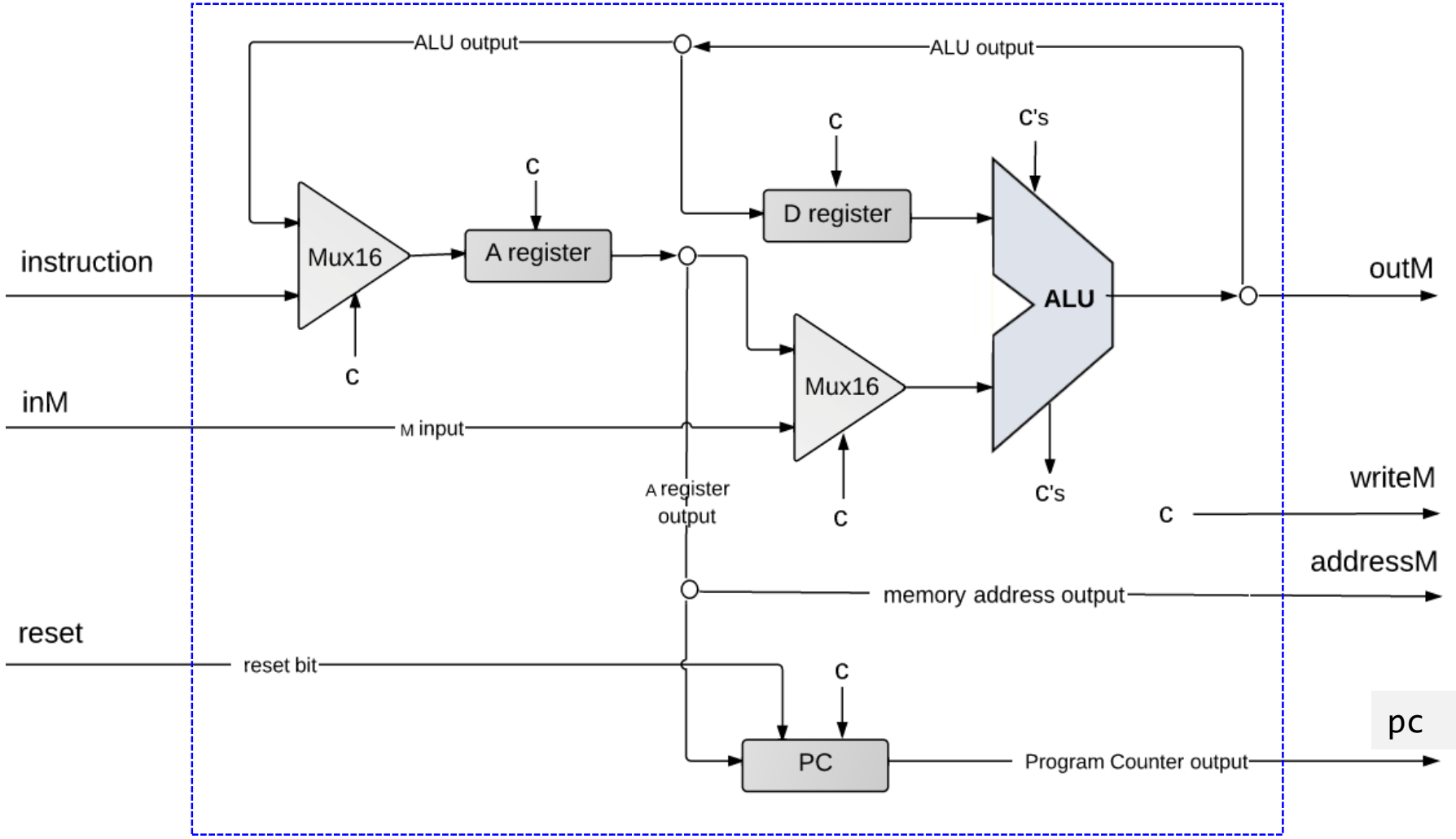


Disclaimer:

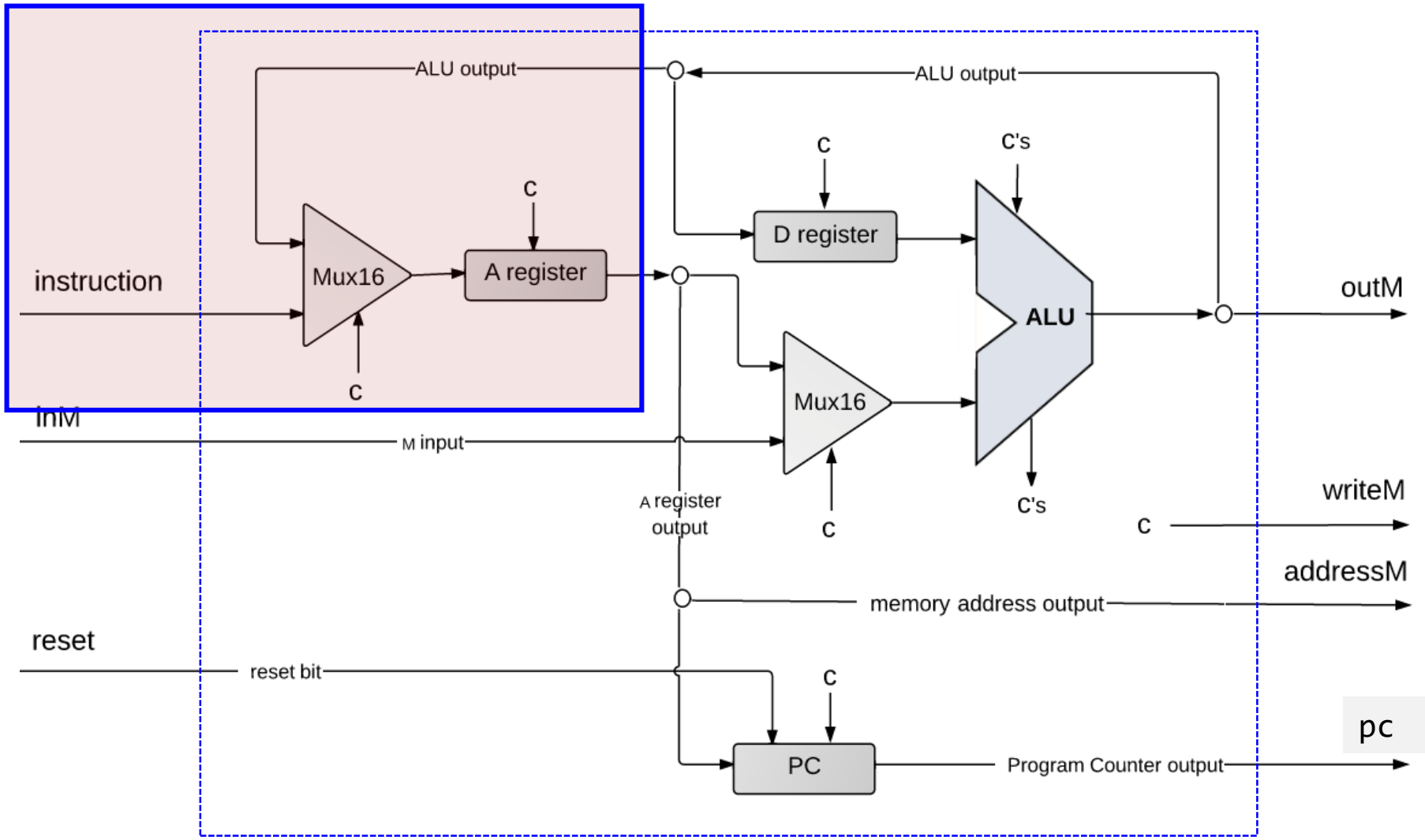
- In what follows we don't explain *all* the details of the CPU implementation, intentionally
- We give enough information to let you figure out the implementation on your own, when you will actually build the CPU in project 5.

(each "c" symbol represents a control bit)

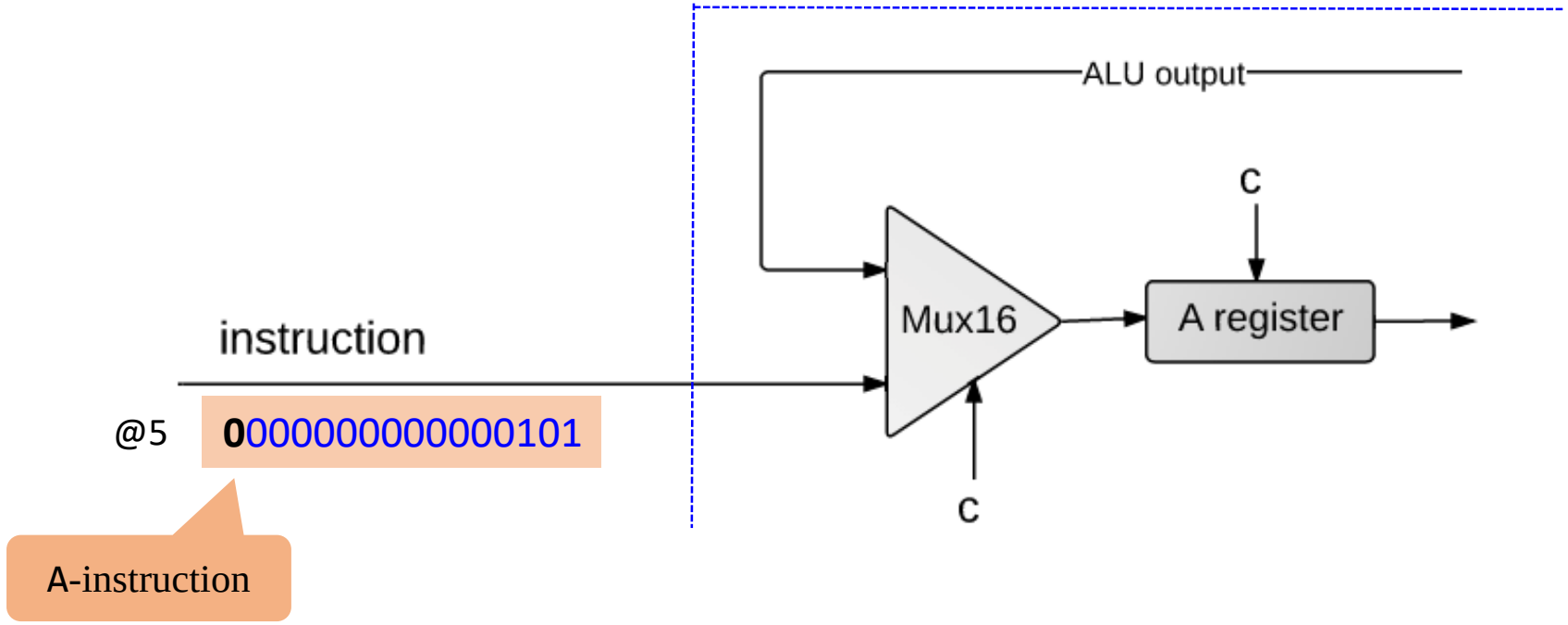
CPU operation



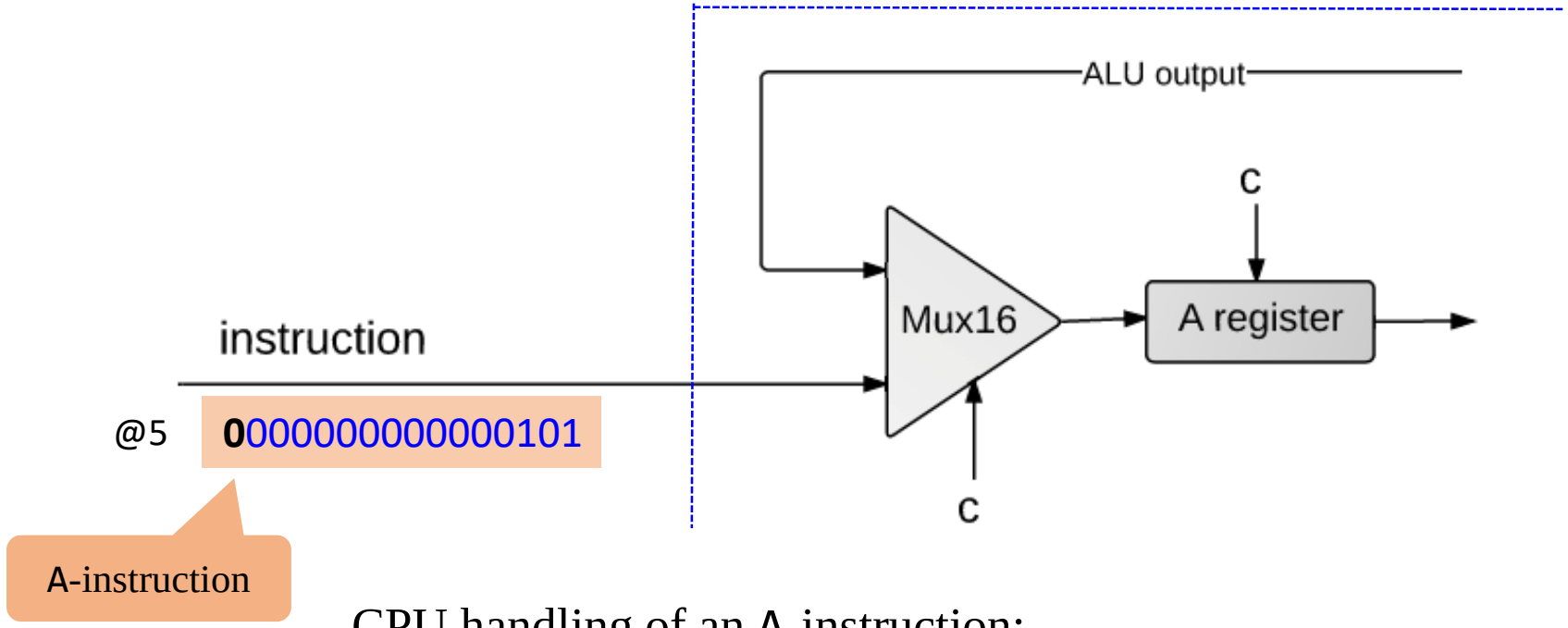
CPU operation: instruction handling



CPU operation: instruction handling

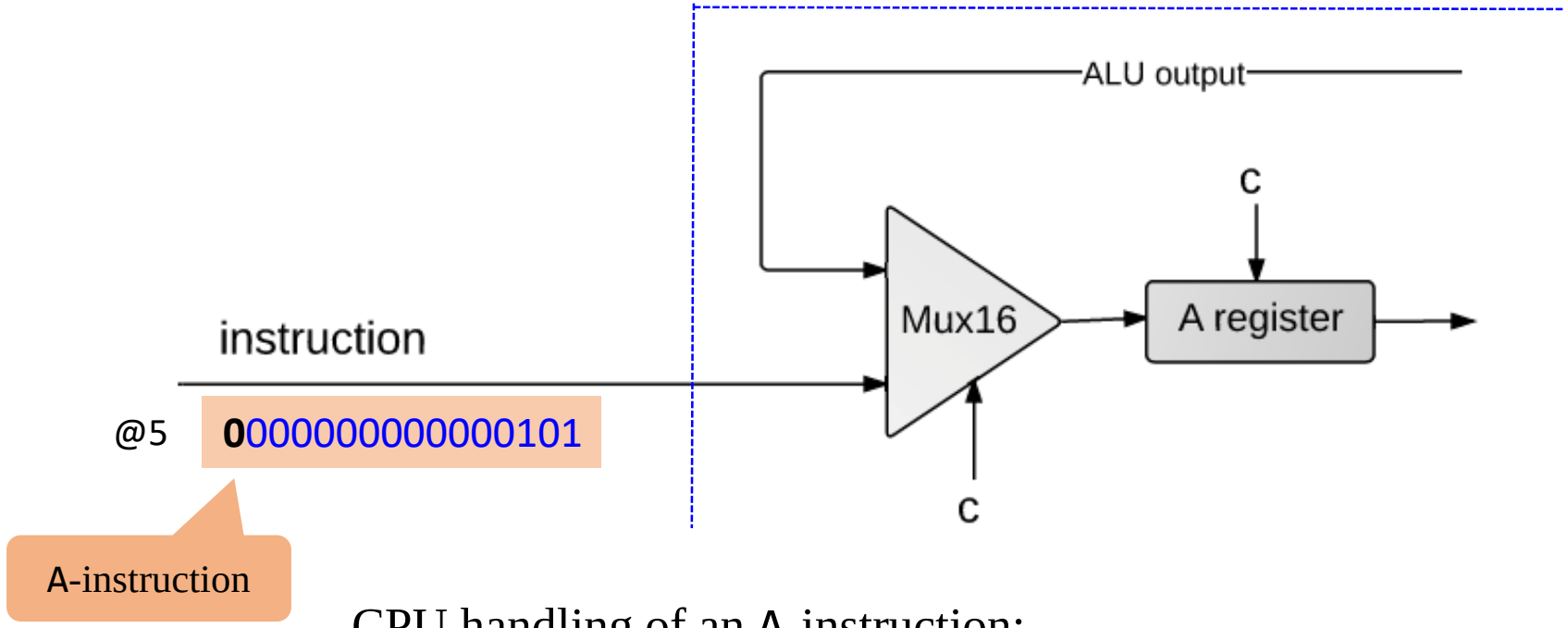


CPU operation: handling A-instructions



CPU handling of an A-instruction:

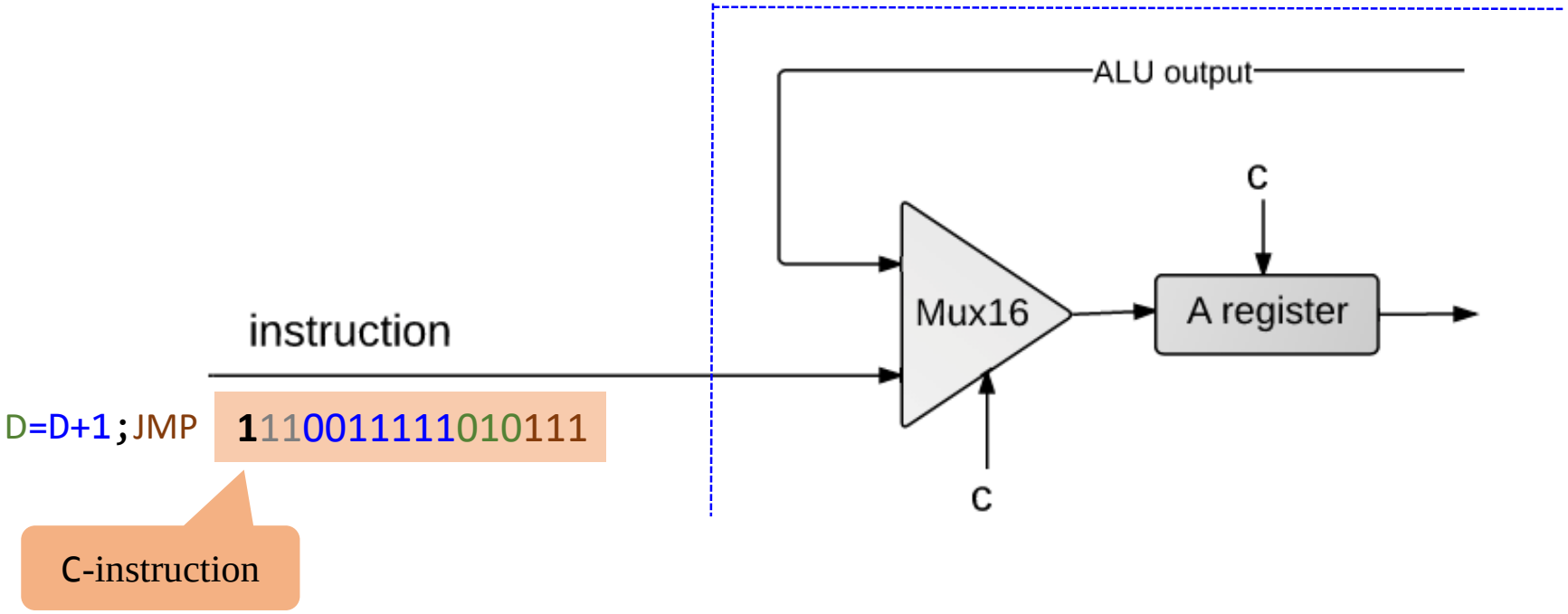
CPU operation: handling A-instructions



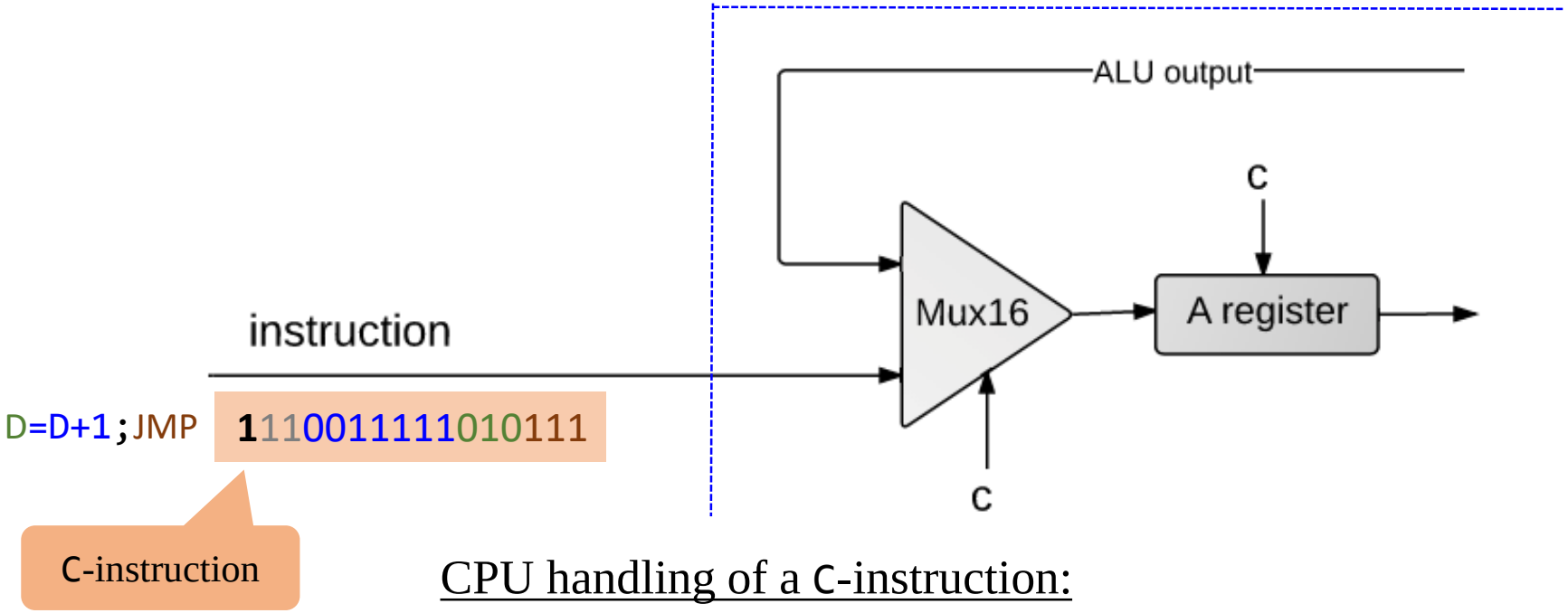
CPU handling of an A-instruction:

- Decodes the instruction into:
  - op-code
  - 15-bit value
- Stores the value in the A-register
- Outputs the value (not shown in this diagram).

CPU operation: instruction handling

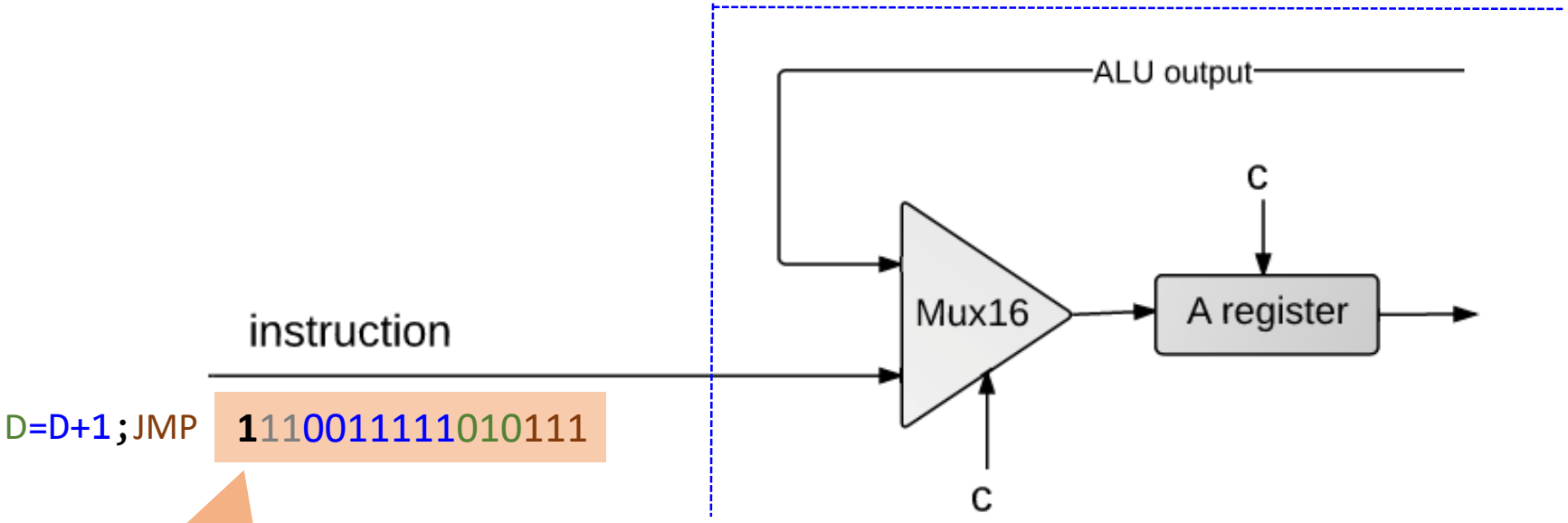


CPU operation: handling C-instructions



CPU handling of a C-instruction:

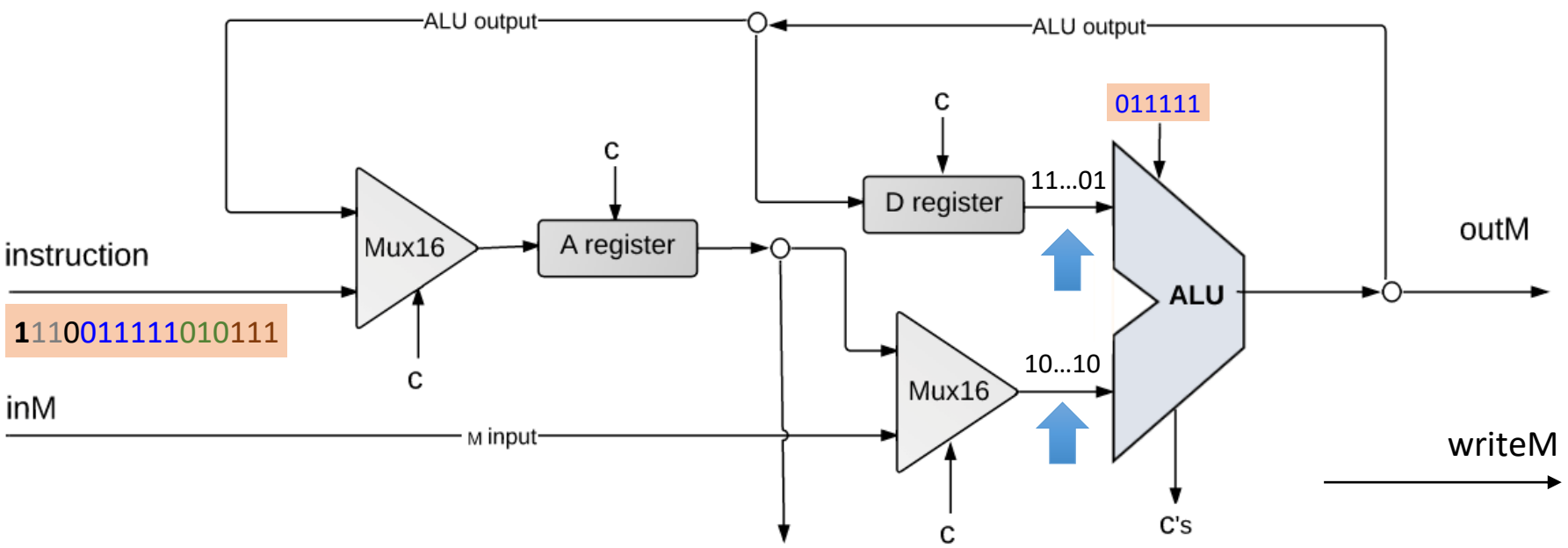
CPU operation: handling C-instructions



CPU handling of a C-instruction:

- Decodes the instruction bits into:
  - Op-code
  - ALU control bits
  - Destination load bits
  - Jump bits
- Routes these bits to their chip-part destinations
- The chip-parts (most notably, the ALU) execute the instruction.

CPU operation: handling c-instructions



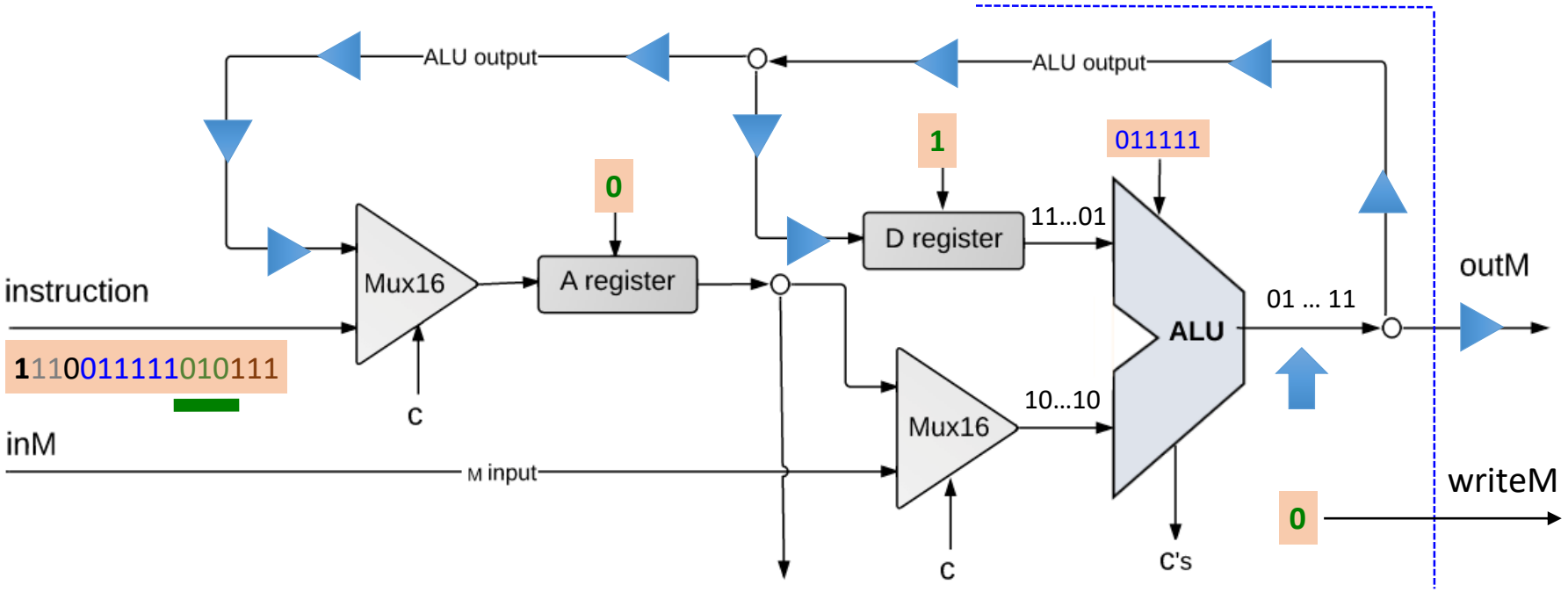
ALU data inputs:

- Input 1: from the D-register
- Input 2: from either:
  - A-register, or
  - data memory

ALU control inputs:

- control bits
  (from the instruction)

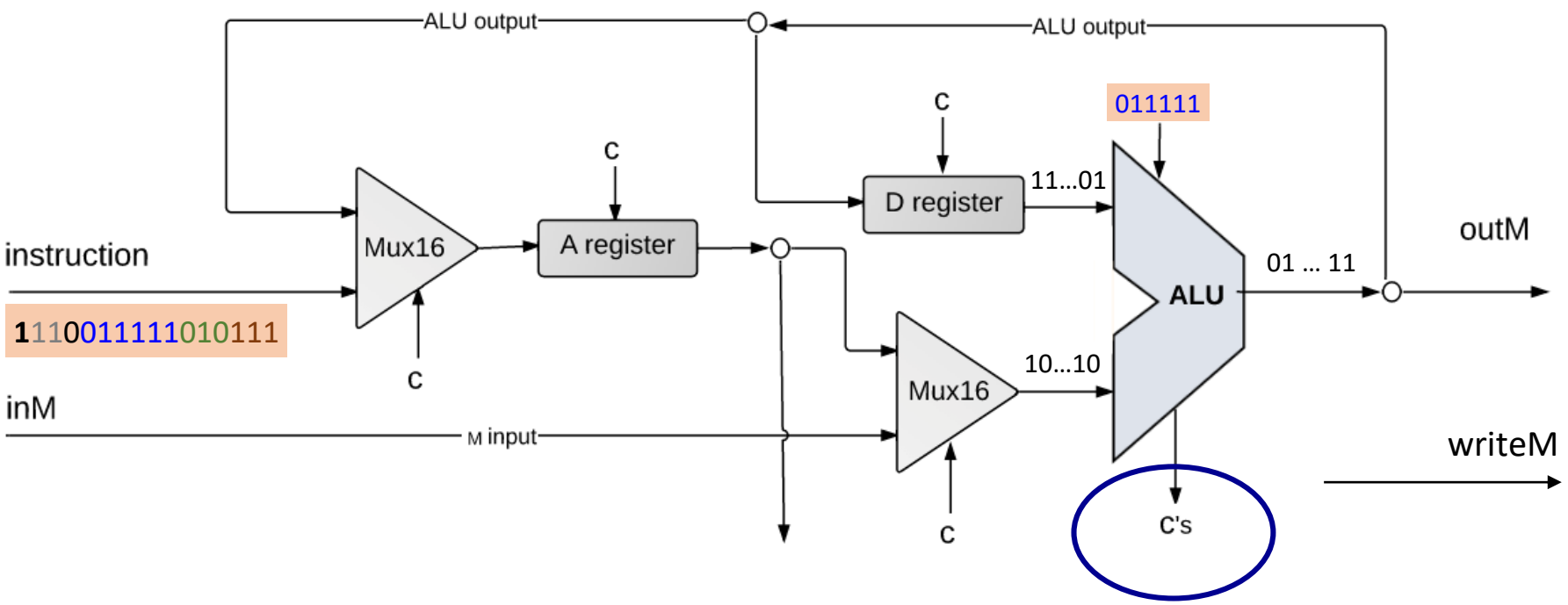
CPU operation: handling C-instructions



ALU data output:

- Result of ALU calculation
- Fed simultaneously to: D-register, A-register, data memory
- Which destination *actually* commits to the ALU output is determined by the instruction's destination bits.

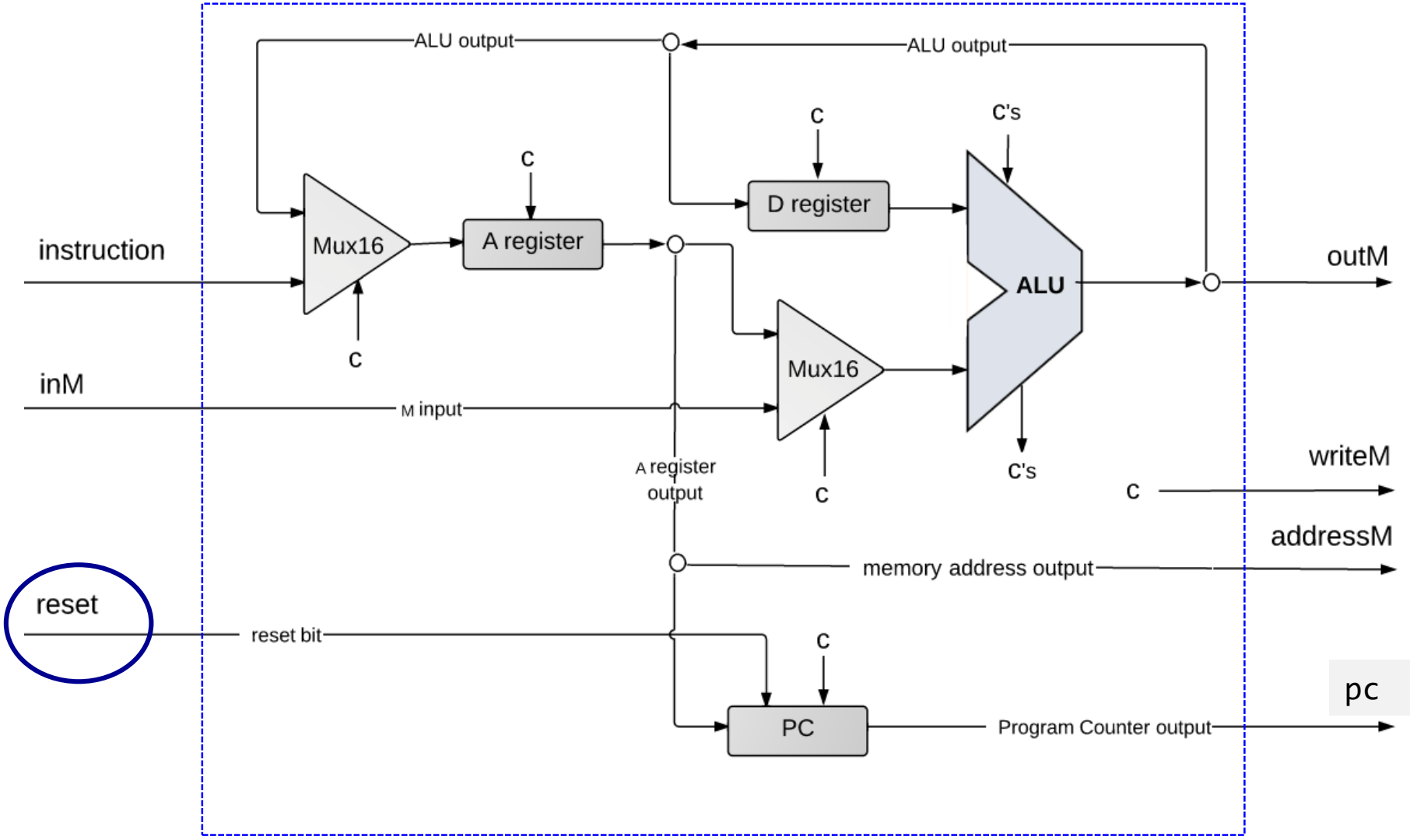
CPU operation: handling c-instructions



ALU control outputs:

- is the output negative?
- is the output zero?

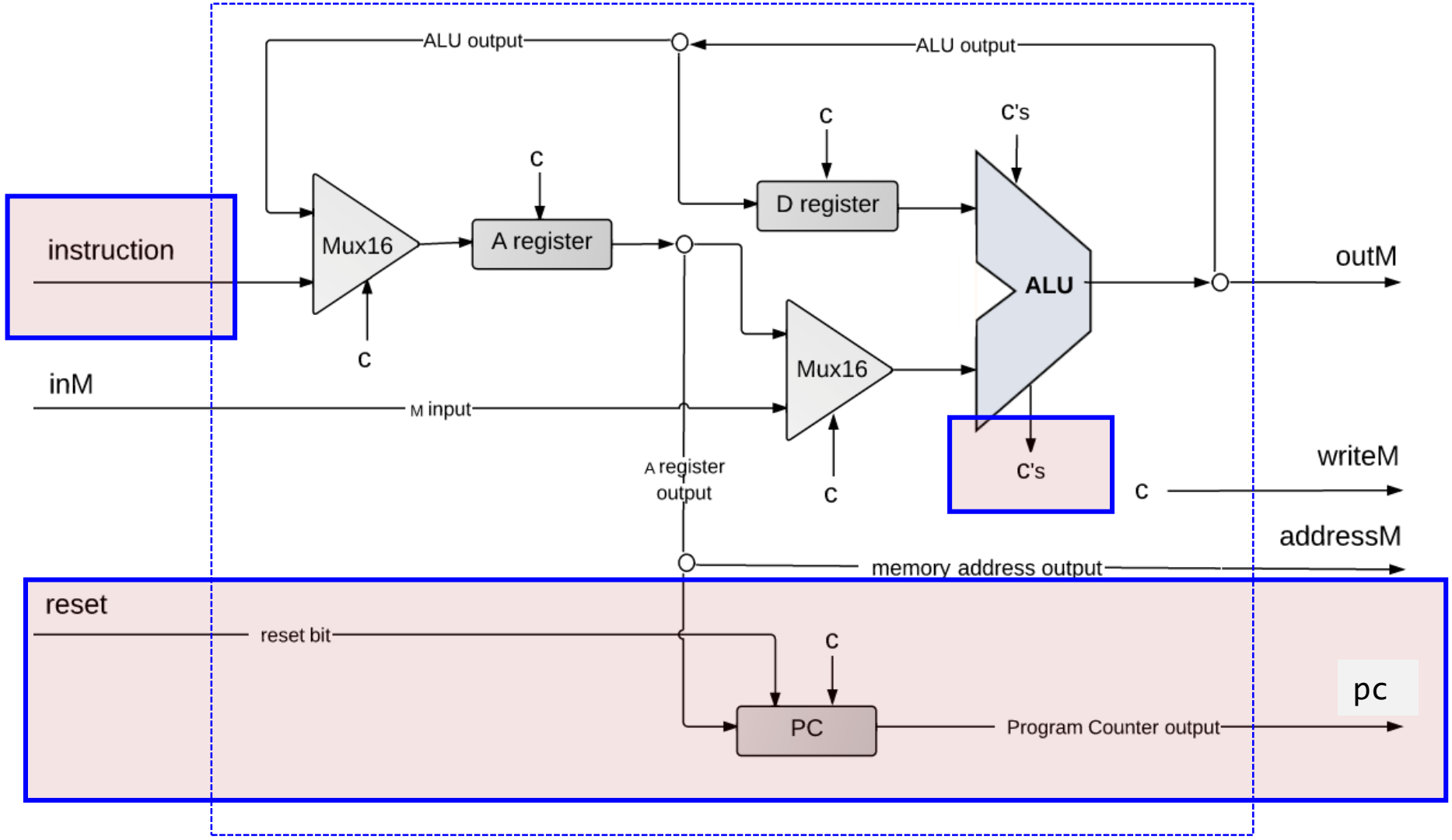
CPU operation: control



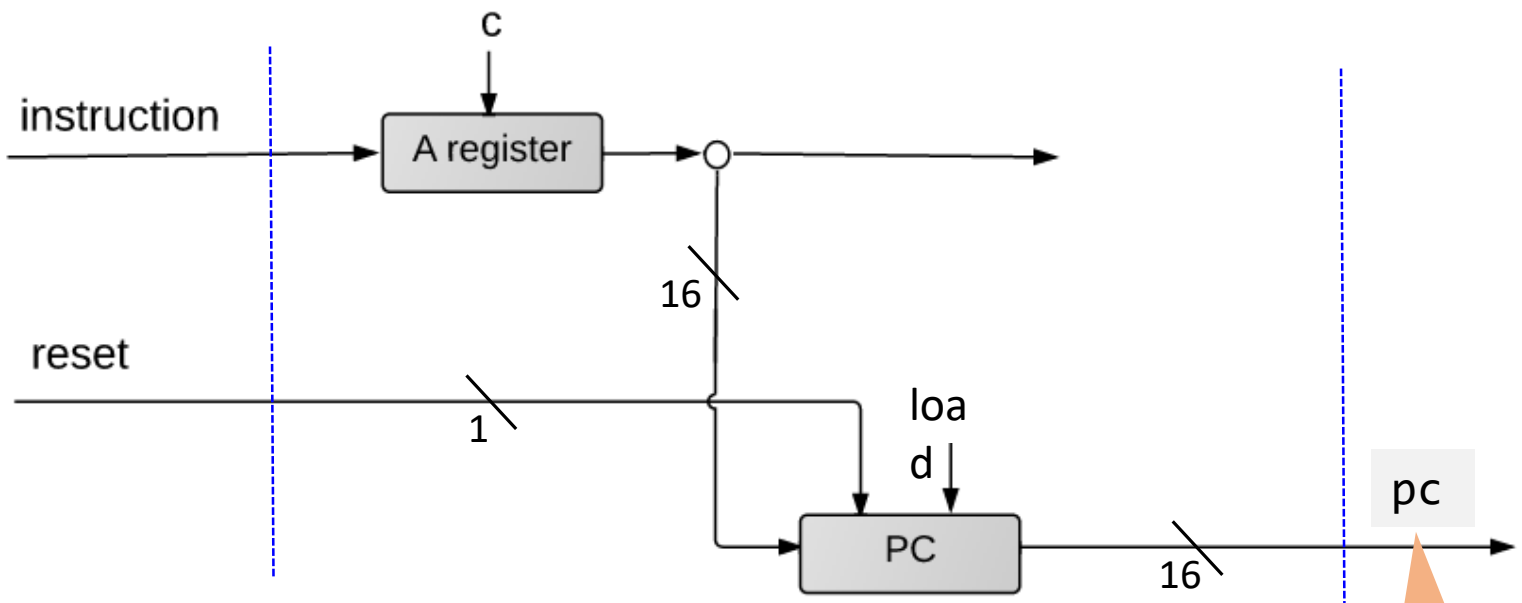
CPU operation: control

- The computer is loaded with some program;
- Pushing r**eset** causes the program to start running.

CPU operation: control



CPU operation: control

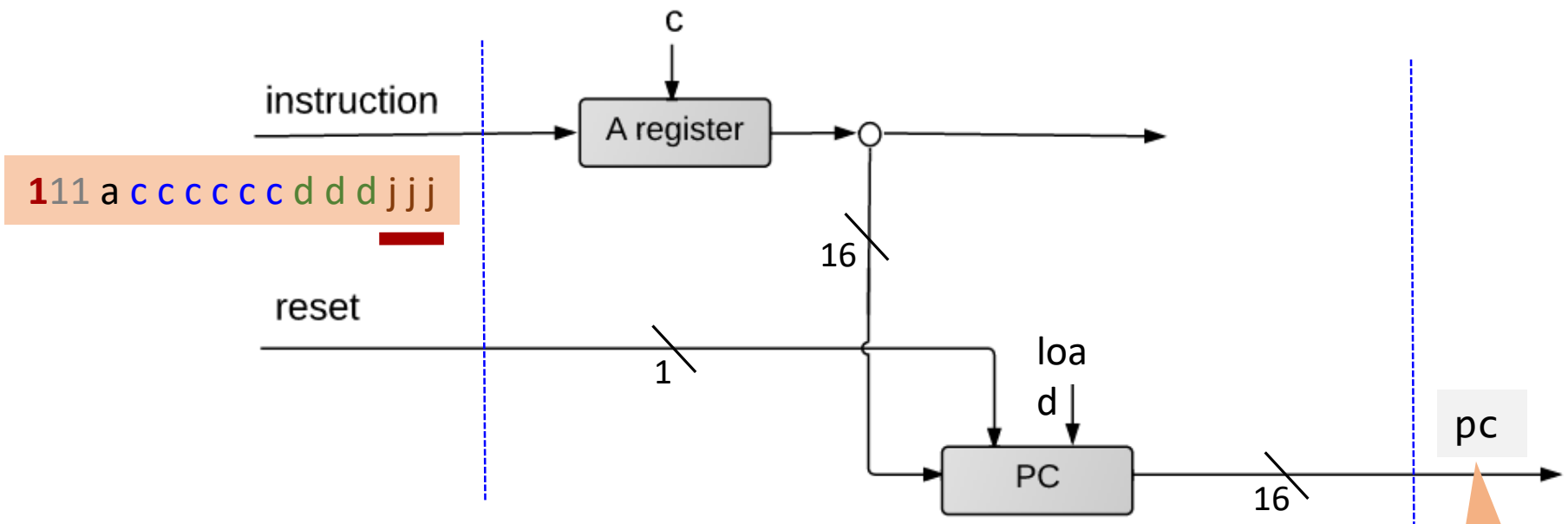


PC operation (abstraction)

Emits the address of the next instruction:

- restart: `PC = 0`
- no jump: `PC++`
- goto: `PC=A`
- conditional goto: if (*condition*) `PC = A` else `PC++`

CPU operation: control



PC operation (implementation)

if (`reset==1`) `PC=0`

else

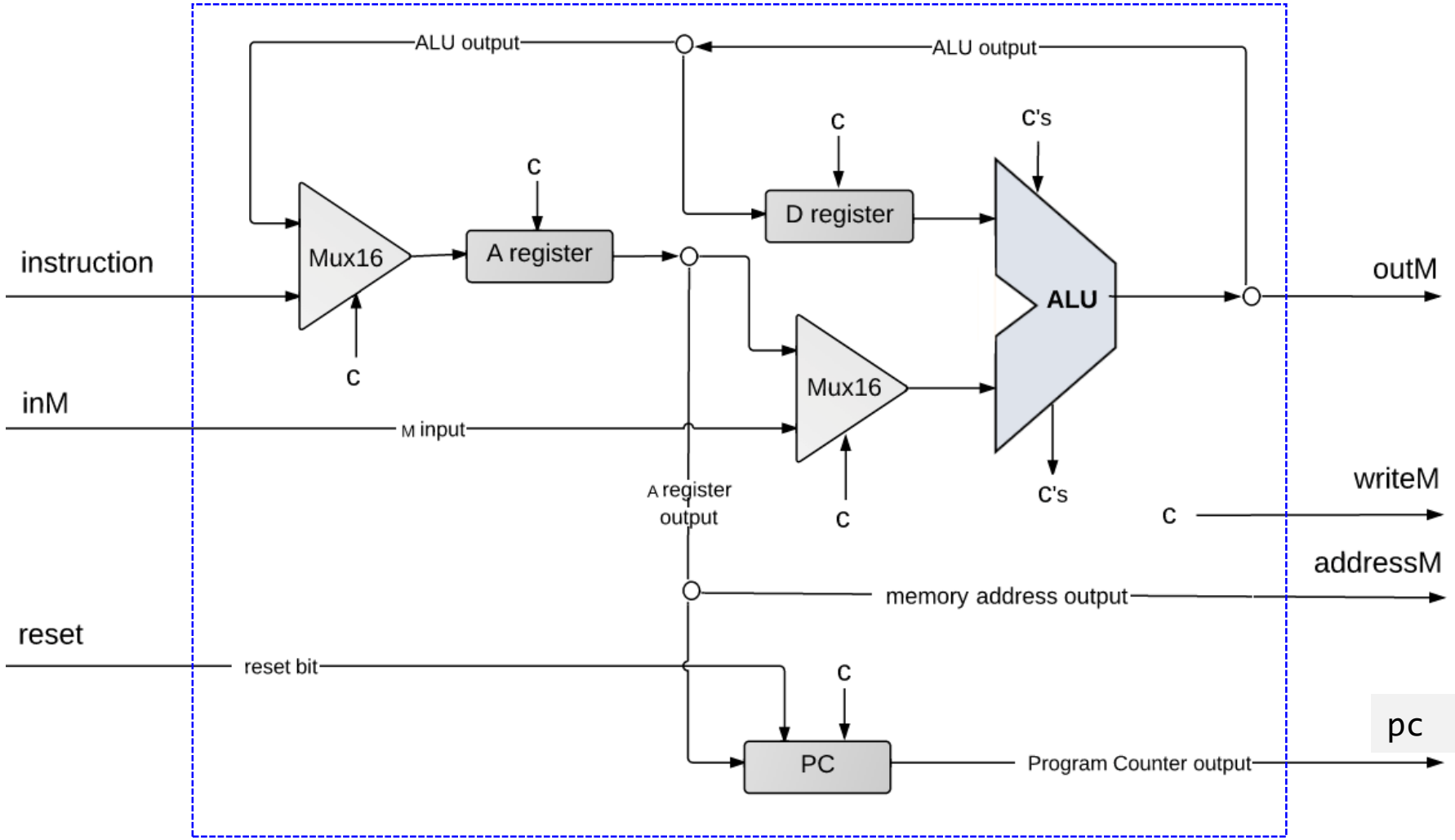
// in the course of handling the current instruction:

load = *f* (jump bits, ALU control outputs)

if (*load* `==1`) `PC=A` // jump

else `PC++` // next instruction

Hack CPU Implementation

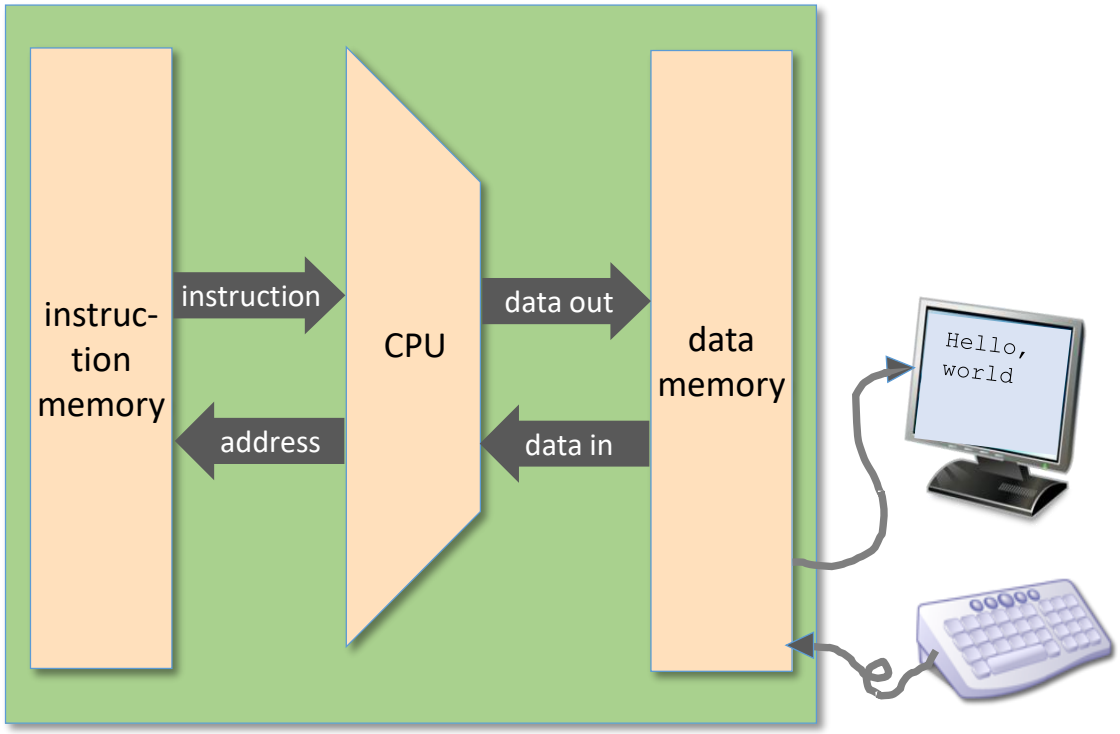


That's It!

Computer Architecture: lecture plan

- ✓ Von Neumann Architecture
- ✓ Fetch-Execute Cycle
- ✓ The Hack CPU
- ➡ The Hack Computer
- Project 5 Overview

Hack Computer



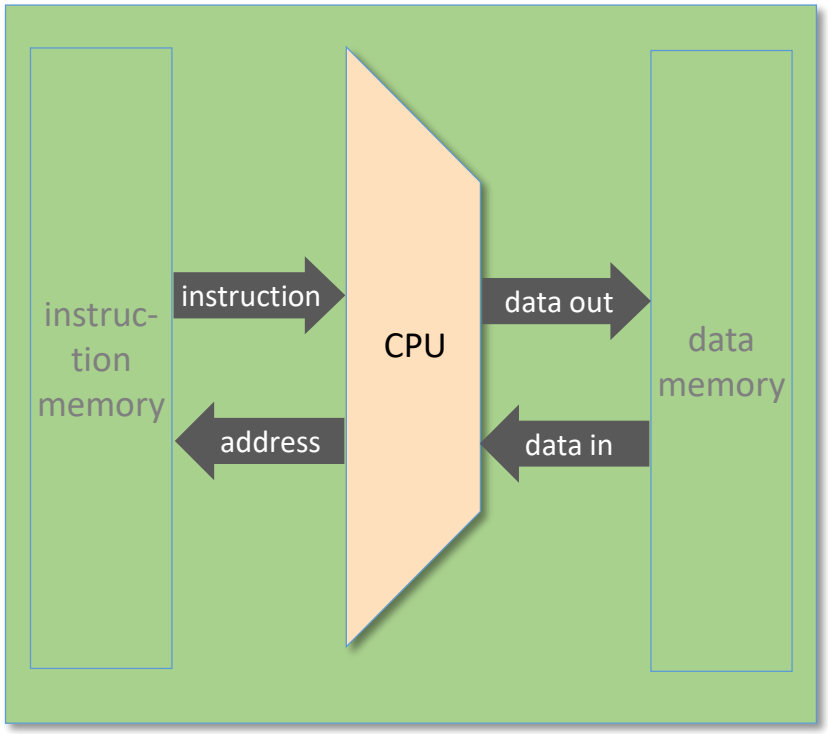
Abstraction:

A computer capable of running programs written in the Hack machine language

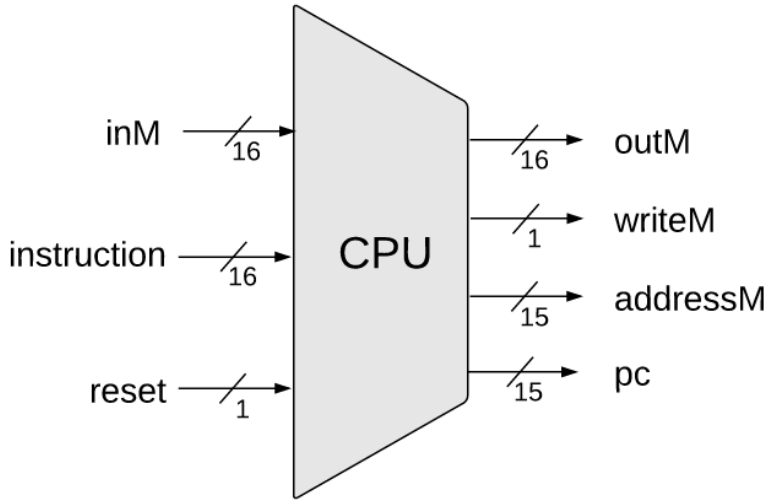
Implementation:

Built from the Hack chip-set.

Hack CPU


instruc-
tion
memory
instruction
address
CPU
data out
data in
data
memory

Hack CPU



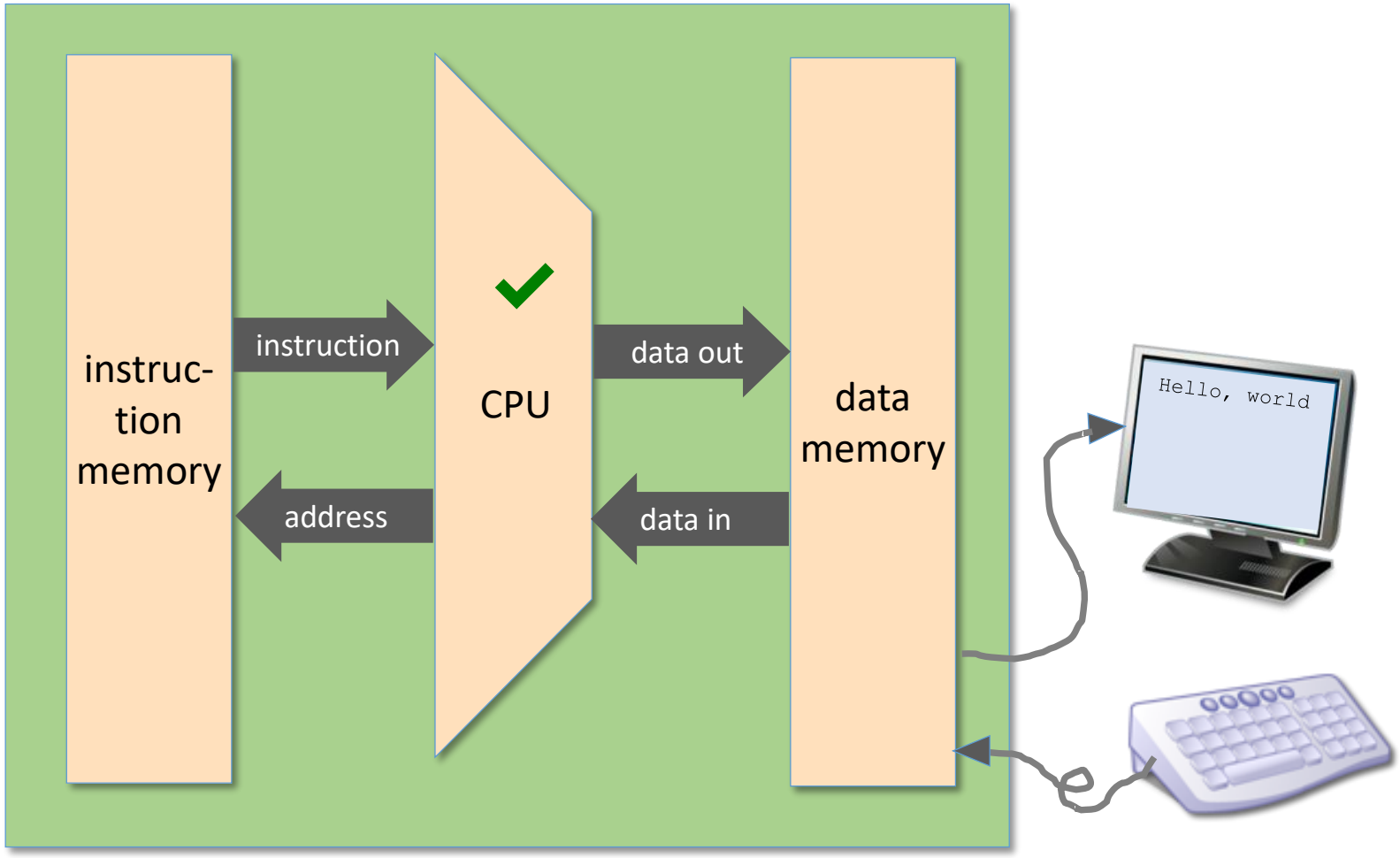
CPU abstraction:

Executes a Hack instruction and figures out which instruction to execute next

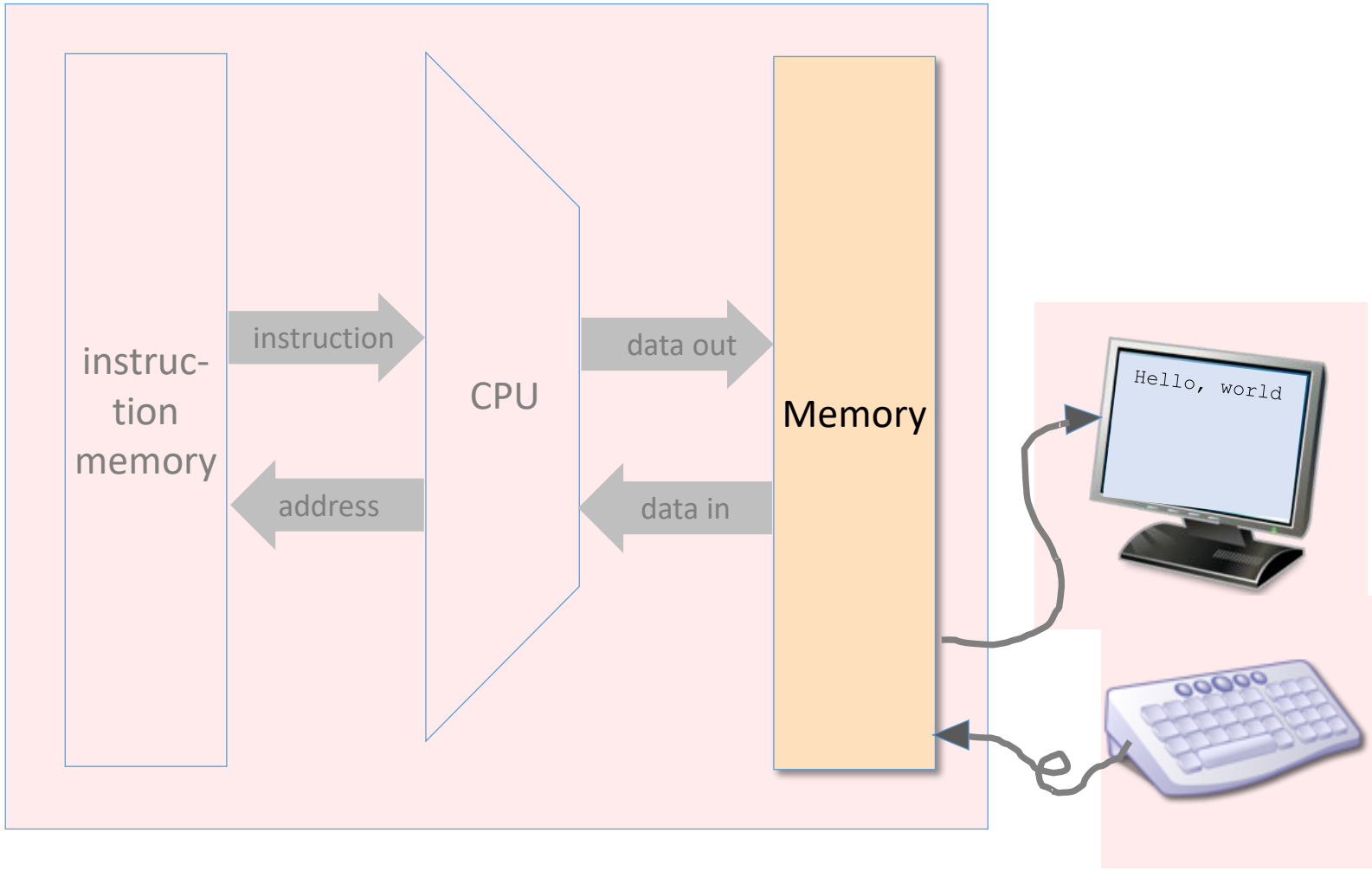
CPU Implementation:

Discussed before.

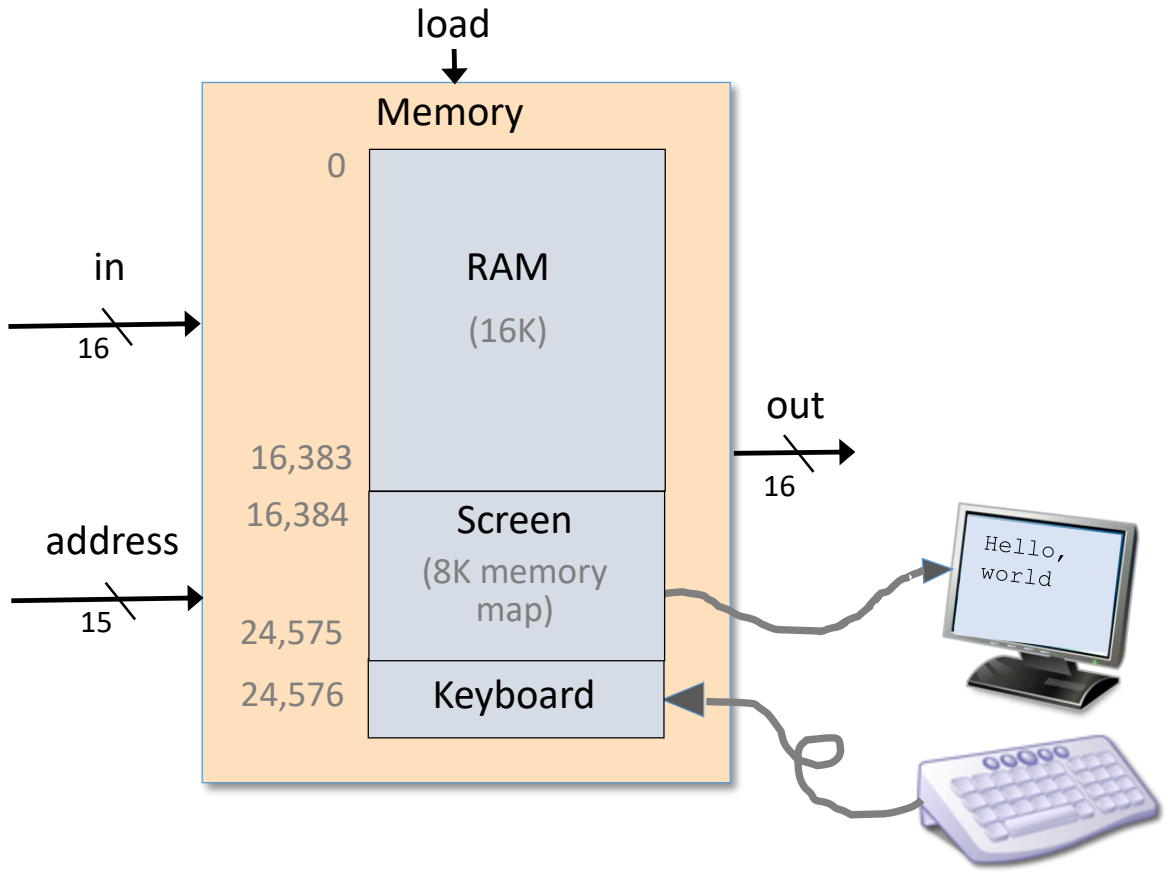
Hack Computer



Memory

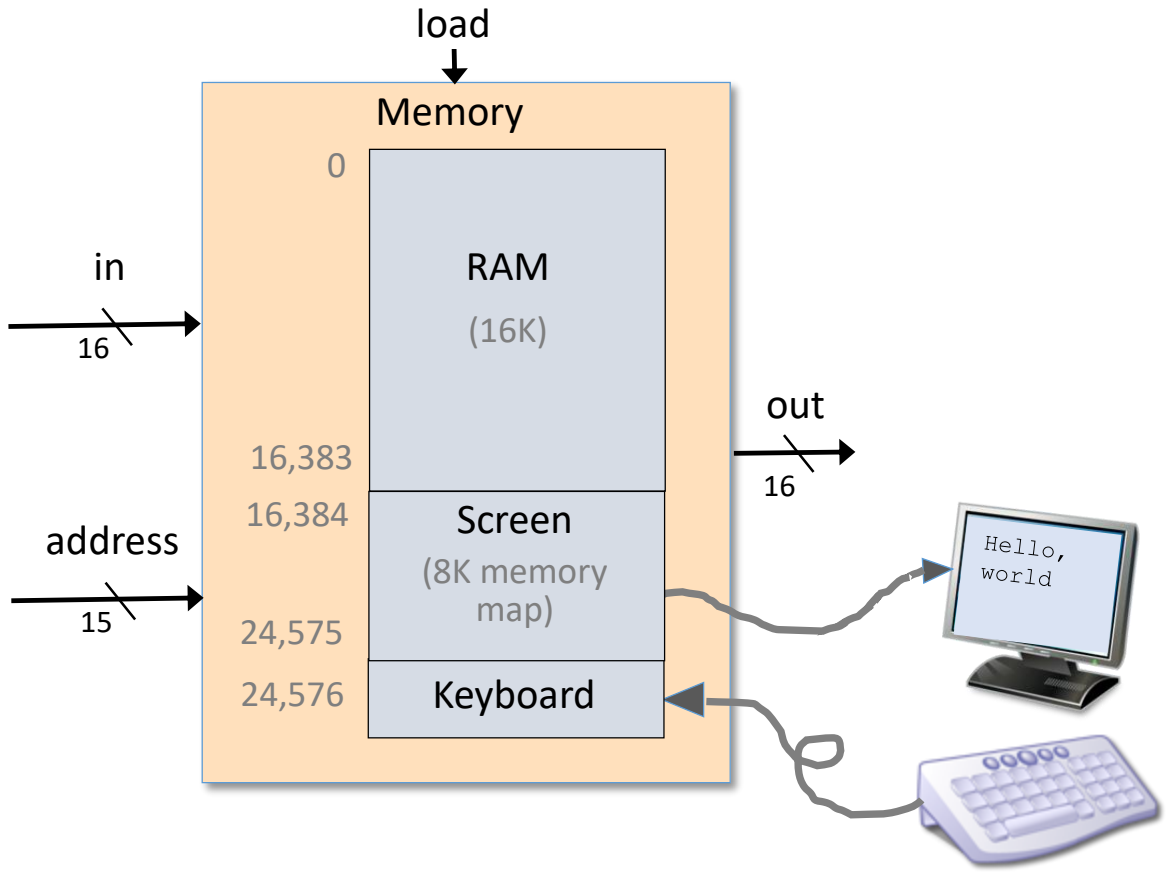

instruc-
tion
memory
instruction
address
CPU
data out
data in
Memory
Hello, world

Memory: abstraction



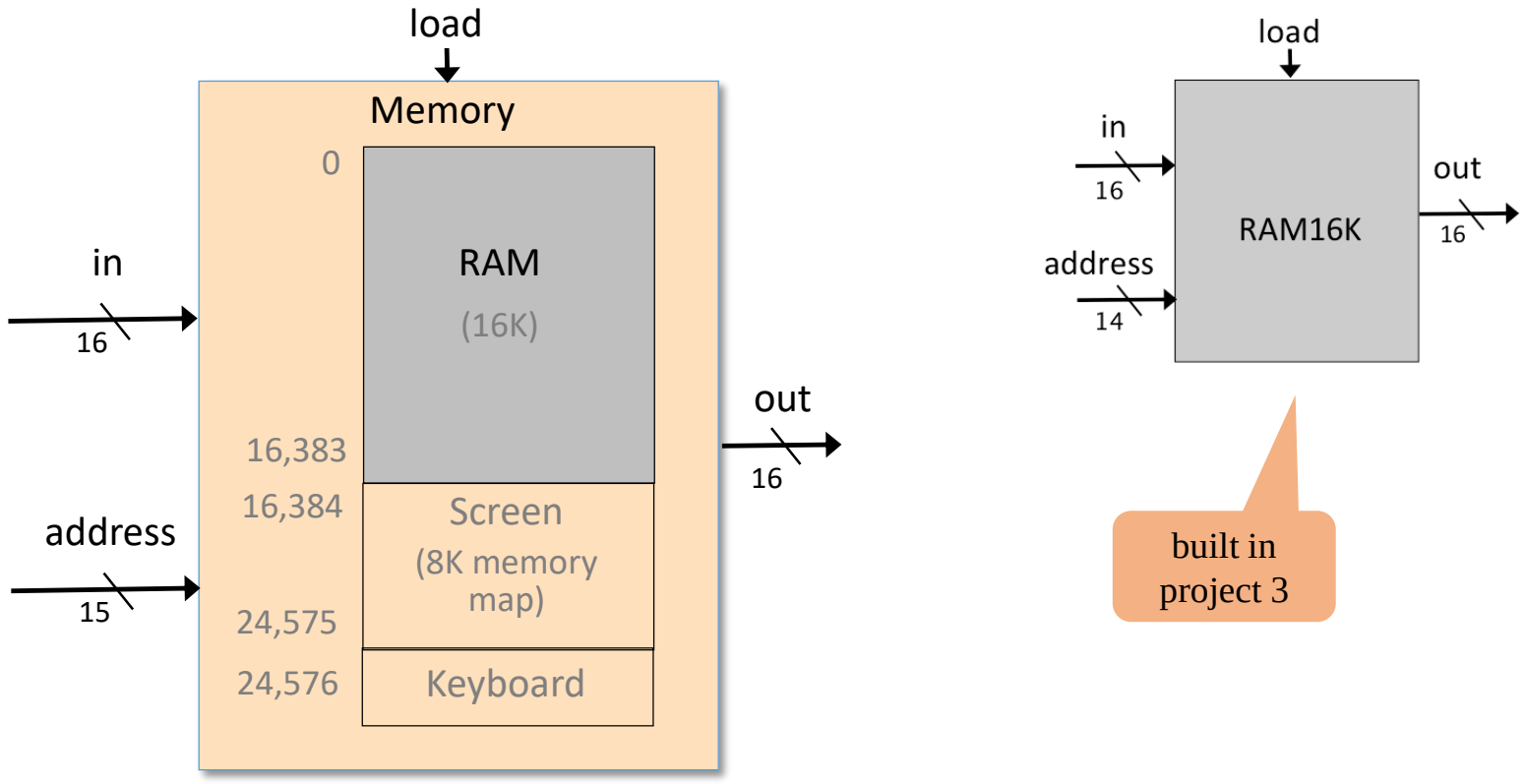
- Address 0 to 16383: data memory
- Address 16384 to 24575: screen memory map
- Address 24576: keyboard memory map

Memory: implementation



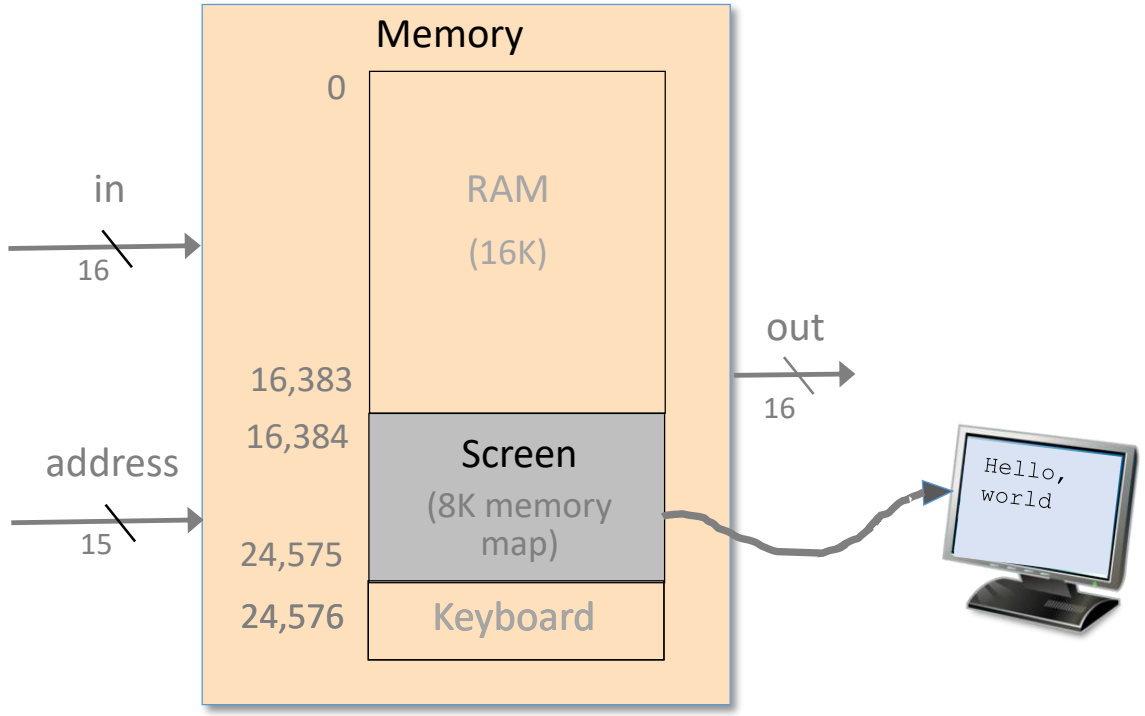
- Address 0 to 16383: data memory
- Address 16384 to 24575: screen memory map
- Address 24576: keyboard memory map

RAM

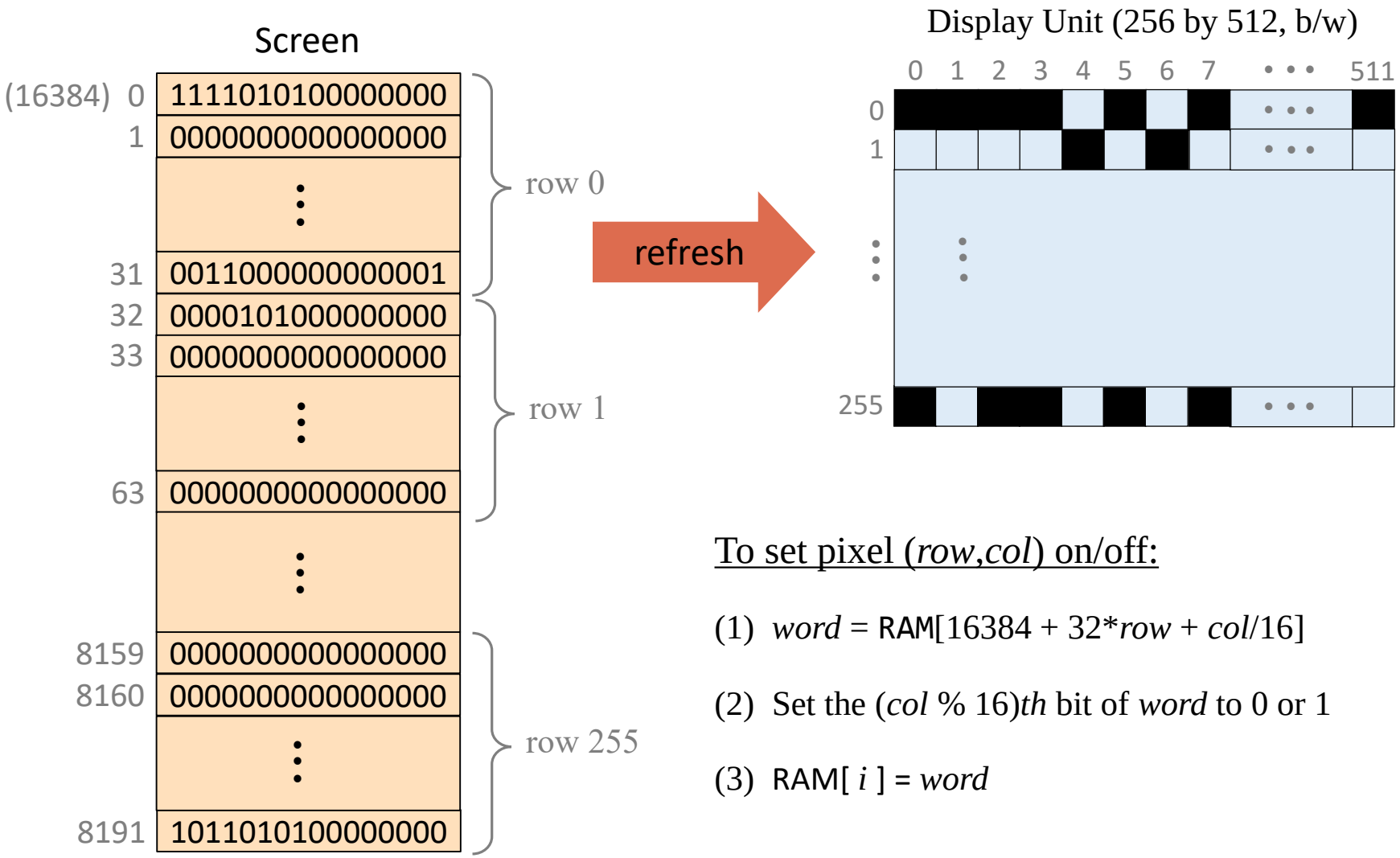


The Hack RAM is realized by the `RAM16K` chip implemented in project 3.

Screen


Memory
0
RAM
(16K)
16,383
16,384
Screen
(8K memory map)
24,575
24,576
Keyboard
in
16
address
15
out
16
Hello, world

Screen memory map



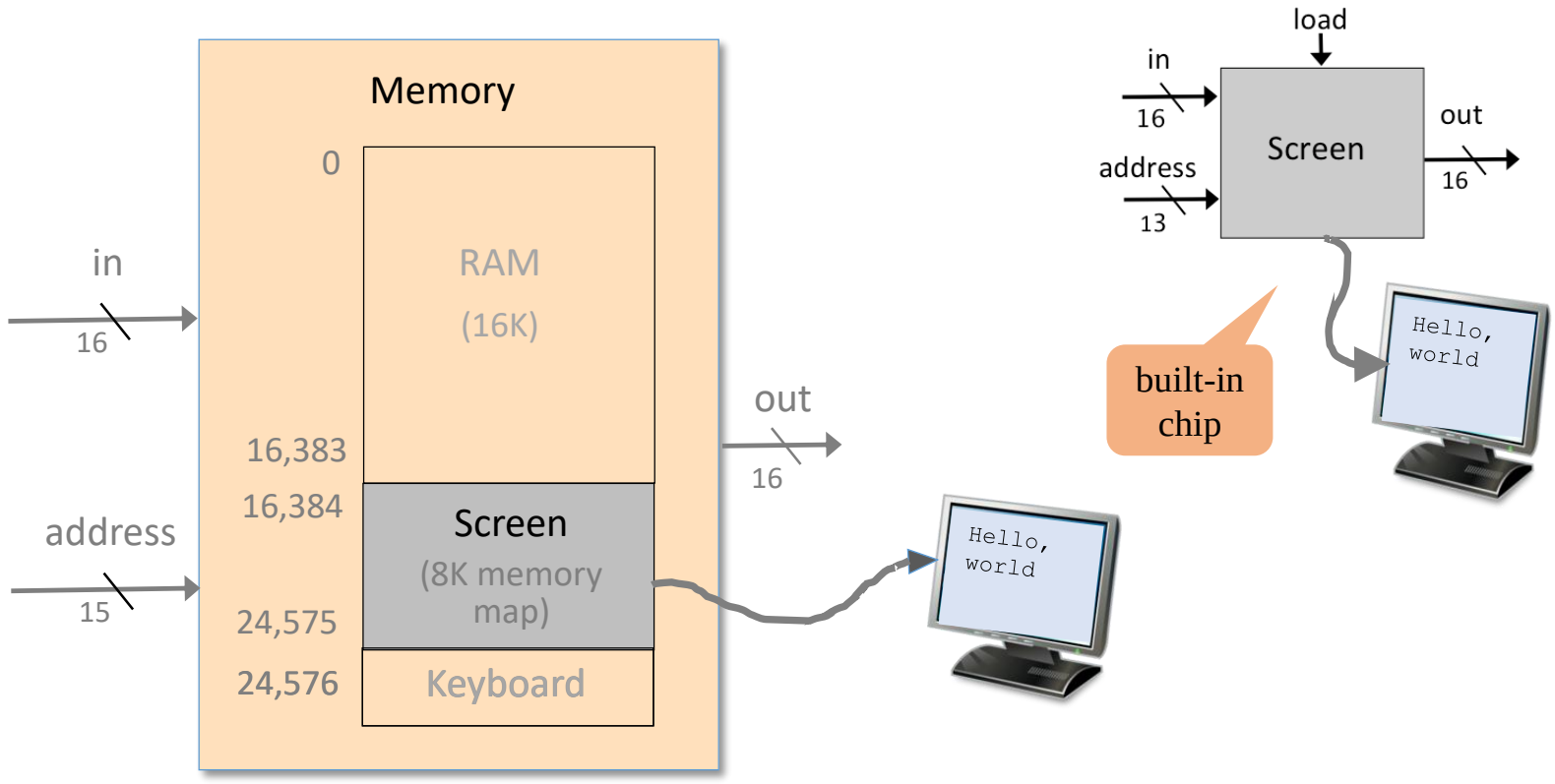
To set pixel (*row*,*col*) on/off:

(1) *word* = RAM[16384 + 32**row* + *col*/16]

(2) Set the (*col* % 16)*th* bit of *word* to 0 or 1

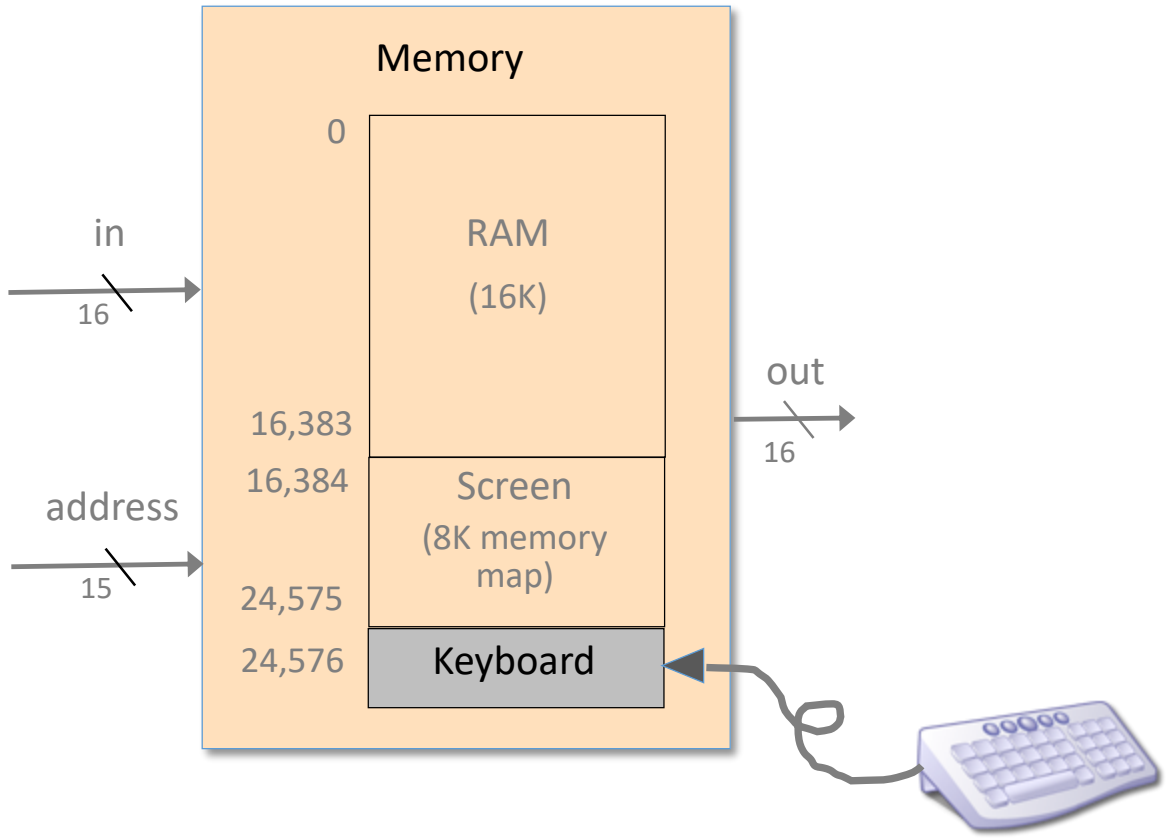
(3) RAM[*i*] = *word*

Screen

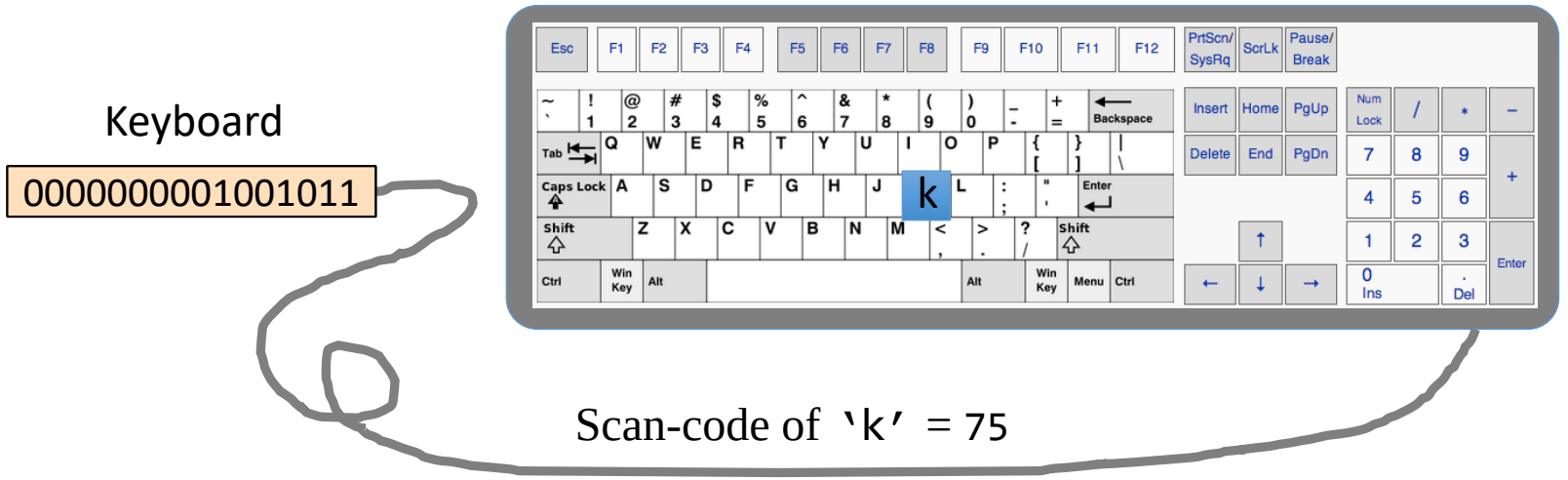


- The Hack screen is realized by a built-in chip named `Screen`
- `Screen`: a regular RAM + display output side-effect.

Keyboard


Memory
0
RAM
(16K)
16,383
16,384
Screen
(8K memory
map)
24,575
24,576
Keyboard
in
16
address
15
out
16

Keyboard memory map



The `Keyboard` chip emits the scan-code of the currently pressed key, or `0` if no key is pressed.

The Hack character set

key	code
(space)	32
!	33
“	34
#	35
$	36
%	37
&	38
‘	39
(	40
)	41
*	42
+	43
,	44
-	45
.	46
/	47

key	code
0	48
1	49
…	…
9	57

:	58
;	59
<	60
=	61
>	62
?	63
@	64

key	code
A	65
B	66
C	…
…	…
Z	90

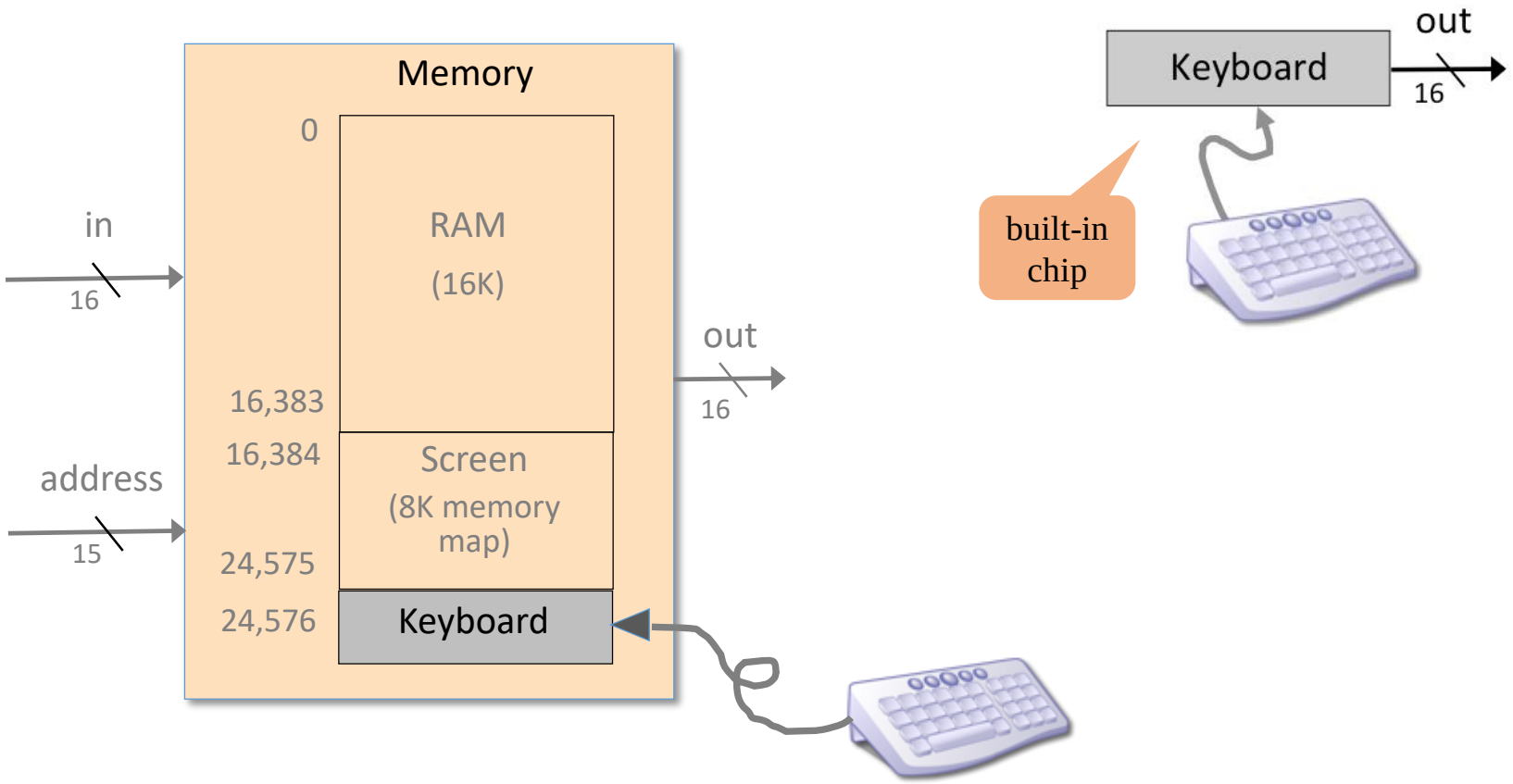
[	91
/	92
]	93
^	94
_	95
`	96

key	code
a	97
b	98
c	99
…	…
z	122

{	123
|	124
}	125
~	126

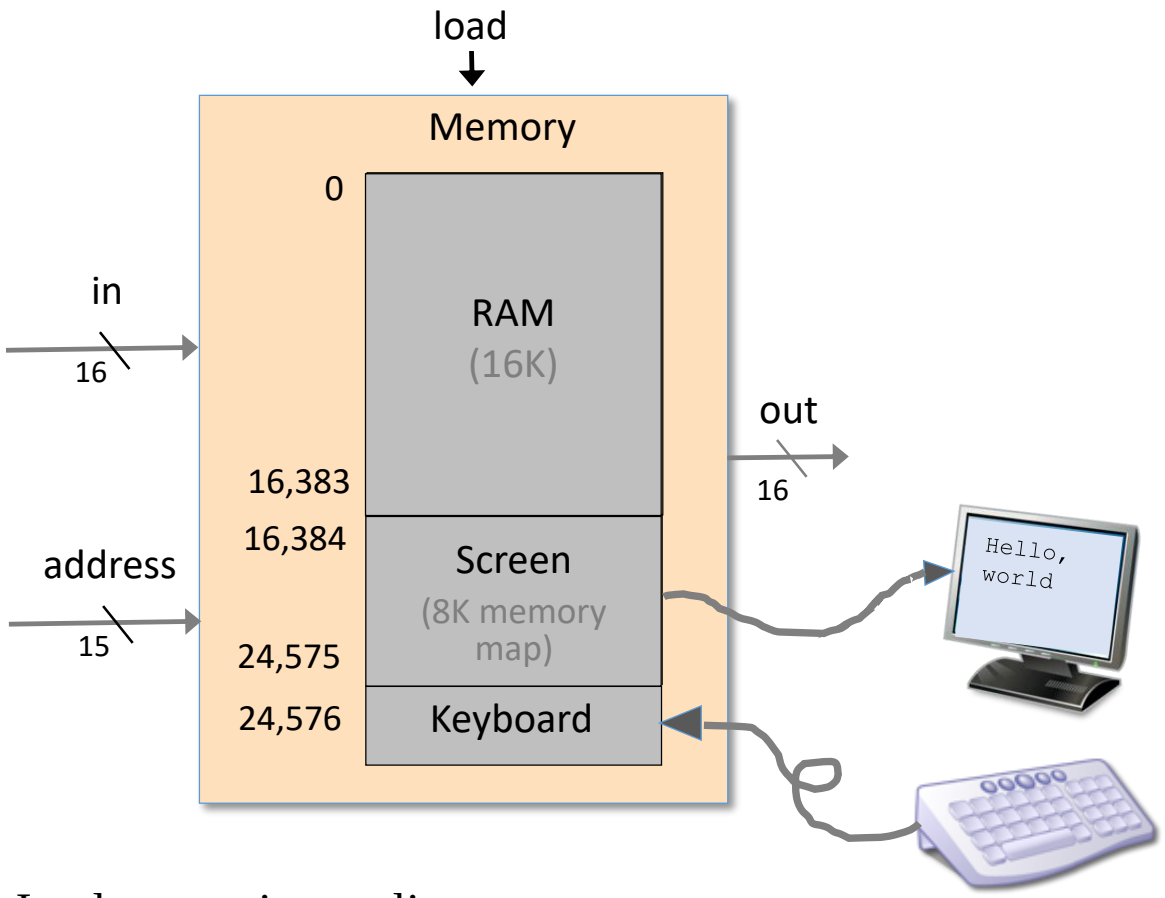
key	code
newline	128
backspace	129
left arrow	130
up arrow	131
right arrow	132
down arrow	133
home	134
end	135
Page up	136
Page down	137
insert	138
delete	139
esc	140
f1	141
…	…
f12	152

Keyboard



- Realized by a built-in chip named `Keyboard`
- `Keyboard`: A read-only 16-bit register + a keyboard input side-effect.

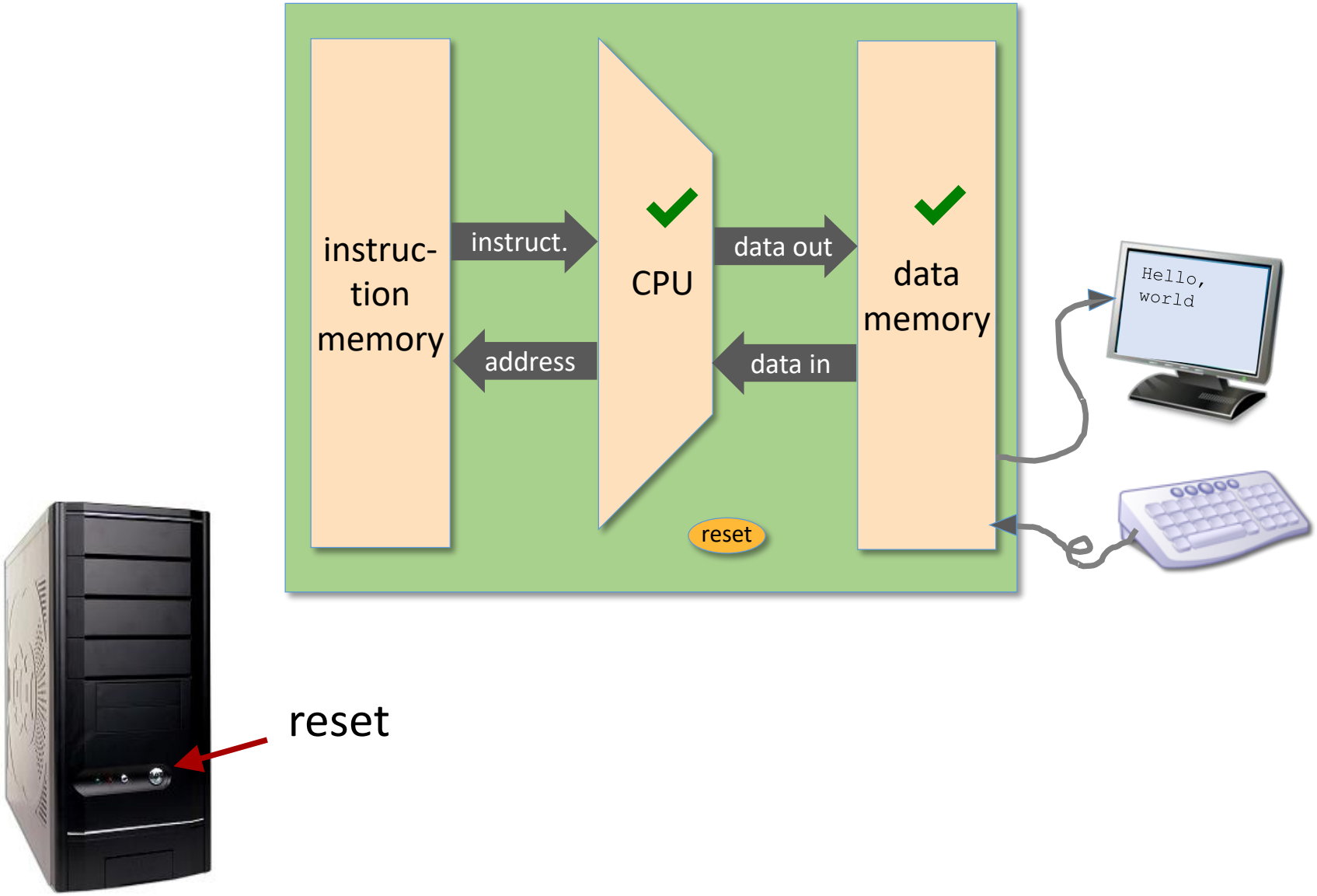
Memory implementation



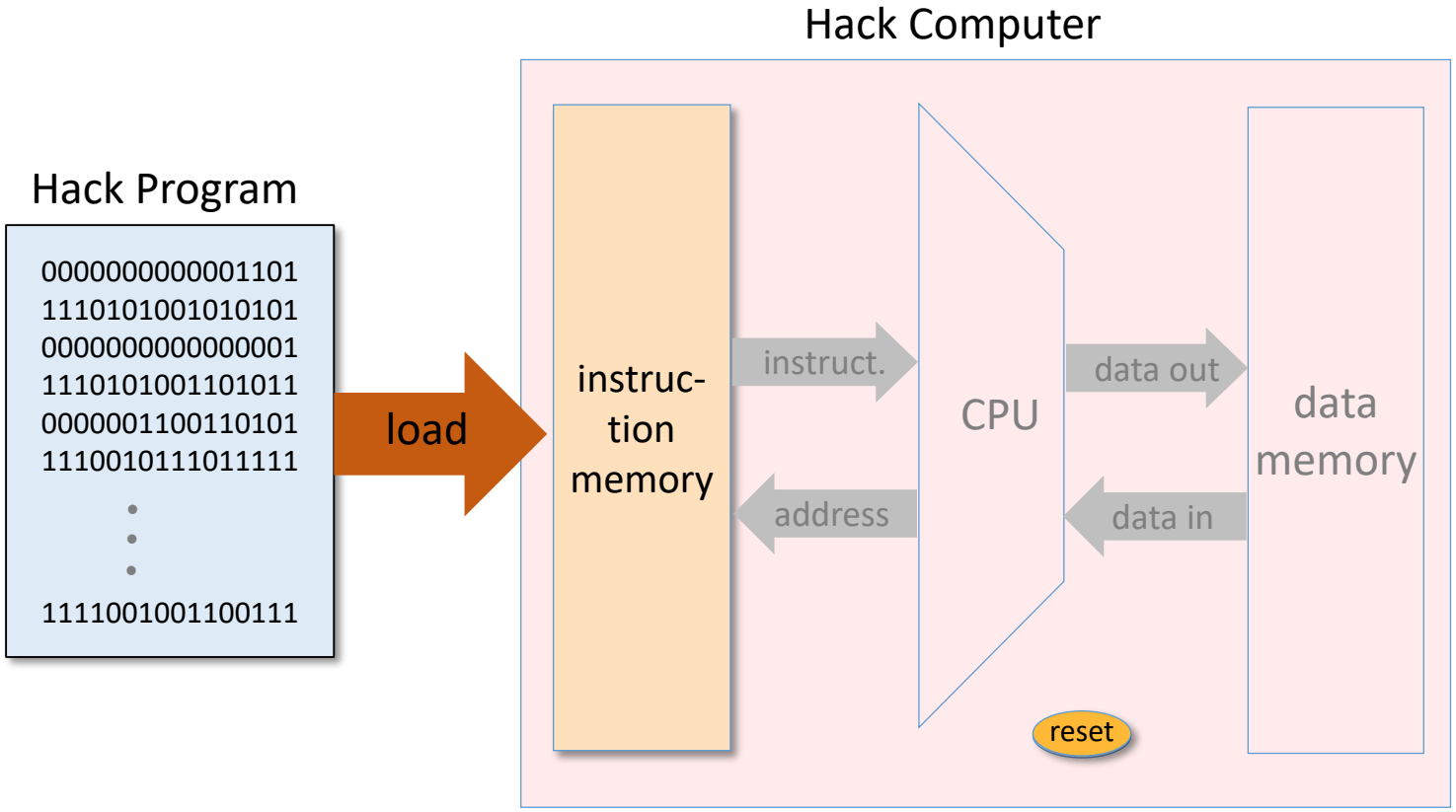
Implementation outline:

- Uses the three chip-parts `RAM16K`, `Screen`, and `Keyboard` (as just described)
- Routes the `address` input to the correct `address` input of the relevant chip-part.

Hack Computer



Instruction memory

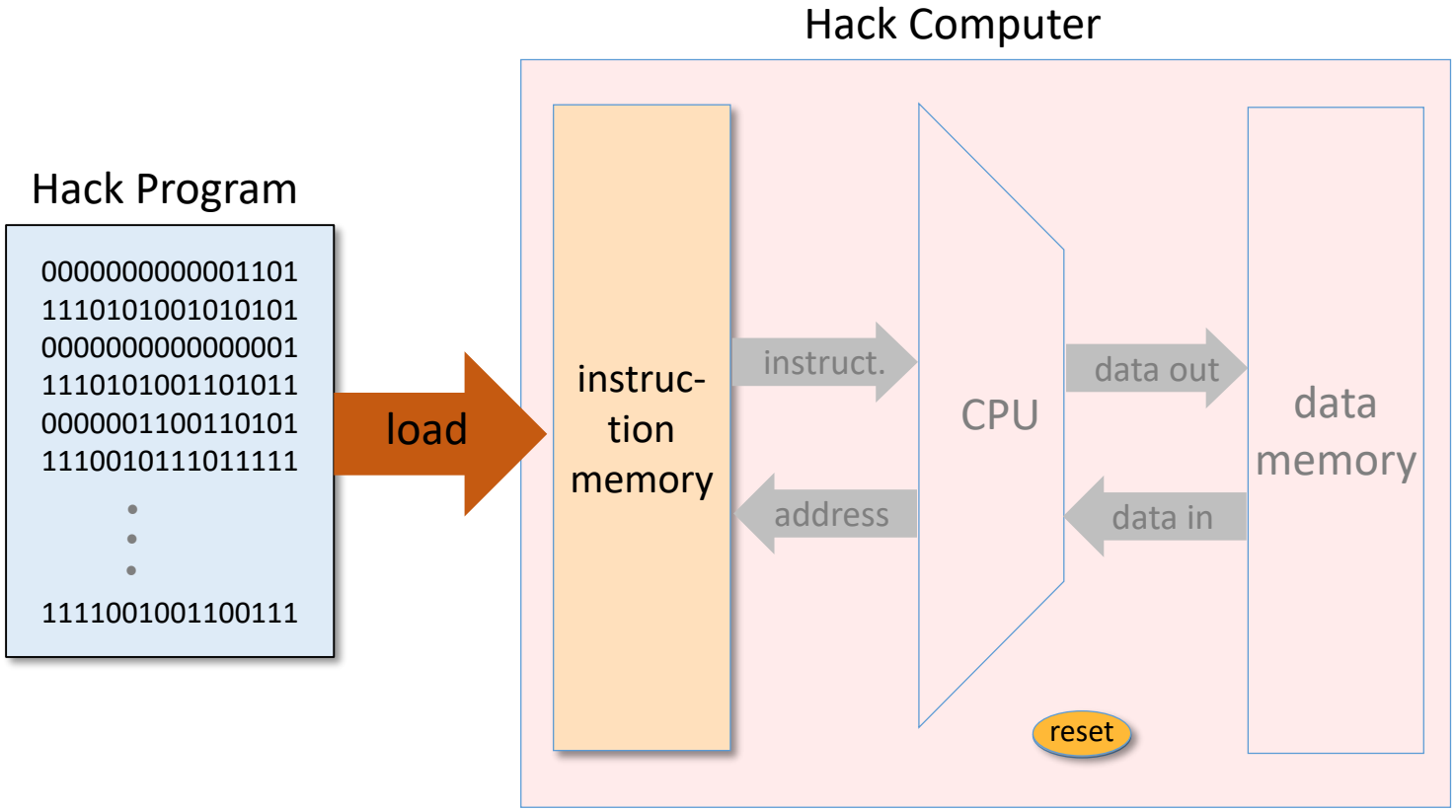


To run a program on the Hack computer:

- Load the program into the Instruction Memory
- Press "reset"
- The program starts running.

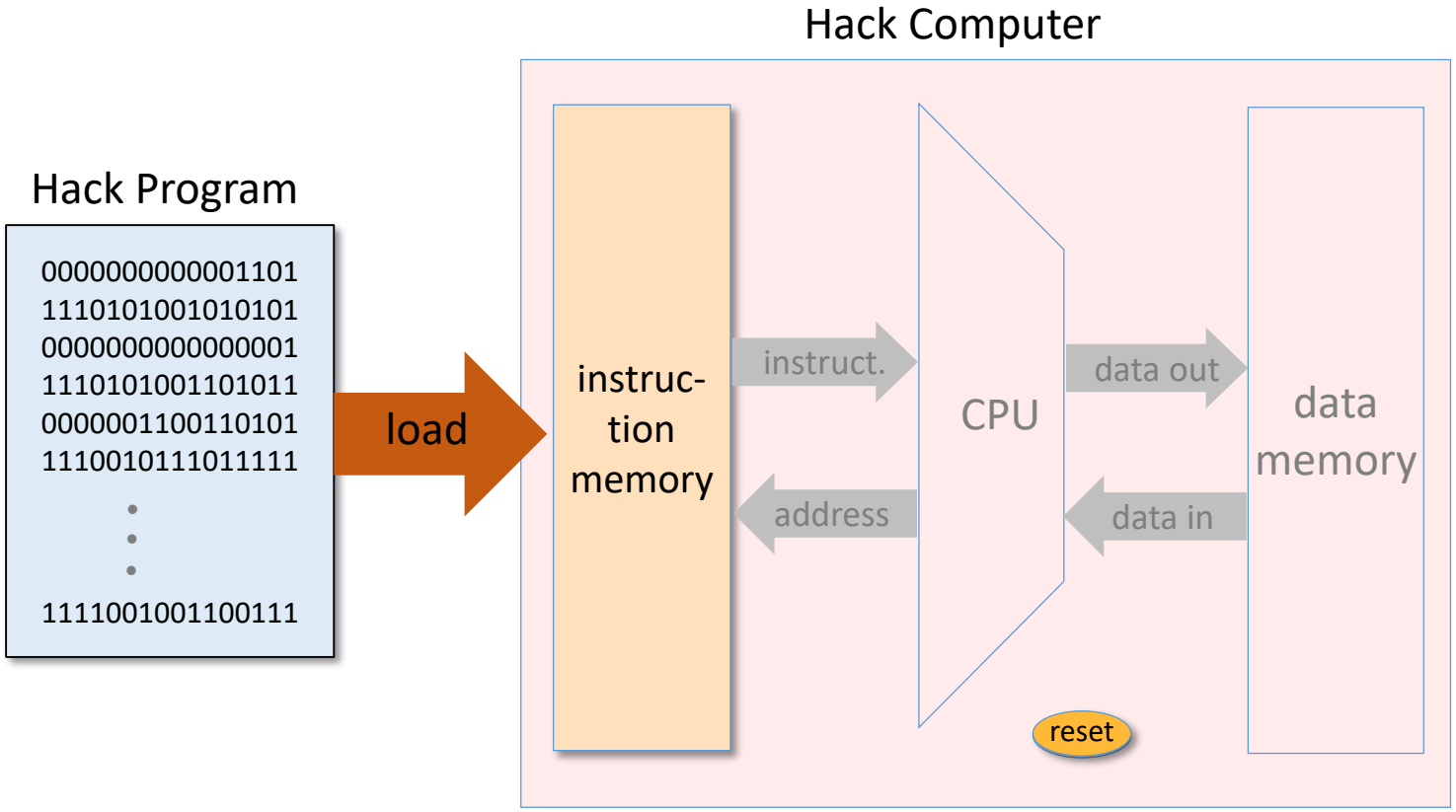
Load a program into the Instruction Memory? How?

Instruction memory



Loading a program into the Instruction Memory:

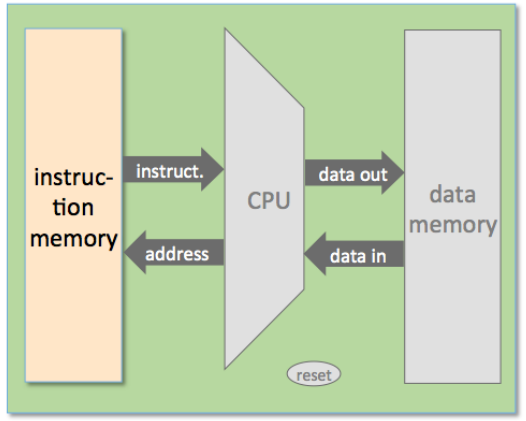
Instruction memory

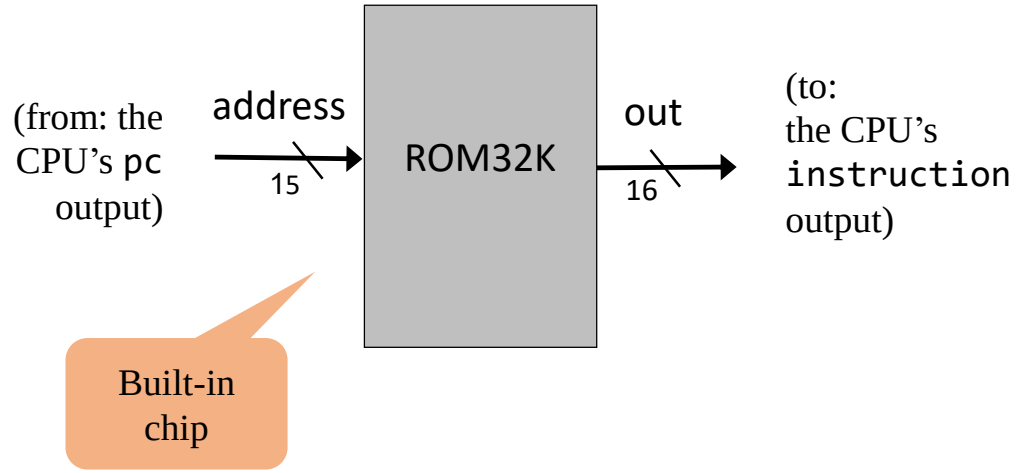


Loading a program into the Instruction Memory:

- Hardware implementation: plug-and-play ROM chips
  (each comes pre-loaded with a program's code)
- Hardware simulation: programs are stored in text files;
  The simulator's software features a load-program service.

Instruction memory

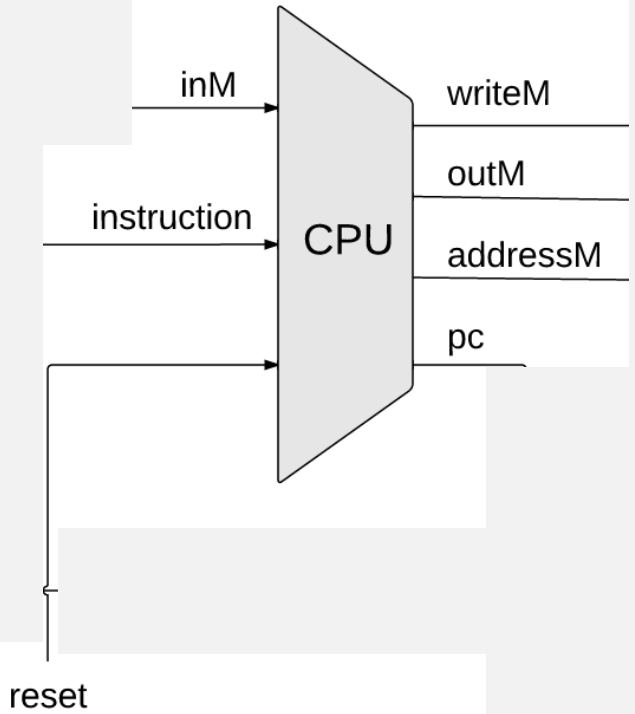




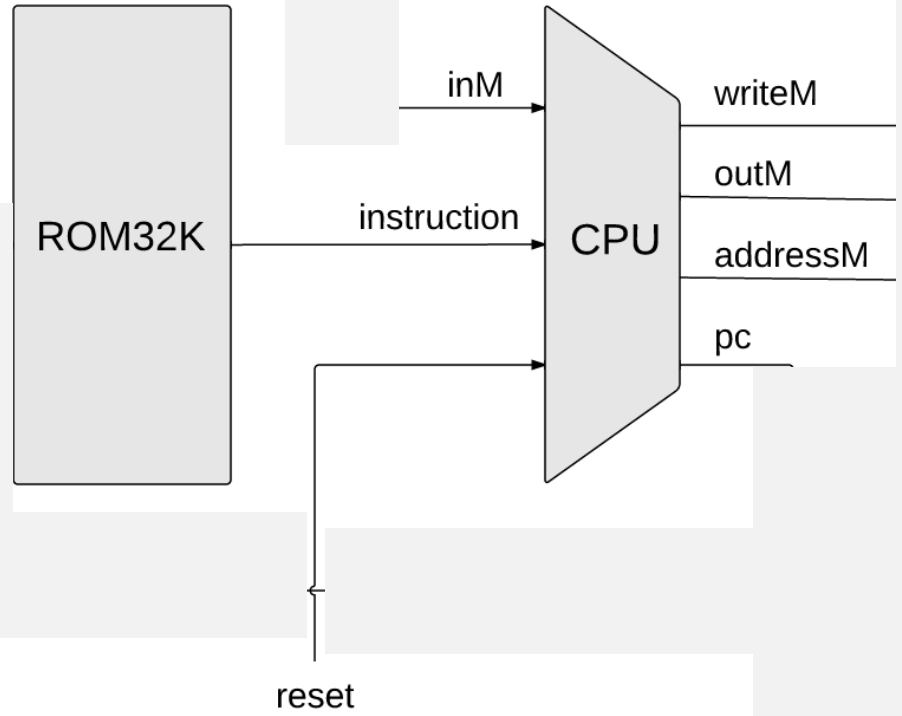
- The Hack Instruction Memory is realized by a built-in chip named `ROM32K`
- `ROM32K`: a read-only, 16-bit, 32K RAM chip + program loading side-effect.

Hack Computer implementation

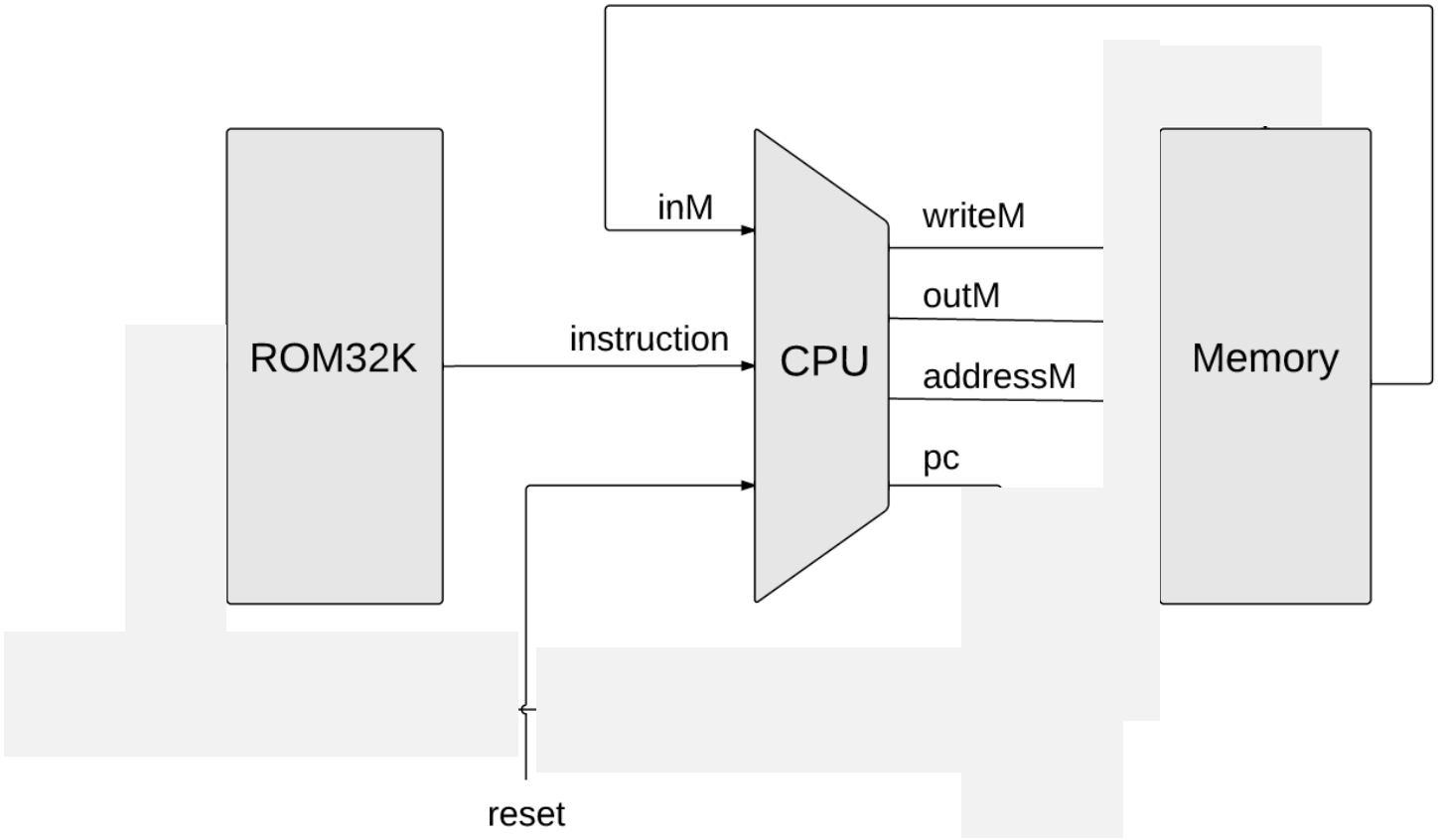
Hack Computer implementation



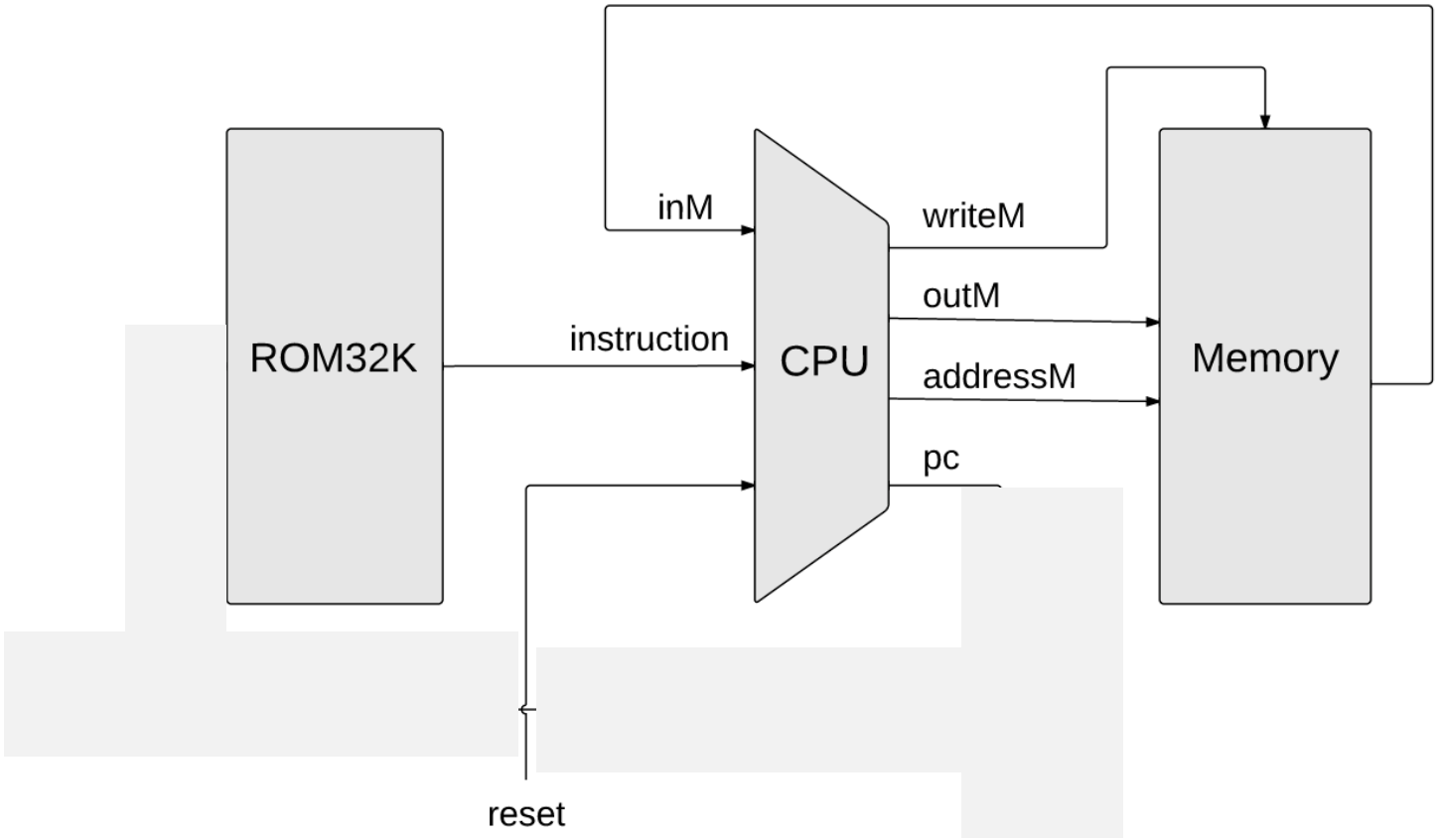
Hack Computer implementation



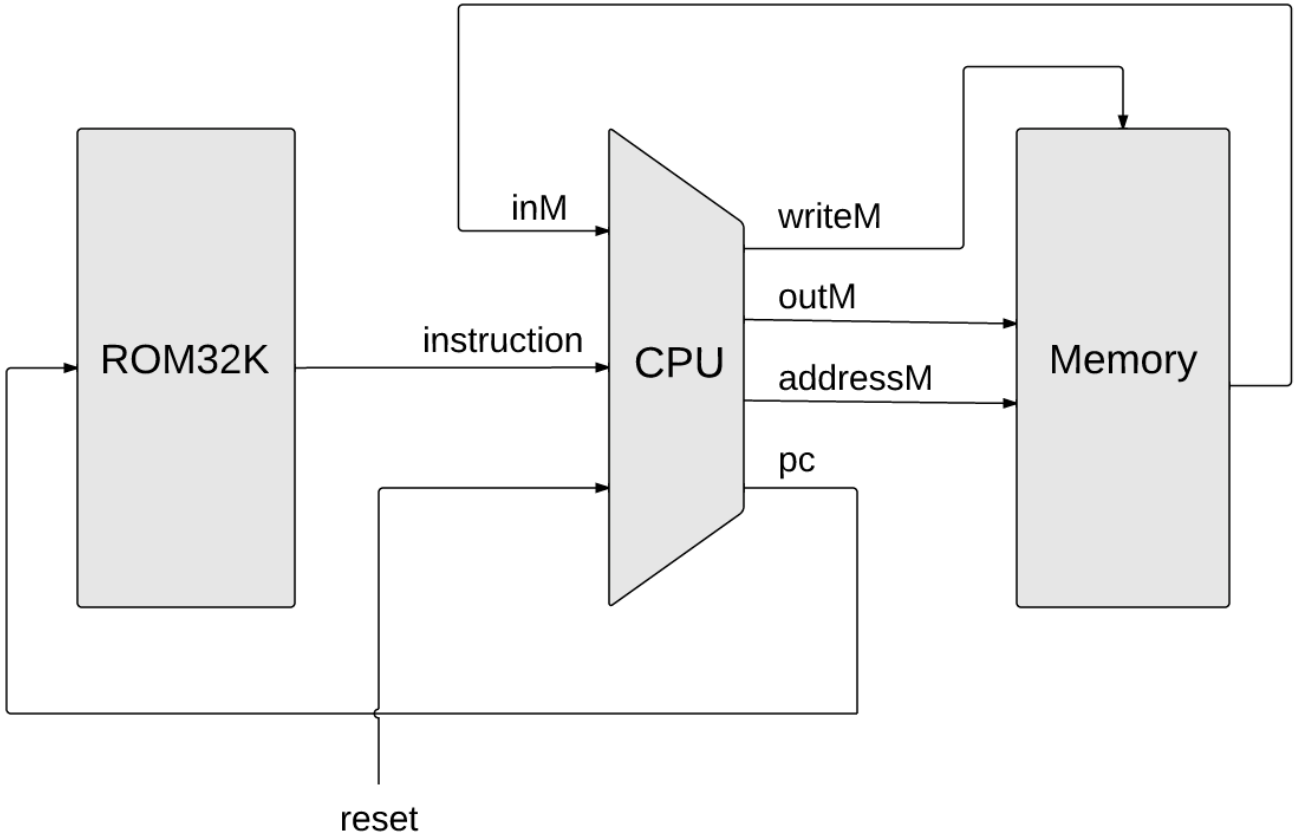
Hack Computer implementation



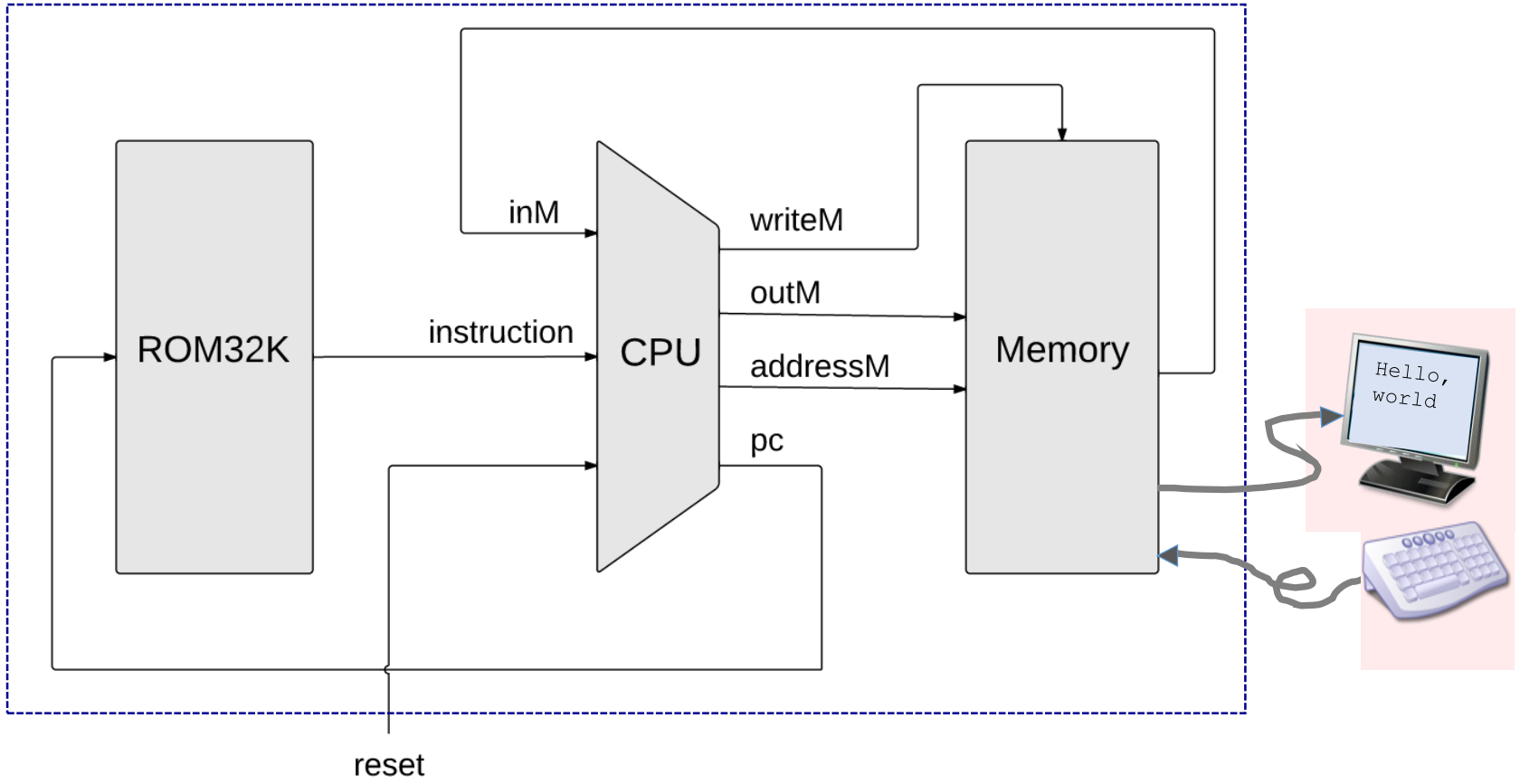
Hack Computer implementation



Hack Computer implementation

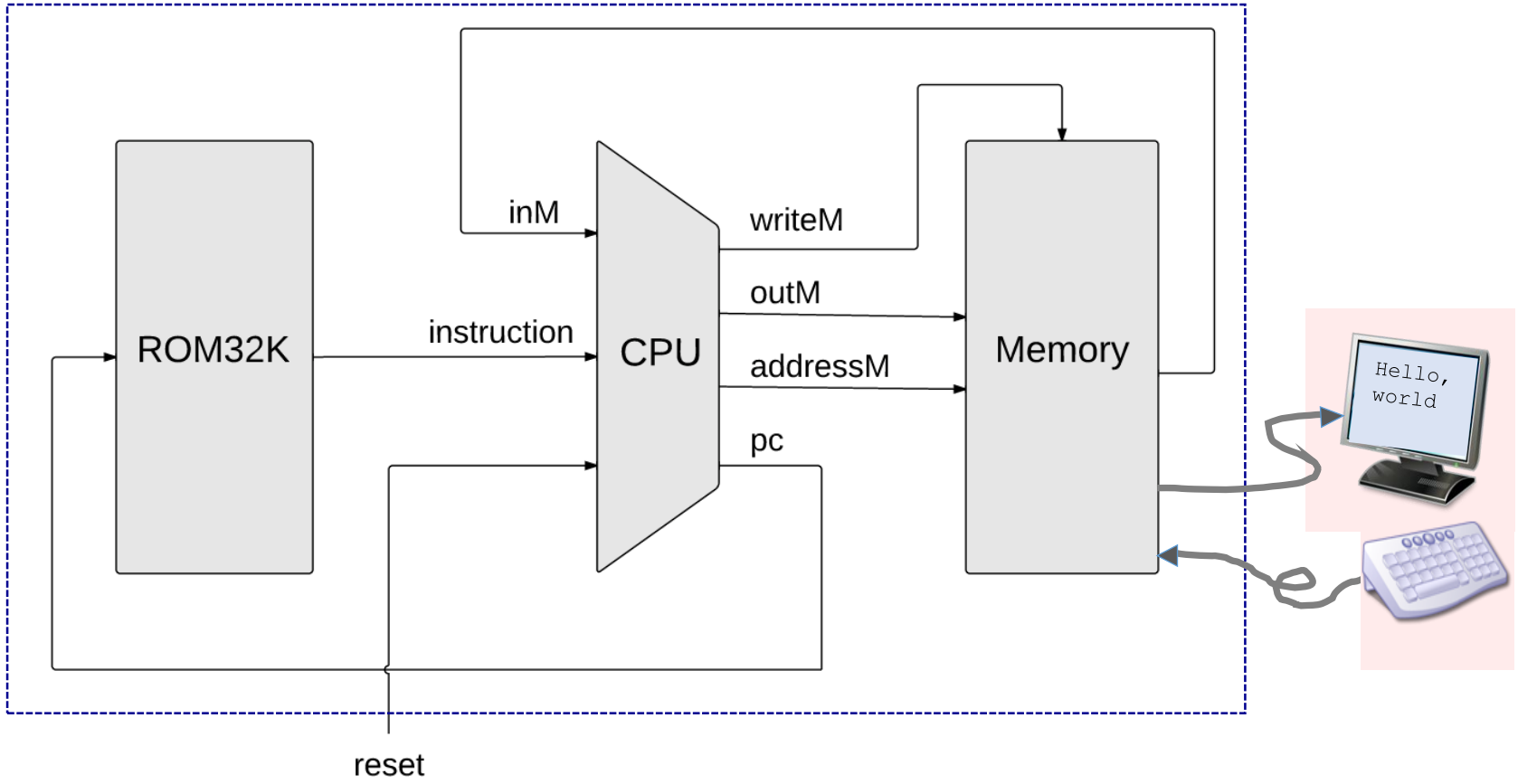


Hack Computer implementation



That's it!

Hack Computer implementation



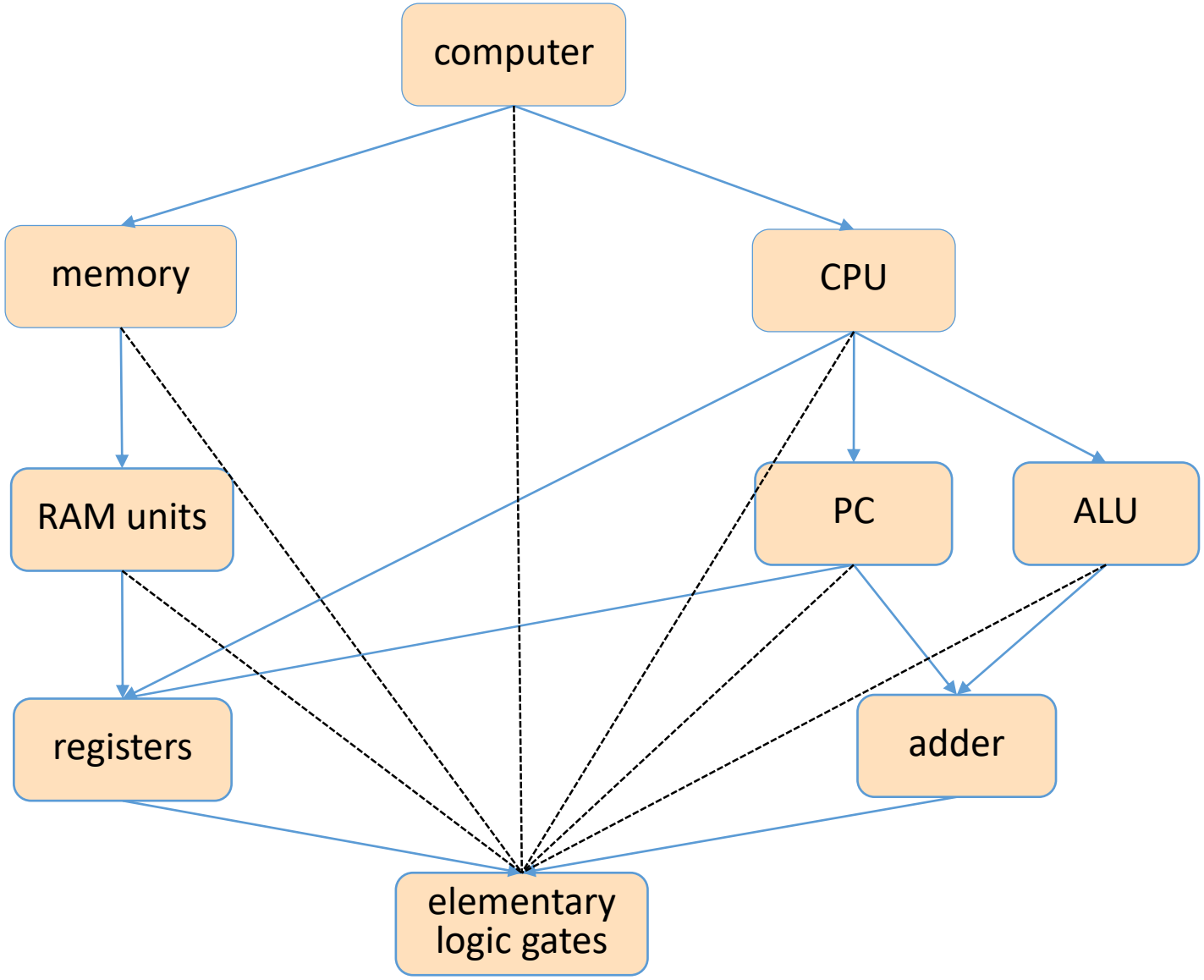
"*We ascribe beauty to that which is simple; which has no superfluous parts; which exactly answers its end; which stands related to all things; which is the mean of many extremes.*"

-- Ralph Waldo Emerson

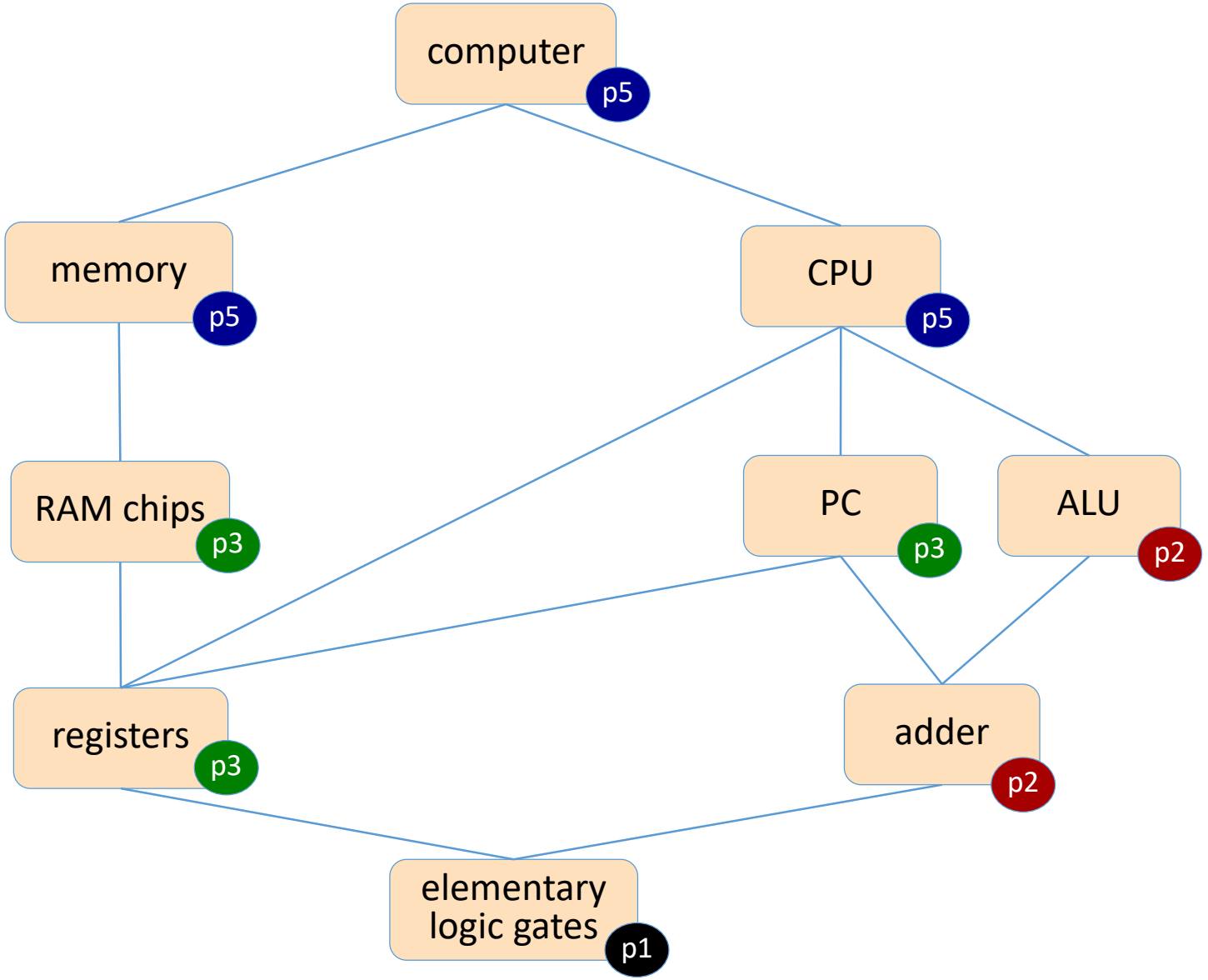
Computer Architecture: lecture plan

- ✓ Von Neumann Architecture
- ✓ Fetch-Execute Cycle
- ✓ The Hack CPU
- ✓ The Hack Computer
- ➡ Project 5 Overview

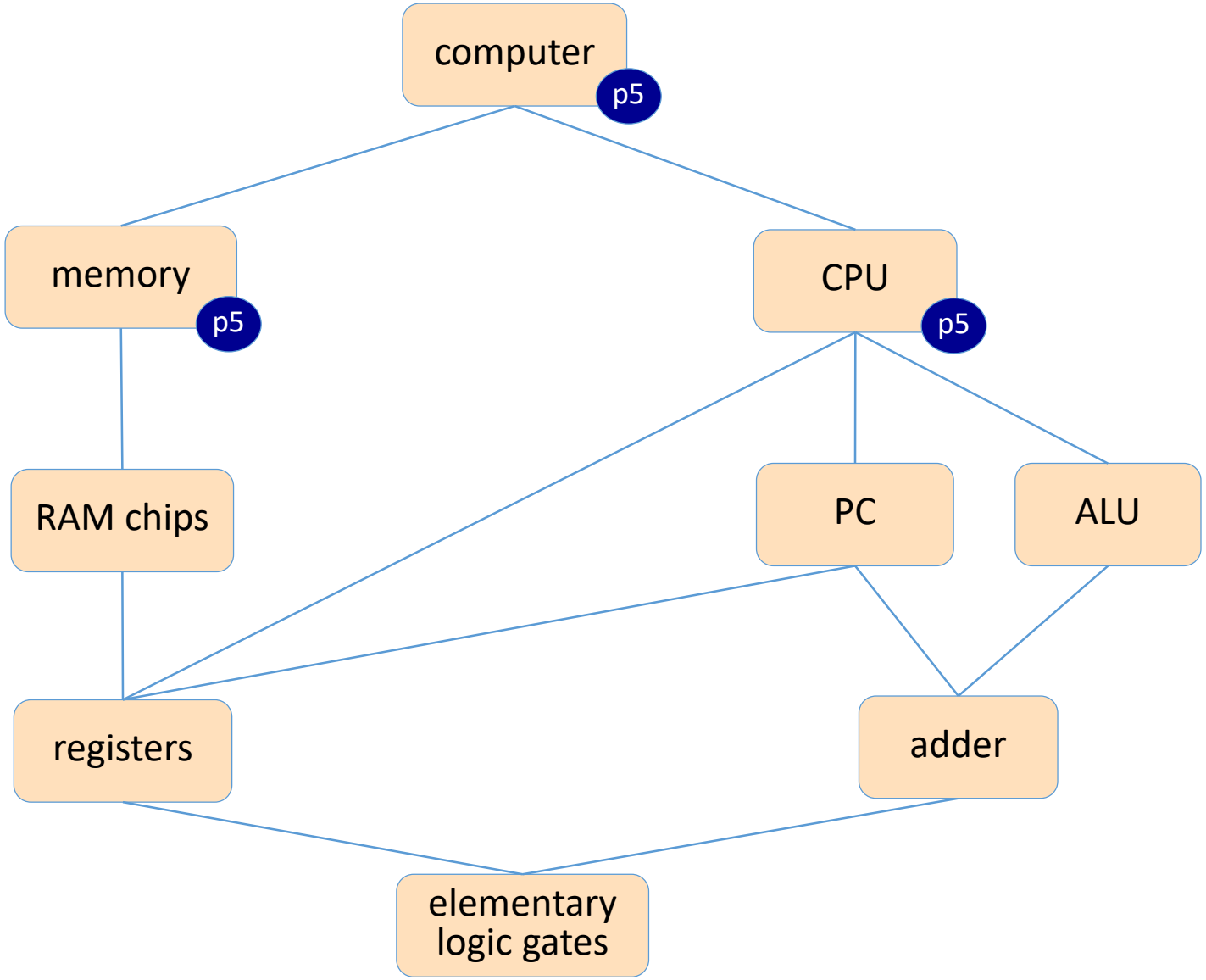
Hardware organization: a hierarchy of chip parts



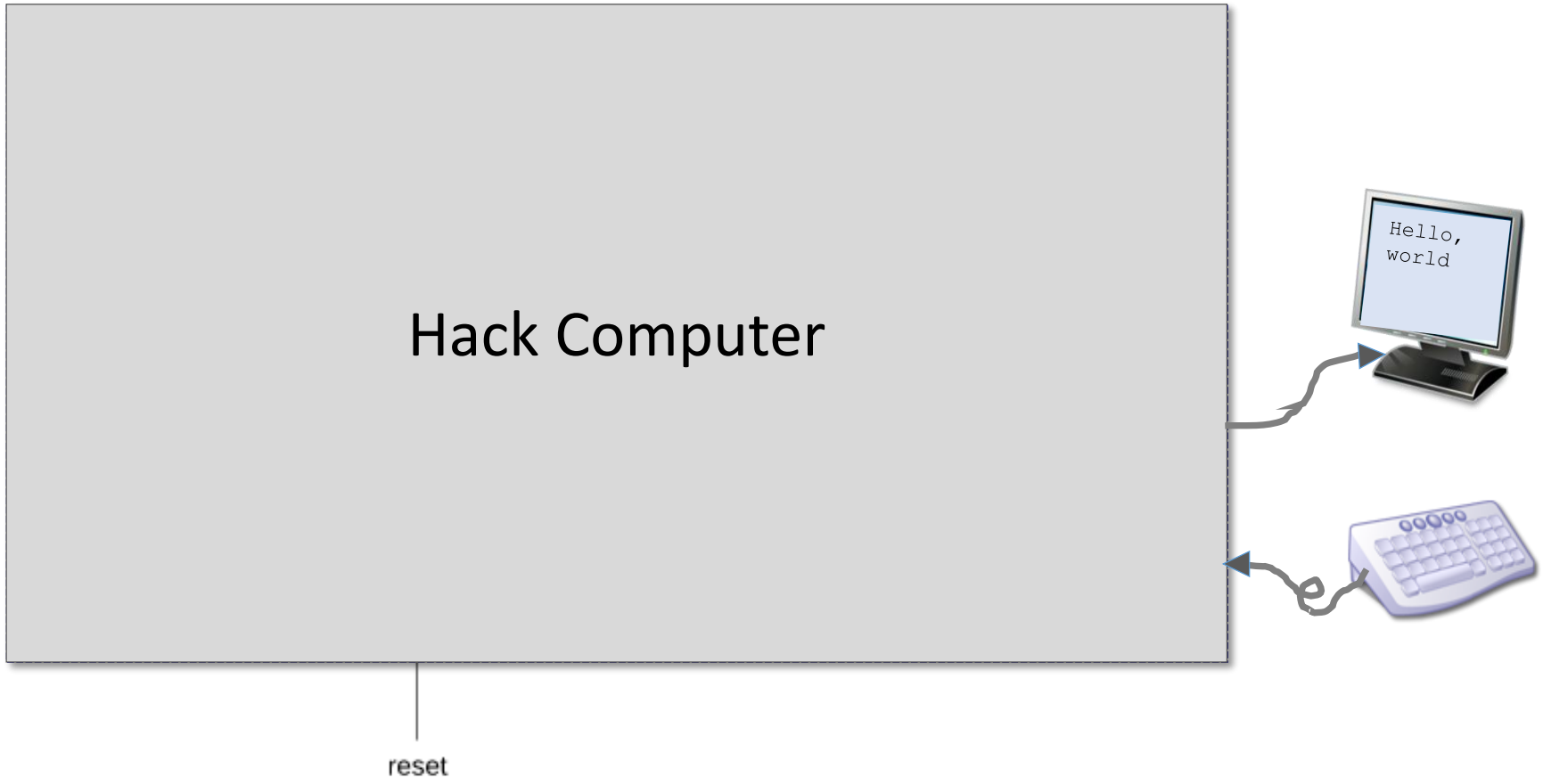
Hardware projects



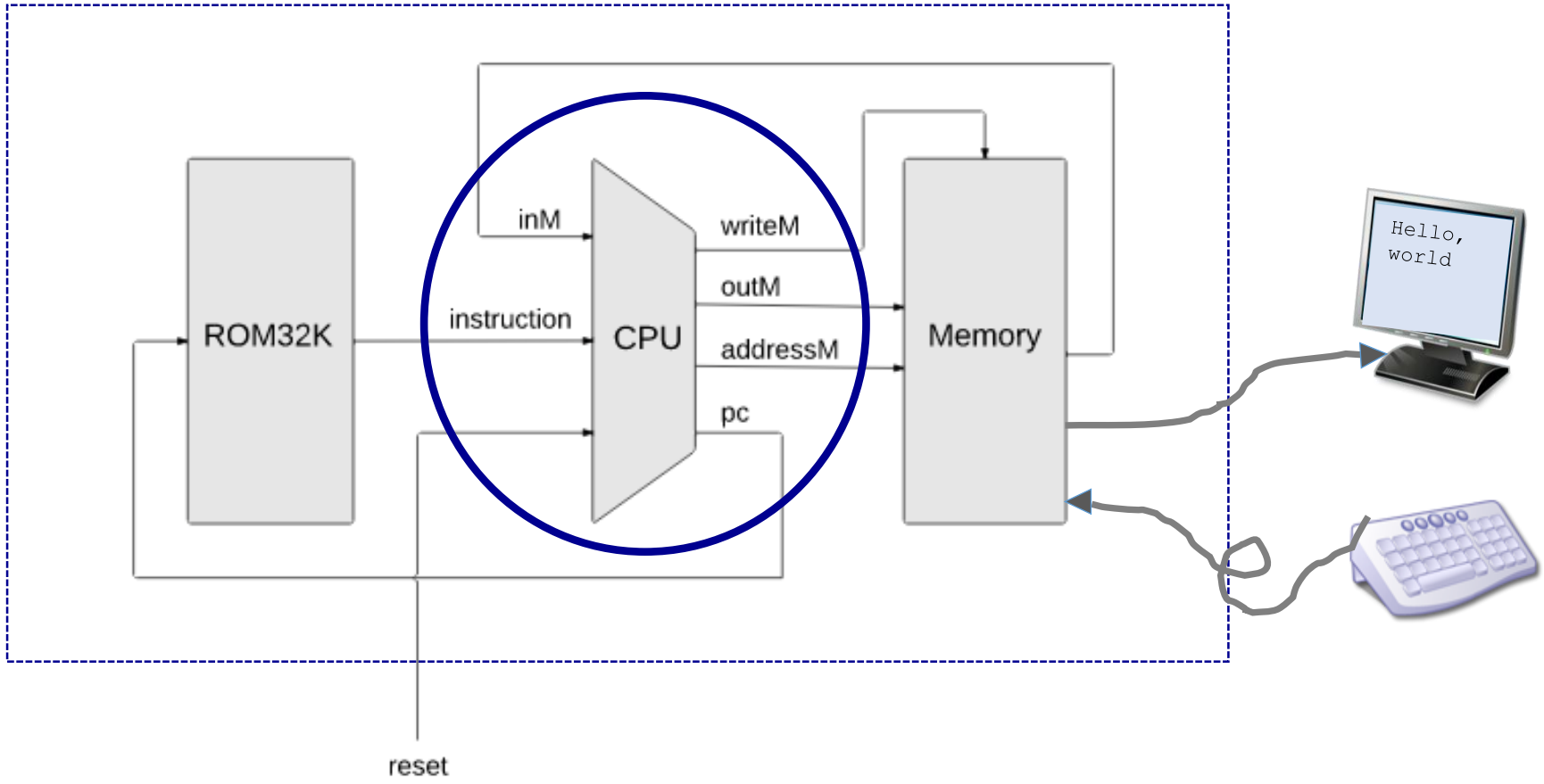
Project 5: building the Hack Computer



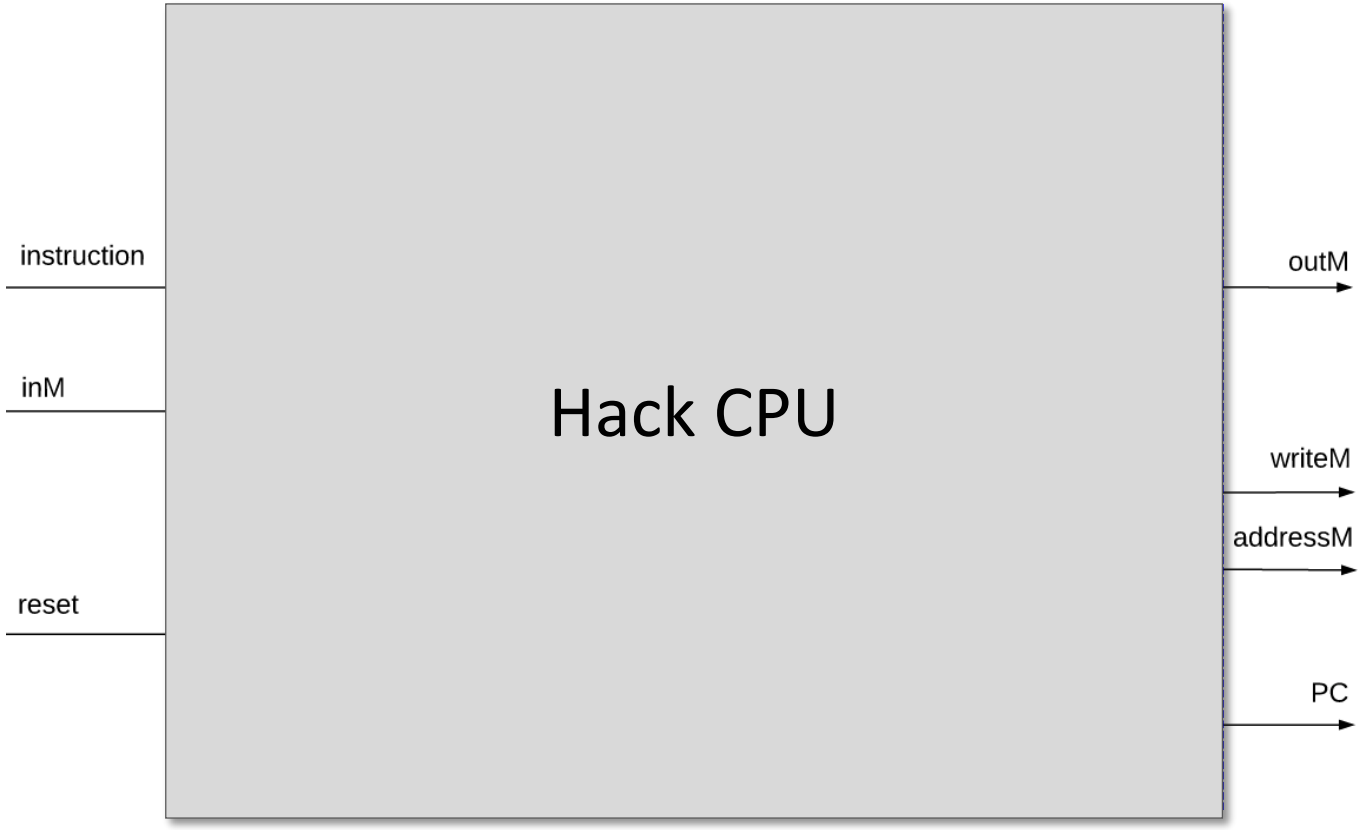
Abstraction



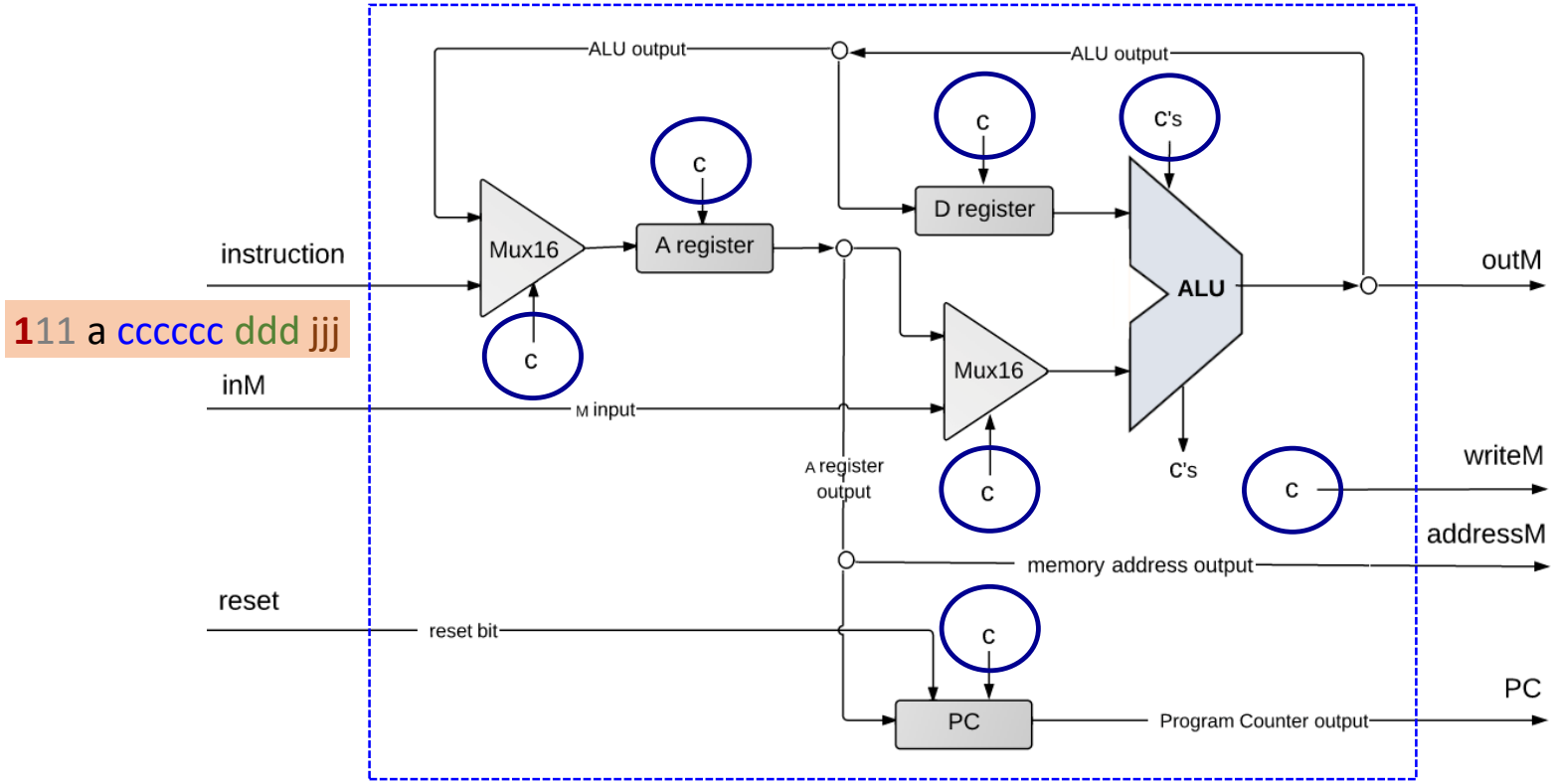
Implementation



CPU Abstraction



CPU Implementation



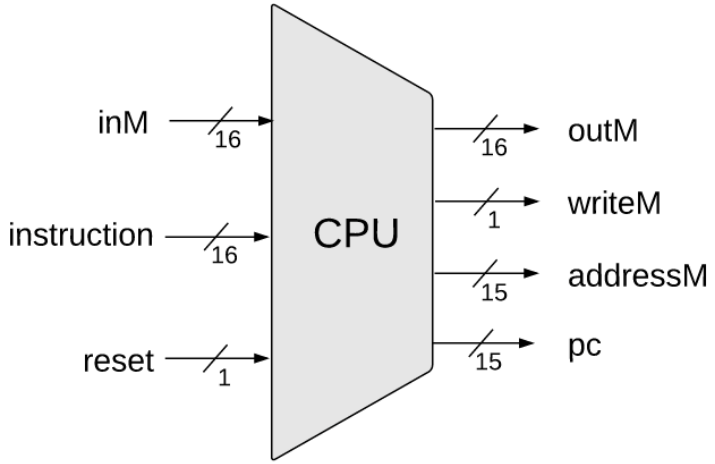
Implementation tips:

- Chip-parts: `Mux16`, `ARegister`, `DRegister`, `PC`, `ALU`, `...`
- Control: use HDL subscripting to parse and route the instruction bits to the control bits of the relevant chip-parts.

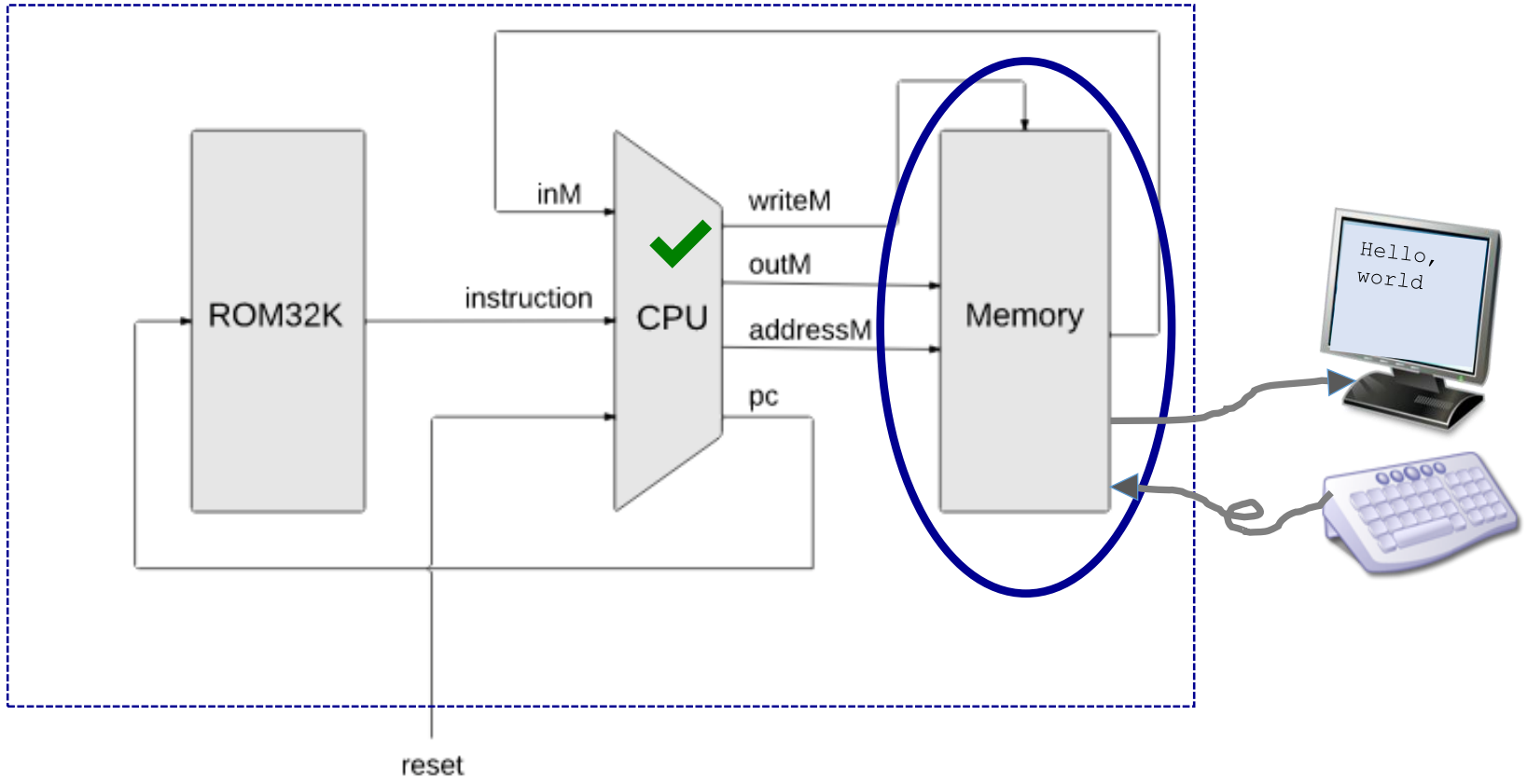
CPU Implementation

CPU.hdl

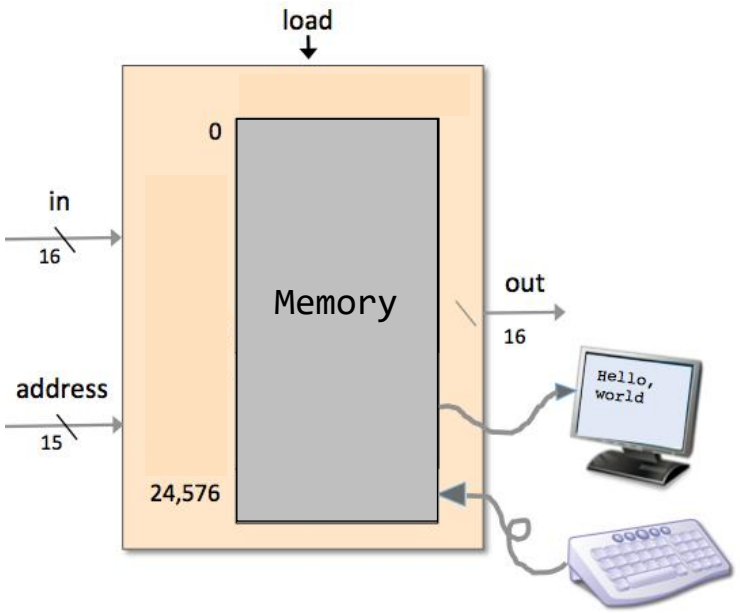
```
/**
 * The Central Processing unit (CPU).
 * Consists of an ALU and a set of registers,
 * designed to fetch and execute instructions
 * written in the Hack machine language.
*/
CHIP CPU {

   IN
      inM[16],         // value of M = RAM[A]
      instruction[16], // Instruction for execution
      reset;           // Signals whether to re-start the current program
                       // (reset == 1) or continue executing the current
                       // program (reset == 0).

    OUT
       outM[16]        // value to write into M = RAM[A]
       writeM,         // Write into M?
       addressM[15],   // RAM address (of M)
       pc[15];         // ROM address (of next instruction)

    PARTS:
    // Put you code here:
}
```



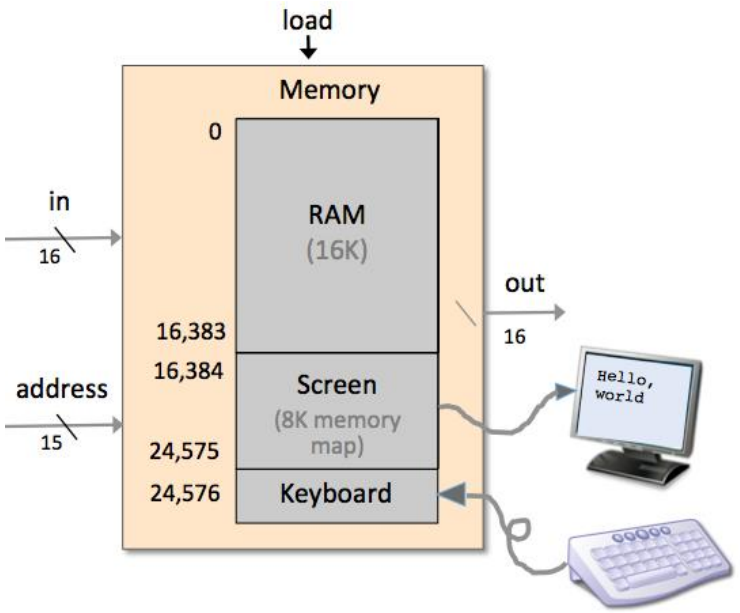
Hack Computer implementation



Memory implementation



Memory implementation




```
/** Memory of 16K 16-bit registers */
CHIP RAM16K {
  IN
    address[14],
```

built in project 3

```
/** Memory of 8K 16-bit registers
 *  with a display unit side effect. */
CHIP Screen {
  IN
    address[13],
    in[16],
    load;
  OUT
    out[16];

    BUILTIN
    CLOCKED
}
```

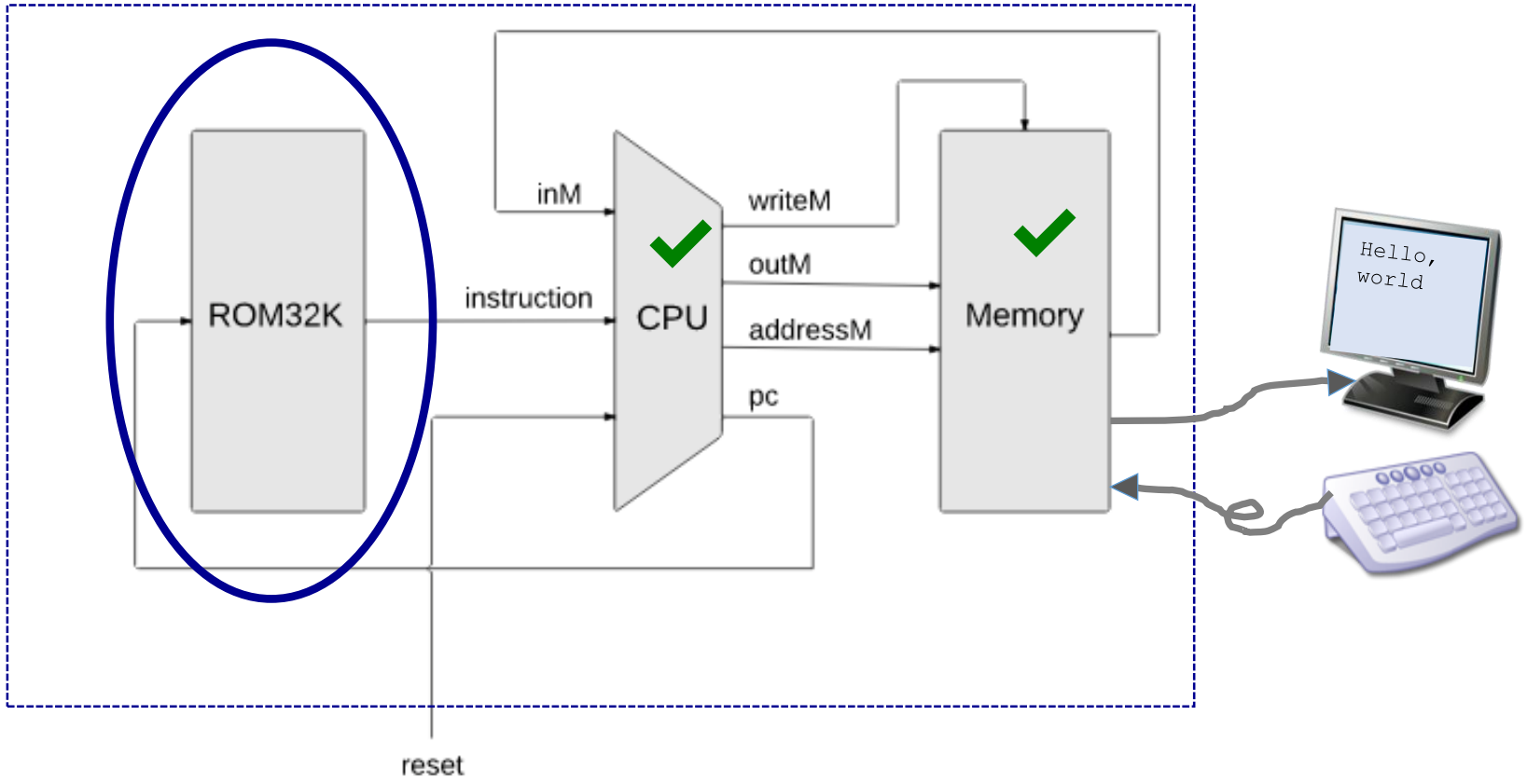
built-in chips

```
/** 16-bit register with a
*  keyboard input side effect */
CHIP Keyboard {
  OUT
    out[16];

    BUILTIN Keyboard;
}
```

Implementation tips:

- Use the three chip-parts: `RAM16K`, `Screen`, and `Keyboard`
- Route the `address` input to the correct `address` input of the relevant chip-part.

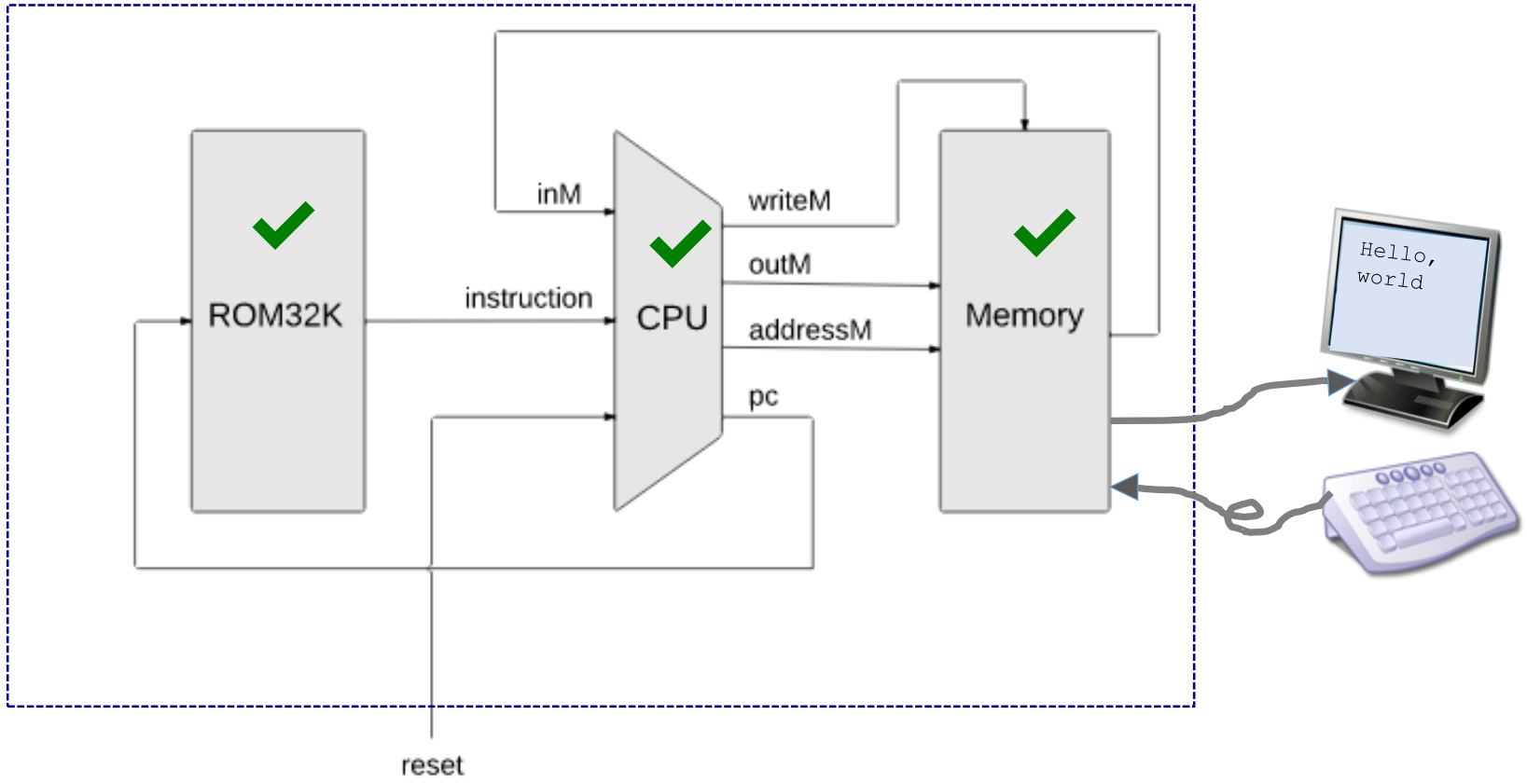
Hack Computer implementation



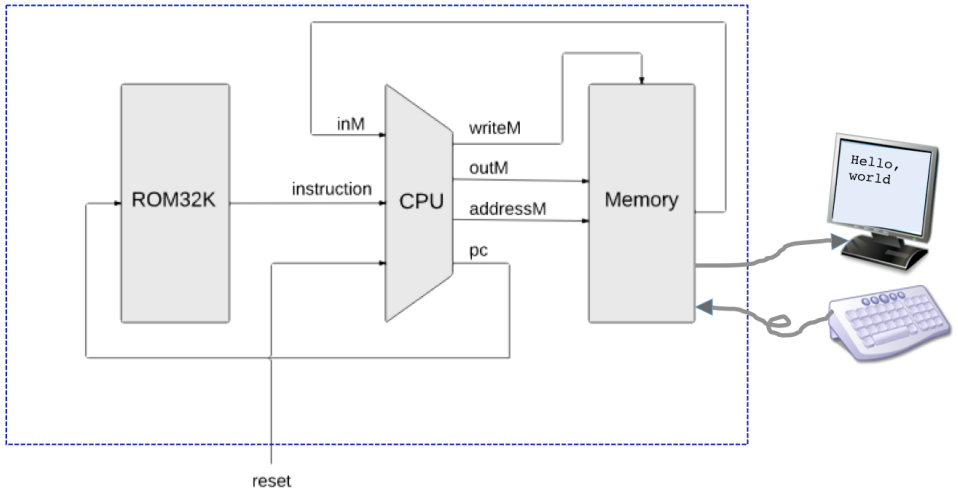
Implementation tip:

Use the built-in `ROM32K` chip.

Hack Computer implementation



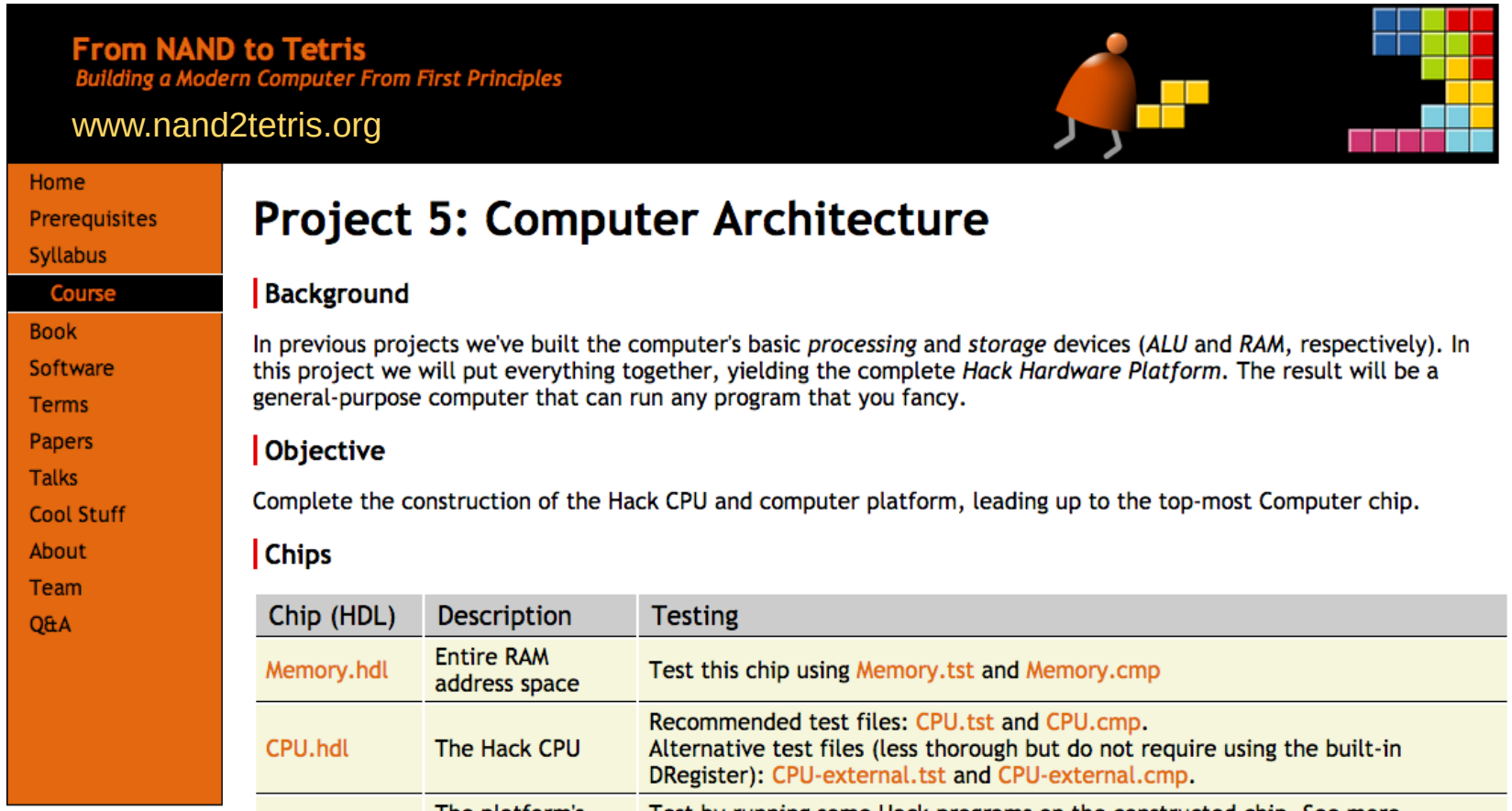
Hack Computer implementation



Computer.hdl

```
/**
 * The HACK computer, including CPU, ROM and RAM.
 * When reset is 0, the program stored in the computer's ROM executes.
 * When reset is 1, the execution of the program restarts.
*/

CHIP Computer {

    IN reset;

    PARTS:
    // Put your code here.
}
```

Project 5 resources



From NAND to Tetris
Building a Modern Computer From First Principles
www.nand2tetris.org

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Project 5: Computer Architecture

Background

In previous projects we've built the computer's basic *processing* and *storage* devices (*ALU* and *RAM*, respectively). In this project we will put everything together, yielding the complete *Hack Hardware Platform*. The result will be a general-purpose computer that can run any program that you fancy.

Objective

Complete the construction of the Hack CPU and computer platform, leading up to the top-most Computer chip.

Chips

Chip (HDL)	Description	Testing
Memory.hdl	Entire RAM address space	Test this chip using Memory.tst and Memory.cmp
CPU.hdl	The Hack CPU	Recommended test files: CPU.tst and CPU.cmp. Alternative test files (less thorough but do not require using the built-in DRegister): CPU-external.tst and CPU-external.cmp.
Computer.hdl	The platform's top-most chip	Test by running some Hack programs on the constructed chip. See more instructions below.

All the necessary project 5 files are available in:

`nand2tetris / projects / 05`

More resources

- HDL Survival Guide
- Hardware Simulator Tutorial
- nand2tetris Q&A forum

All available in: `www.nand2tetris.org`

Best practice advice

- Try to implement the chips in the given order
- Strive to use as few chip-parts as possible
- You will have to use chips that you've implemented in previous projects
- The best practice is to use their built-in versions.

Computer Architecture: lecture plan

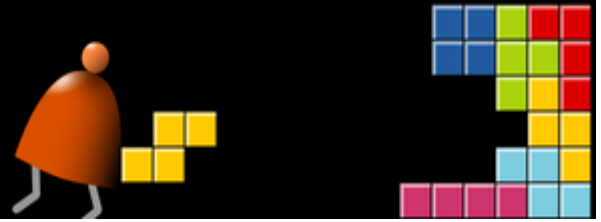

Von Neumann Architecture


Fetch-Execute Cycle


The Hack CPU


The Hack Computer


Project 5 Overview



Chapter 5

Computer Architecture

These slides support chapter 5 of the book

The Elements of Computing Systems

By Noam Nisan and Shimon Schocken

MIT Press