Chapter 4

Machine Language

These slides support chapter 4 of the book

The Elements of Computing Systems

By Noam Nisan and Shimon Schocken

MIT Press

Machine Language: lecture plan

- Machine languages
- Basic elements
- The Hack computer and machine language
- The Hack language specification
- Input / Output
- Hack programming
- Project 4 overview

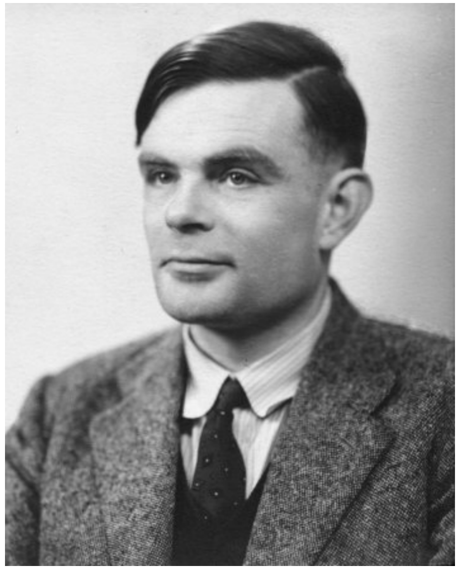
Computers are flexible

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

Universality

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

Theory



Alan Turing:

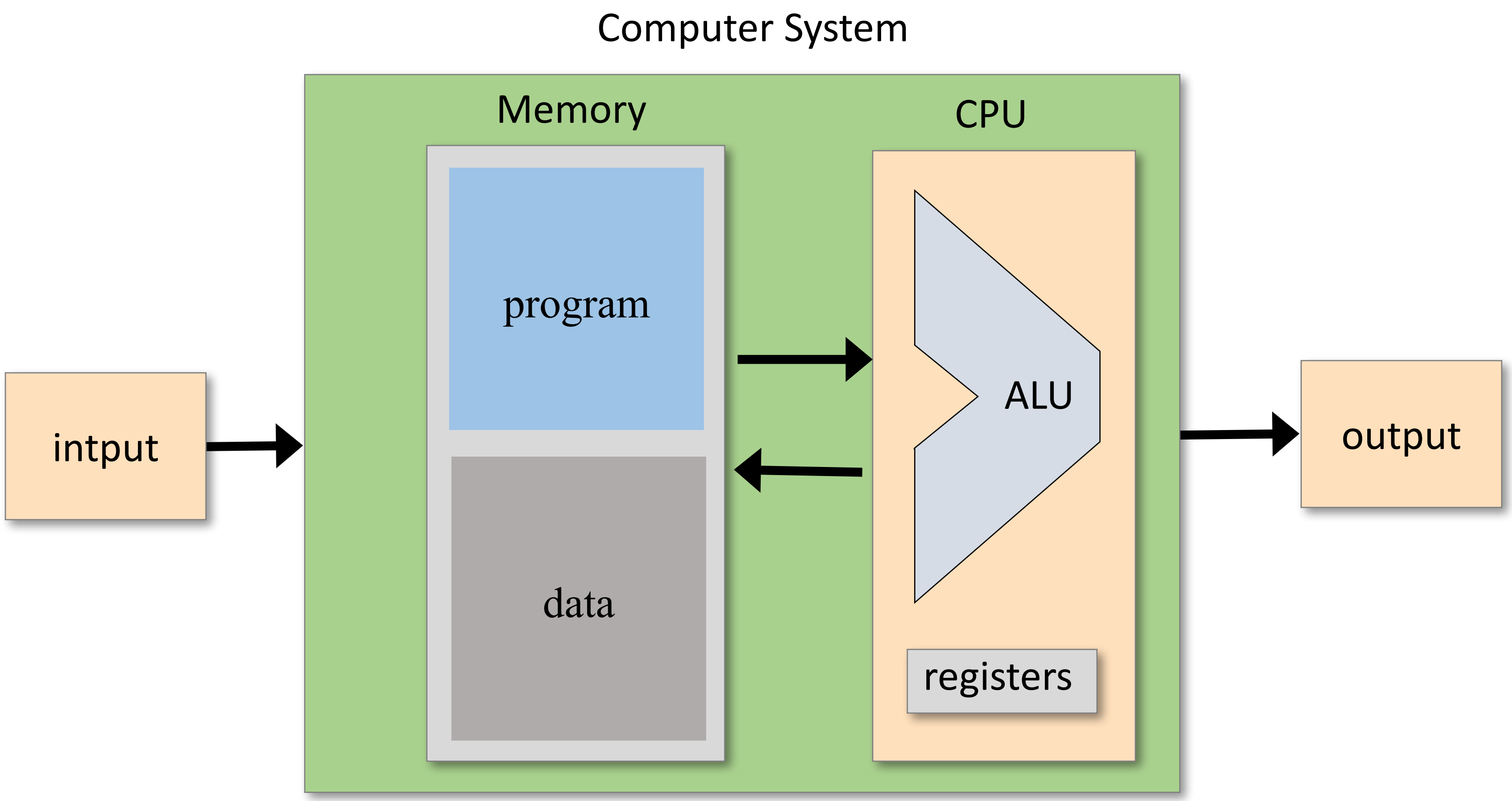
Universal Turing Machine

Practice

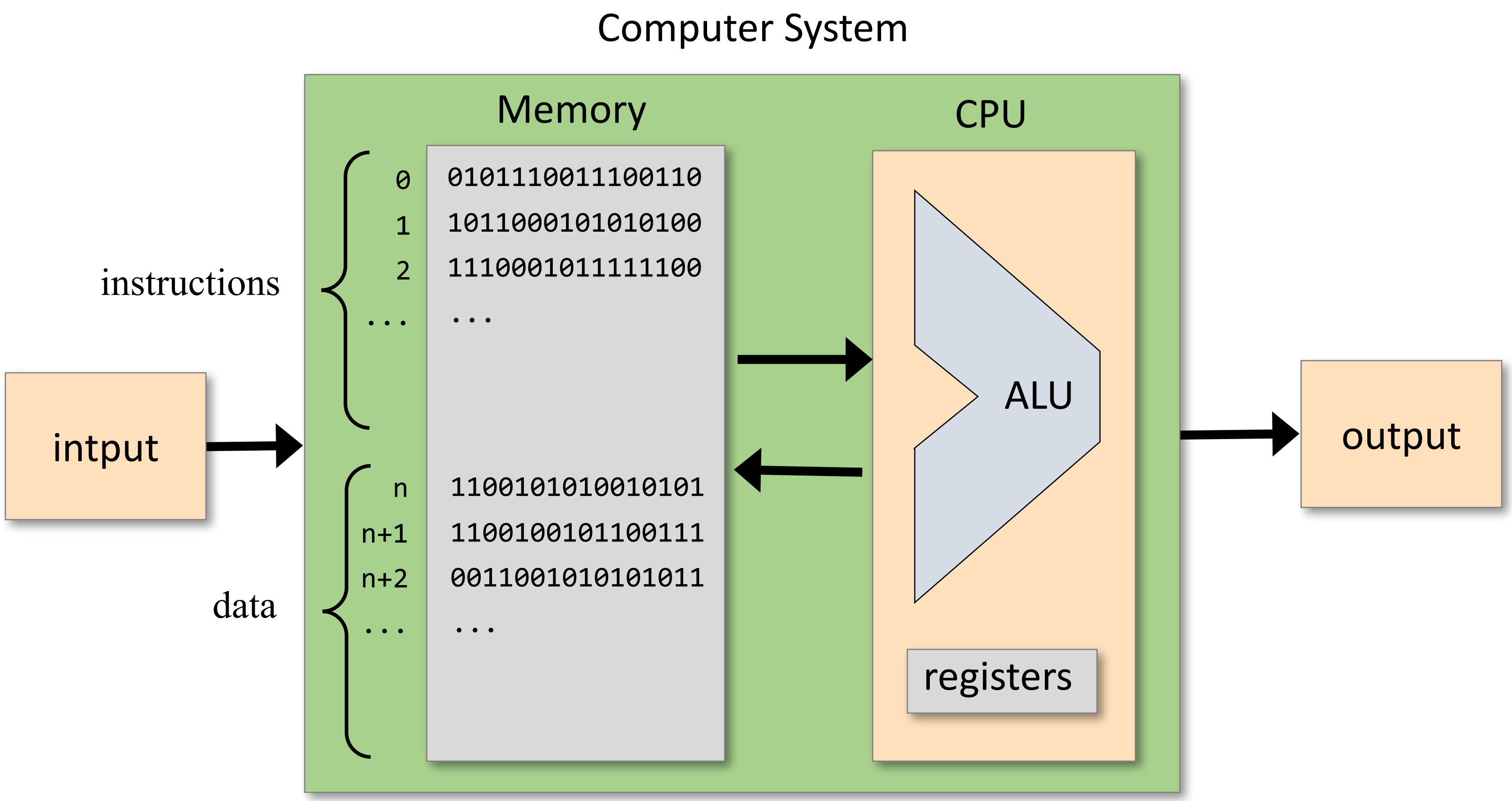
John Von Nuemann:

Stored Program Computer

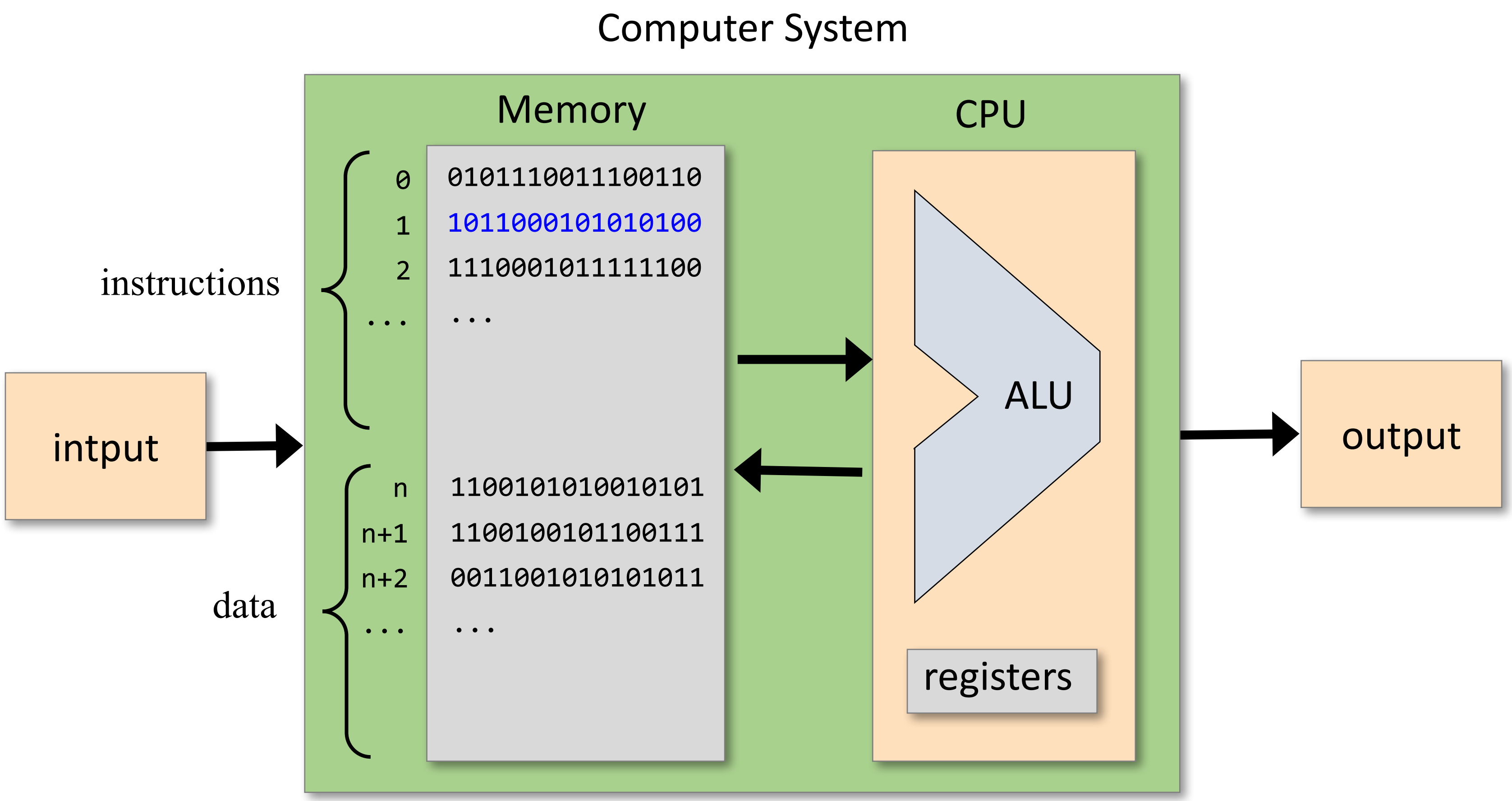
Stored program concept



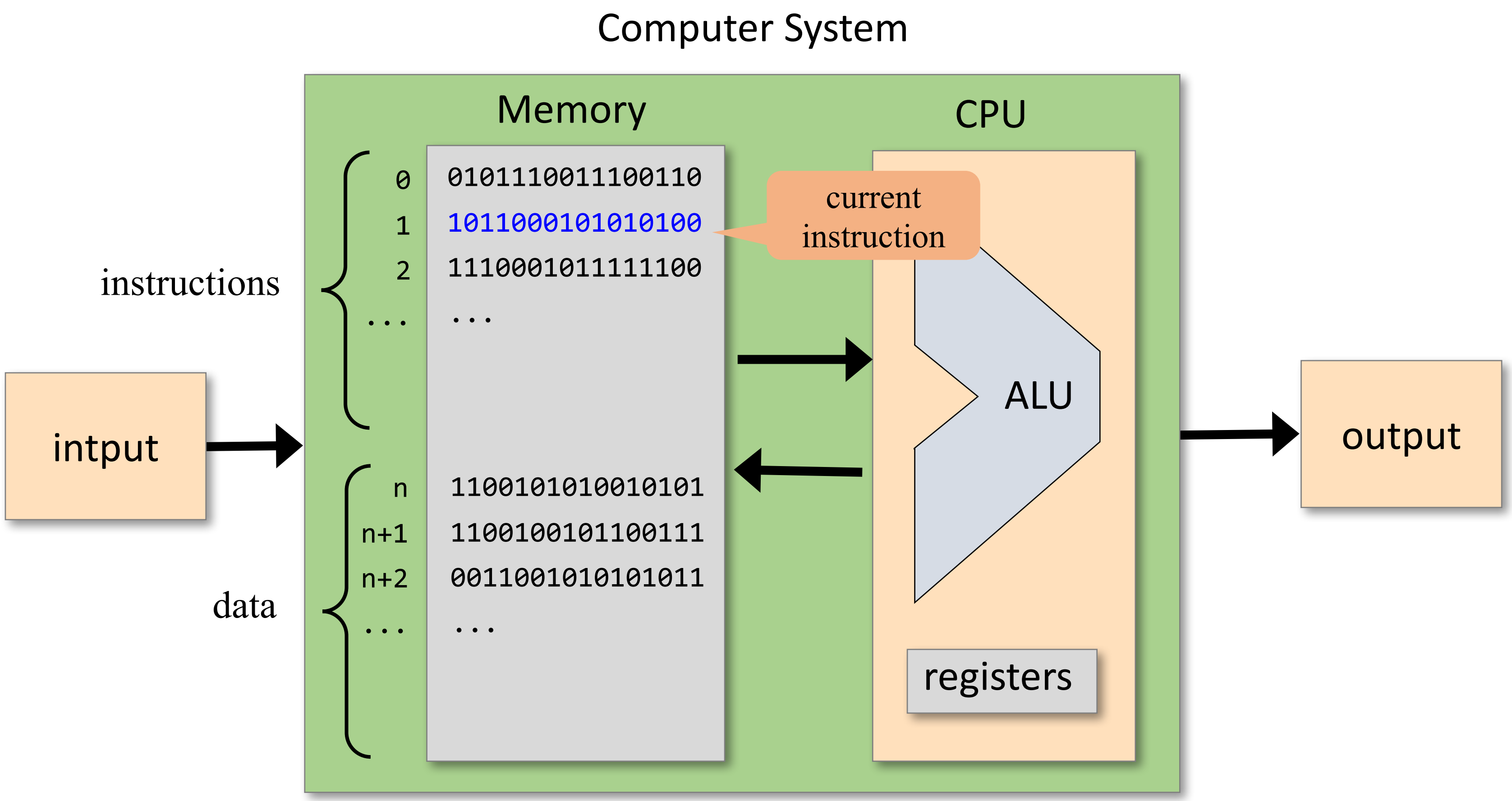
Stored program concept



Machine language



Machine language



Handling instructions:

- `1011` means "addition" — operation
- `000101010100` means "operate on memory address 340" — addressing
- Next we have to execute the instruction at address 2 — control

Compilation

high-level program

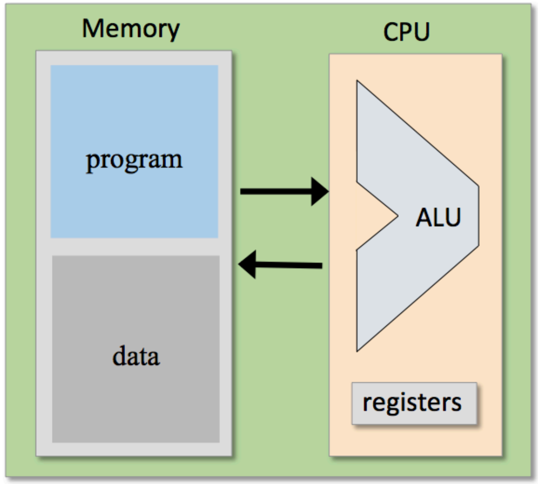
```
while (n < 100) {
    sum += arr[i];
    n++
}
```

compile

machine language

```
0101111100111100
1010101010101010
1101011010101010
1001101010010101
1101010010101010
1110010100100100
0011001010010101
1100100111000100
1100011001100101
0010111001010101
...
```

load and execute



Mnemonics

Instruction:

`1011` `000011` `000010`

add R3 R2

sample instruction

Interpretation 1:

- The symbolic form `add R3 R2` doesn't really exist
- It is just a convenient mnemonic that can be used to present machine language instructions to humans

Mnemonics

Instruction:

1011	000011	000010
add	R3	R2

sample instruction

Interpretation 2:

- Allow humans to write symbolic machine language instructions, using *assembly language*
- Use an *assembler* program to translate the symbolic code into binary form.

Symbols

Instruction:

`1011 0001 10000001`

add 1 Mem[129]

Assembly:

```
add 1, Mem[129]
```

```
add 1, index
```

Friendlier syntax:
we assume that `index`
stands for `Mem[129]`

The assembler will resolve the symbol `index` into a specific address.

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Machine language

- Specification of the hardware/software interface:
  - What supported operations?
  - What do they operate on?
  - How is the program controlled?

- Usually in close correspondence to the hardware architecture
  - But not necessarily so

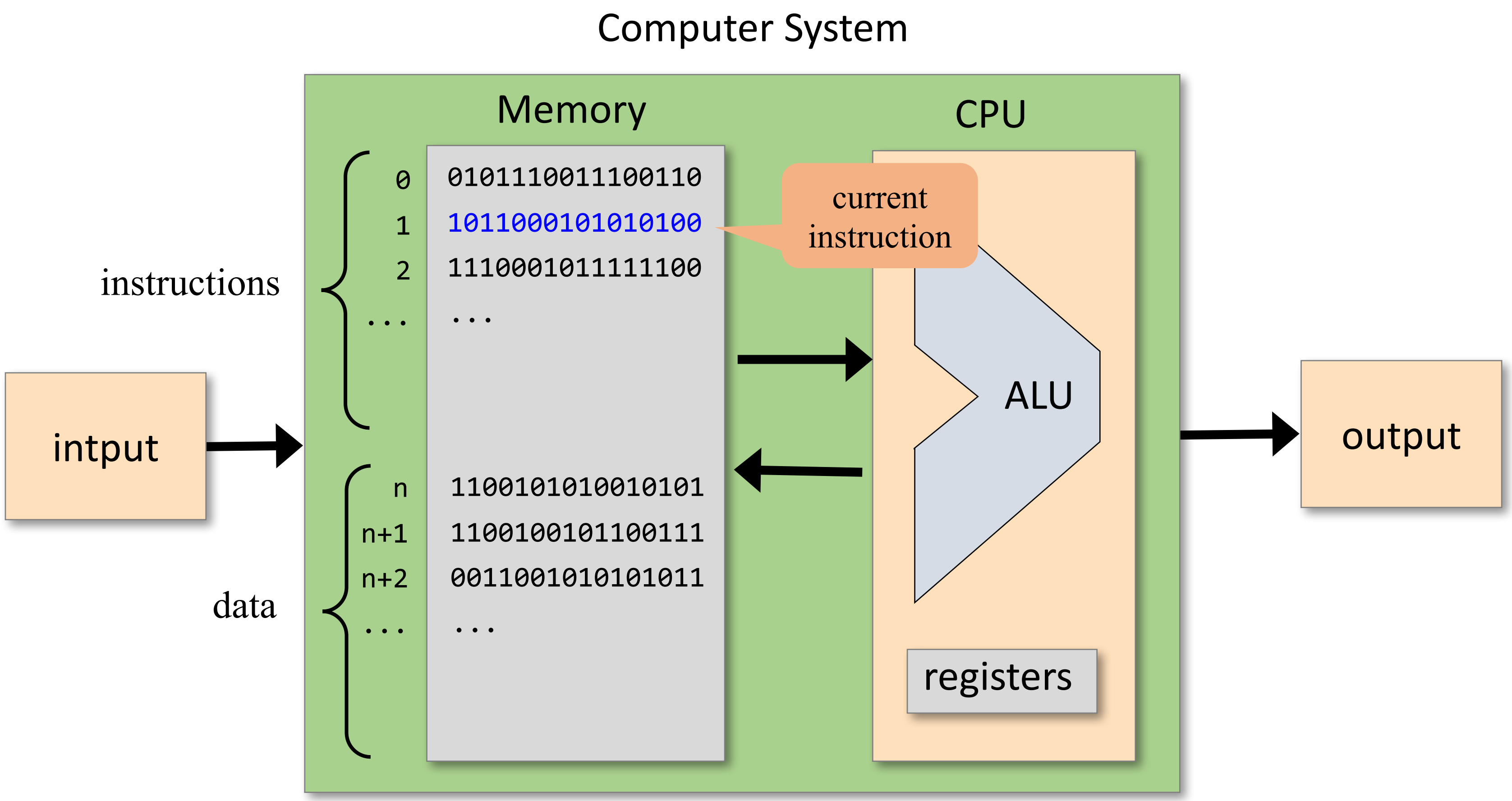
- Cost-performance tradeoffs:
  - Silicon area
  - Time to complete instruction.

Machine operations

- Usually correspond to the operations that the hardware is designed to support:
  - Arithmetic operations: add, subtract, …
  - Logical operations: and, or, …
  - Flow control: “goto instruction *n*”
    “if (condition) then goto instruction *n*”

- Differences between machine languages:
  - Instruction set richness (division? bulk copy? …)
  - Data types (word width, floating point…).

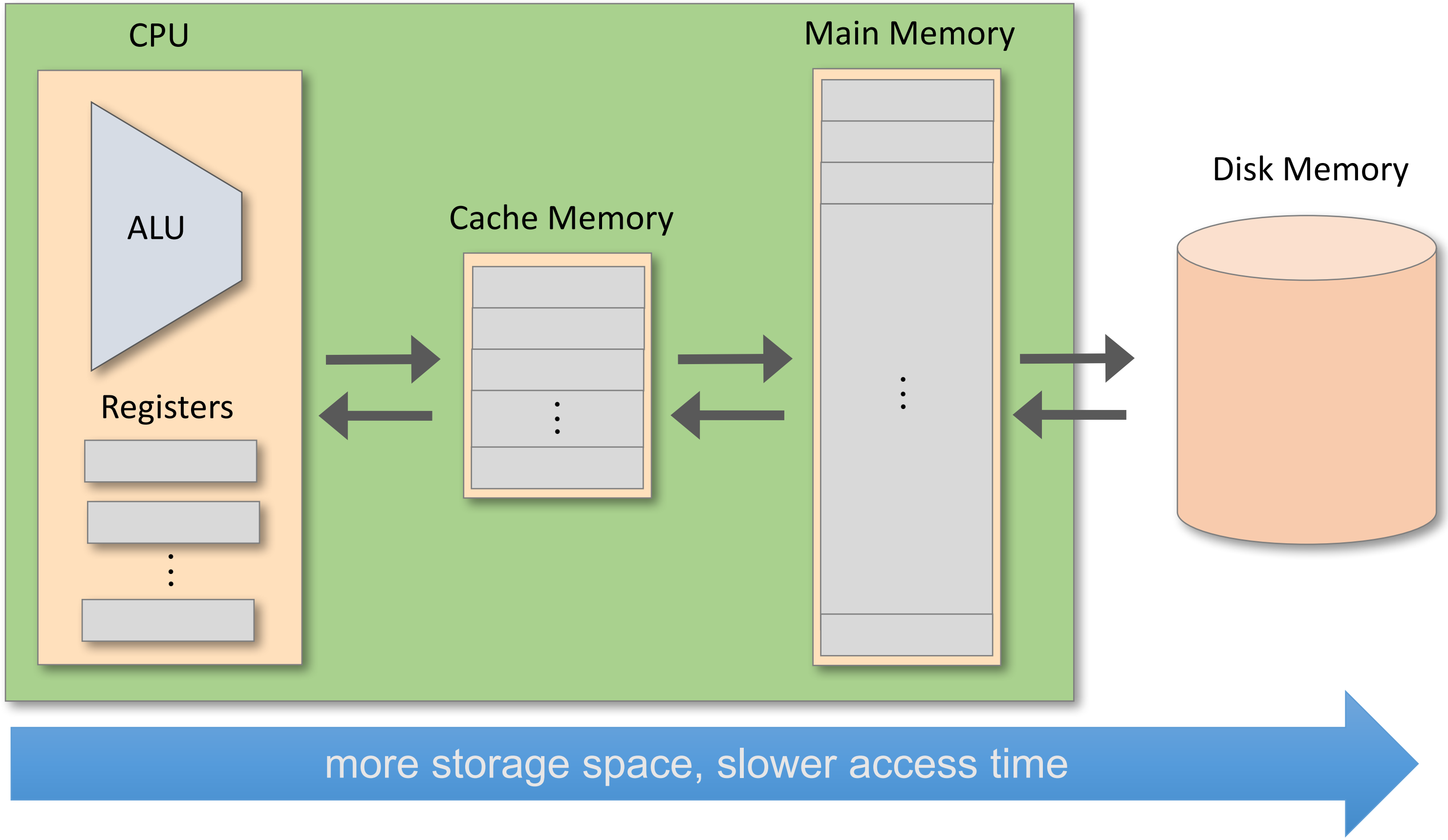
Addressing



How does the language allow us to specify on which data the instruction should operate?

Memory hierarchy

- Accessing a memory location is expensive:
  - Need to supply a long address
  - Getting the memory contents into the CPU takes time
- Solution: memory hierarchy:



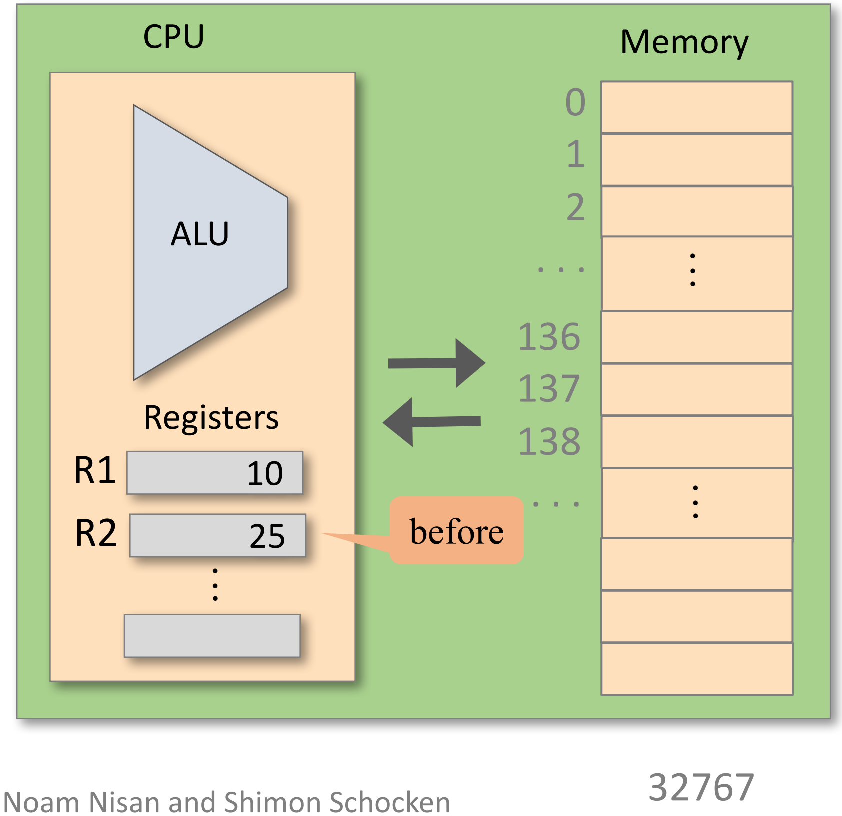
Registers

Registers

- The CPU typically contains a few, easily accessed, *registers*
- Their number and functions are a central part of the machine language

Data registers:

```
add R1, R2
```



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<u>Data registers:</u>

```
add R1, R2
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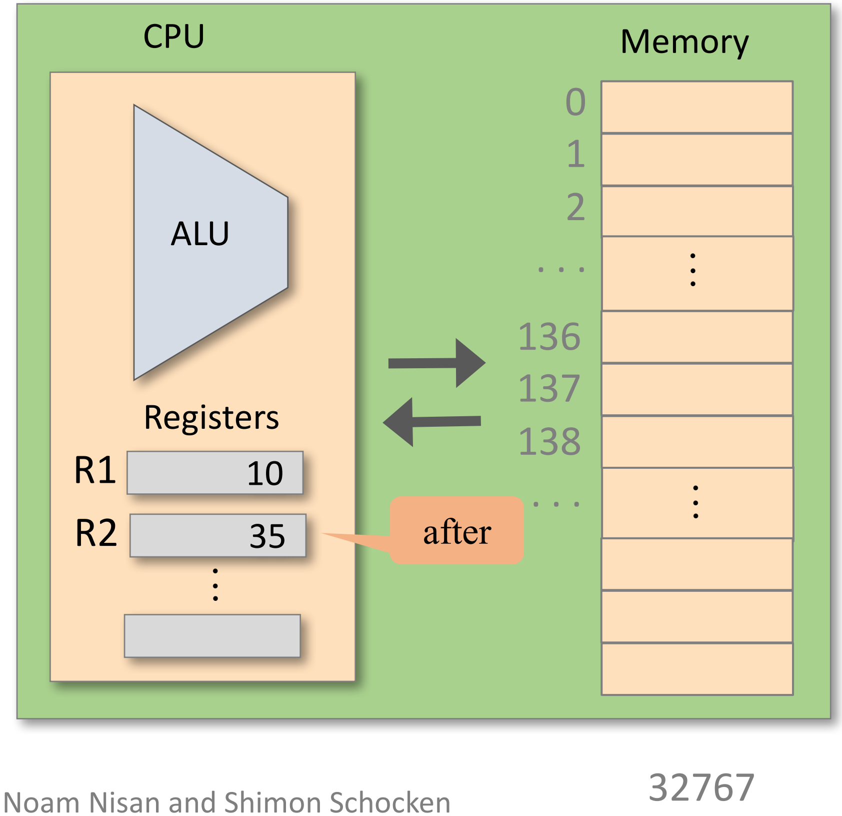


Registers

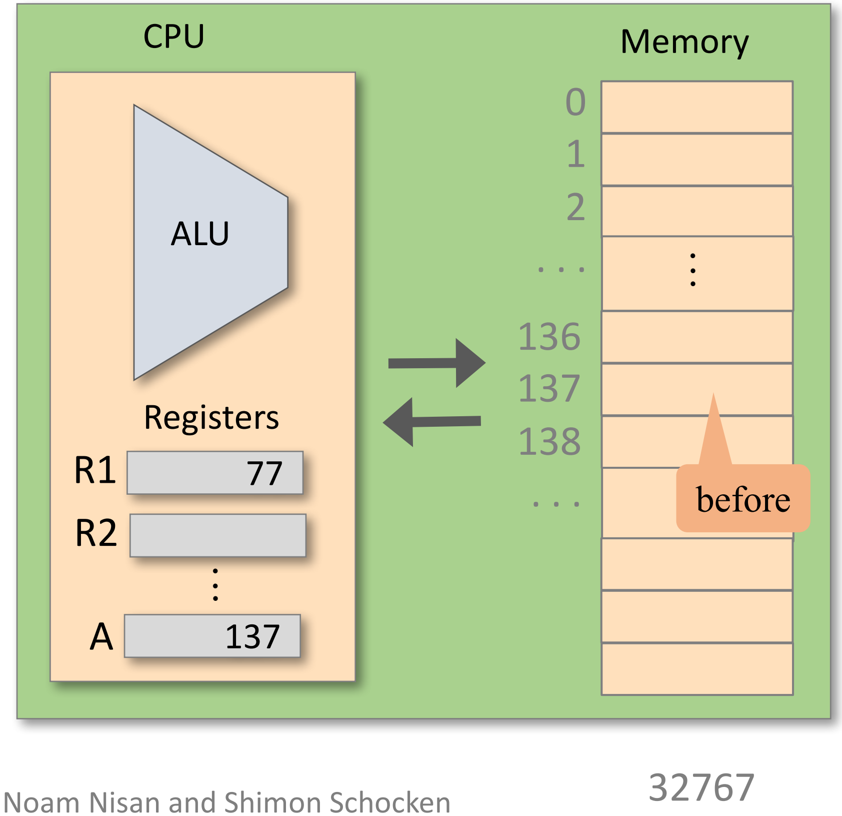
- The CPU typically contains a few, easily accessed, *registers*
- Their number and functions are a central part of the machine language

Data registers:

```
add R1, R2
```

Address registers:

```
store R1, @A
```



Registers

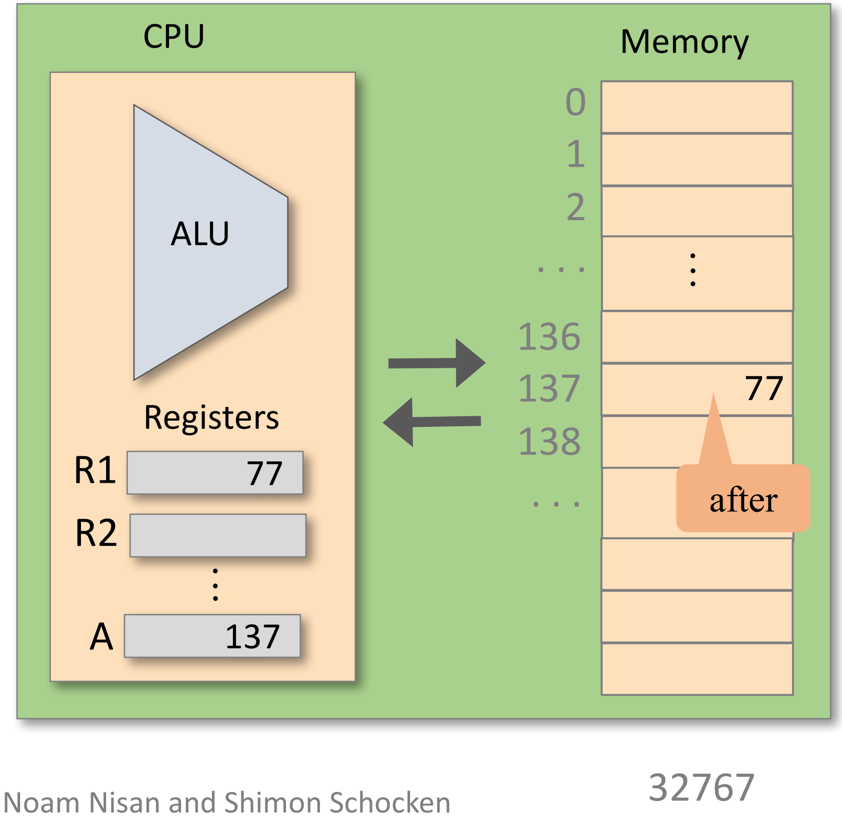
- The CPU typically contains a few, easily accessed, *registers*
- Their number and functions are a central part of the machine language

<u>Data registers:</u>

```
add R1, R2
```

<u>Address registers:</u>

```
store R1, @A
```



Addressing modes

Register

```
add R1, R2        // R2 ← R2 + R1
```

Direct

```
add R1, M[200]    // Mem[200] ← Mem[200] + R1
```

Indirect

```
add R1, @A        // Mem[A] ← Mem[A] + R1
```

Immediate

```
add 73, R1        // R1 ← R1 + 73
```

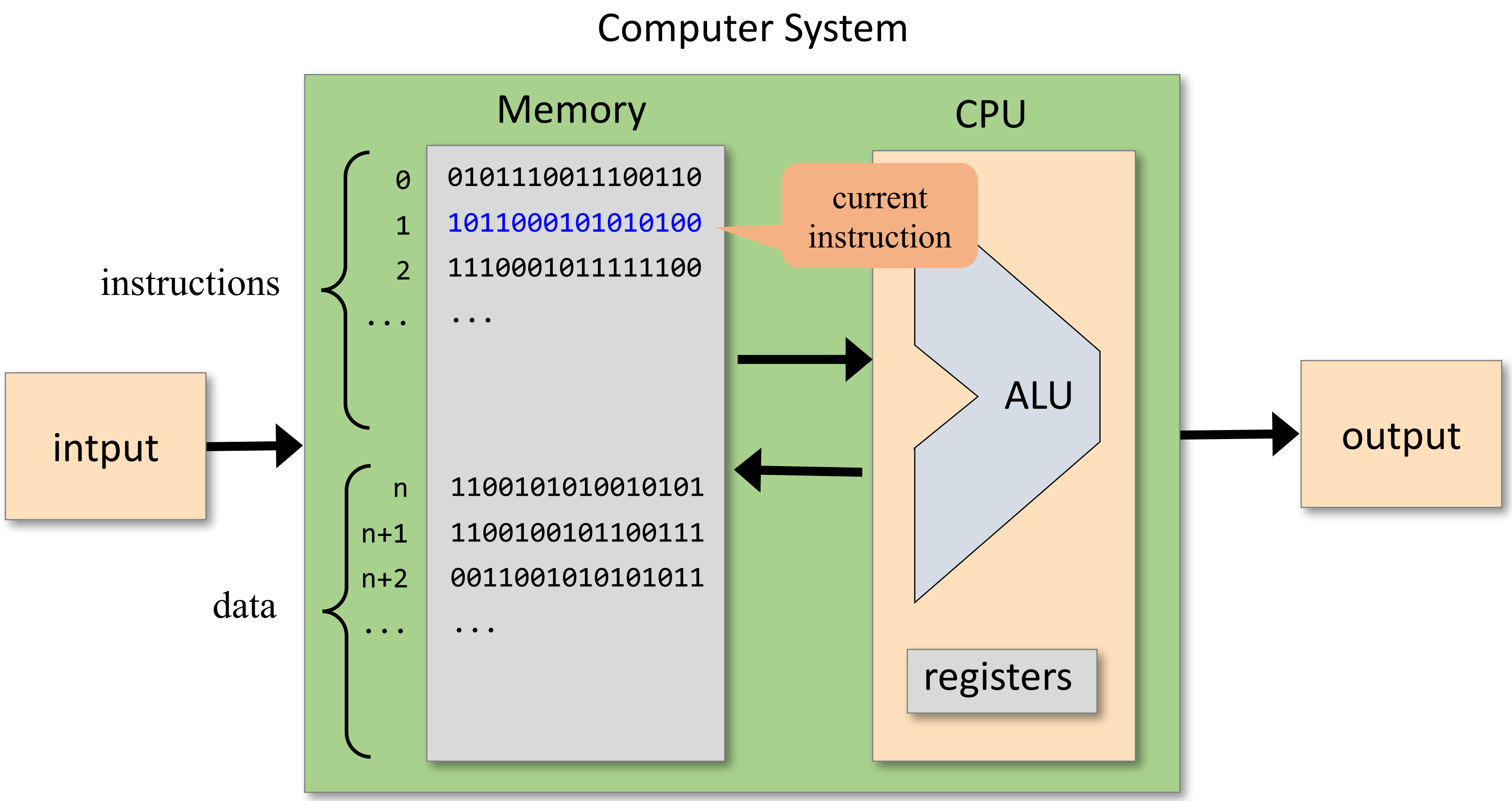
Input / Output

- Many types of input and output devices:
  - Keyboard, mouse, camera, sensors, printers, screen, sound…

- The CPU needs some agreed-upon protocol to talk to each of them
  - Software drivers realize these protocols

- One general method of interaction uses *memory mapping*:
  - Memory location 12345 holds the direction of the last movement of the mouse
  - Memory location 45678 tells the printer to print single-side or double side
  - Etc.

Flow control



How does the language allow us to decide, and specify, which instruction to process next?

Flow control

- Usually the CPU executes machine instructions in sequence

- Sometimes we need to “jump” unconditionally to another location, e.g. in order to implement a loop:

Example:

```
101:  load R1,0
102:  add 1, R1
103:  ...
...   // do something with R1 value
...   ...
156:  jmp 102   // goto 102
```

Symbolic version:

```
    load R1,0
LOOP:
    add 1, R1
    ...
    // do something with R1 value
    ...
    jmp LOOP  // goto loop
```

Flow control

- Usually the CPU executes machine instructions in sequence

- Sometimes we need to “jump” unconditionally to another location, e.g. in order to implement a loop

- Sometimes we need to jump only if some condition is met:

Example:

```
    jgt R1, 0, CONT   // if R1>0 jump to CONT
    sub R1, 0, R1     // R1 ← (0 - R1)
  CONT:
     ...
    // Do something with positive R1
```

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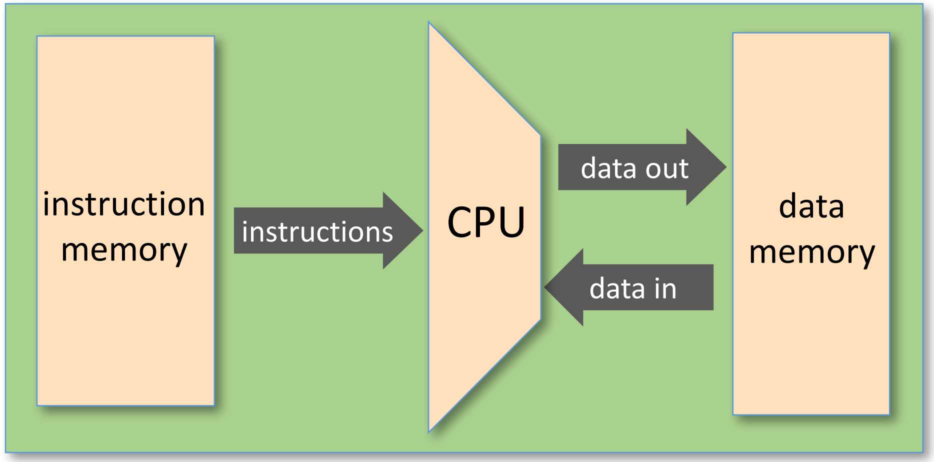
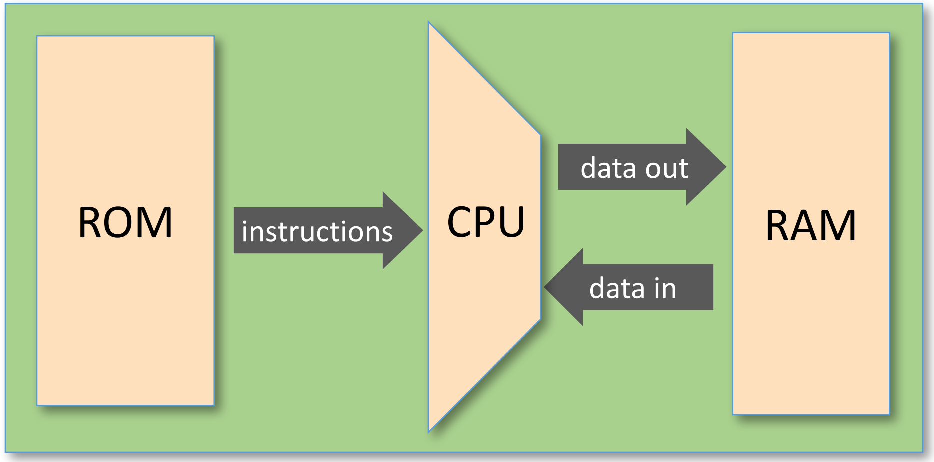
Hack computer: hardware



A 16-bit machine consisting of:

- Data memory (RAM): a sequence of 16-bit registers:
  RAM[0], RAM[1], RAM[2],...
- Instruction memory (ROM): a sequence of 16-bit registers:
  ROM[0], ROM[1], ROM[2],...
- Central Processing Unit (CPU): performs 16-bit instructions
- Instruction bus / data bus / address buses.

Hack computer: software

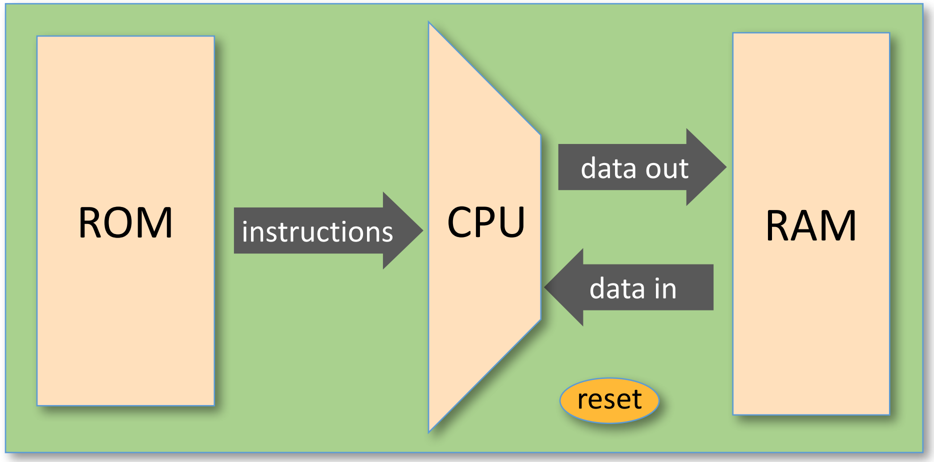


Hack machine language:

- 16-bit A-instructions
- 16-bit C-instructions

Hack program = sequence of instructions written in the
Hack machine language

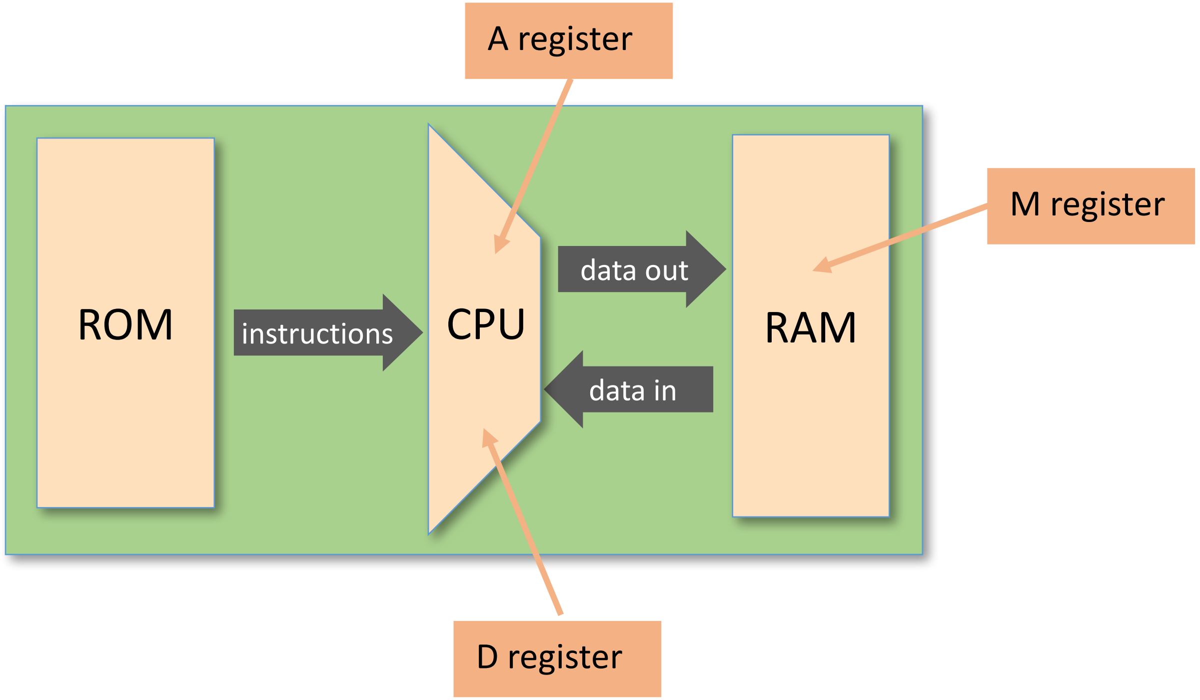
Hack computer: control



Control:

- The ROM is loaded with a Hack program
- The *reset* button is pushed
- The program starts running

Hack computer: registers



<u>The Hack machine language recognizes three 16-bit registers:</u>

- `D`: used to store data
- `A`: used to store data / address the memory
- `M`: represents the currently addressed memory register: `M = RAM[A]`

The A-instruction

<u>Syntax:</u>

```
@value
```

Where *value* is either:

- a non-negative decimal constant or
- a symbol referring to such a constant (later)

<u>Semantics:</u>

- Sets the `A` register to *value*
- Side effects:
  - `RAM[A]` becomes the selected `RAM` register
  - `ROM[A]` becomes the selected `ROM` register

Example:

```
// Sets A to 17
@17
```

The C-instruction

Syntax: *dest* = *comp* ; *jump* (both *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` refers to `RAM[A]`)

jump =

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

Semantics:

- Computes the value of *comp*
- Stores the result in *dest*
- If the Boolean expression (*comp jump* `0`) is true, jumps to execute the instruction at `ROM[A]`

The C-instruction

<u>Syntax:</u> *dest* = *comp* ; *jump* (both *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` refers to `RAM[A]`)

jump =

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

<u>Semantics:</u>

- Computes the value of *comp*
- Stores the result in *dest*
- If the Boolean expression (*comp jump* `0`) is true, jumps to execute the instruction at `ROM[A]`

Example:

```
// Sets the D register to -1
D=-1
```

The C-instruction

Syntax: `dest = comp ; jump` (both *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 refers to `RAM[A]`)

jump =

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

Semantics:

- Computes the value of *comp*
- Stores the result in *dest*
- If the Boolean expression (*comp jump* `0`) is true, jumps to execute the instruction at `ROM[A]`

Example:

```
// Sets RAM[300] to the value of the D register plus 1
@300   // A = 300
M=D+1  // RAM[300] = D + 1
```

The C-instruction

Syntax: `dest = comp ; jump` (both *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` refers to `RAM[A]`)

jump = `null, JGT, JEQ, JGE, JLT, JNE, JLE, JMP`

Semantics:

- Computes the value of *comp*
- Stores the result in *dest*
- If the Boolean expression (*comp jump* `0`) is true, jumps to execute the instruction at `ROM[A]`

Example:

```
// If (D-1 == 0) jumps to execute the instruction stored in ROM[56]
@56      // A = 56
D-1;JEQ  // if (D-1 == 0) goto to instruction ROM[A]
```

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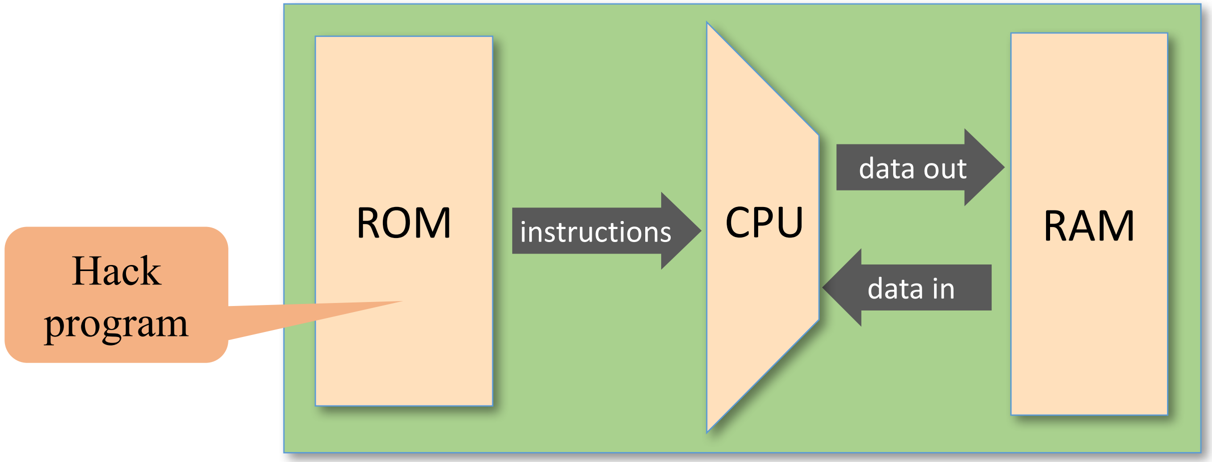
Hack machine language



Two ways to express the same semantics:

Symbolic:

```
@17
D+1;JLE
```

translate

Binary:

```
0000000000010001
1110011111000110
```

load & execute

A-instruction specification

<u>Semantics:</u> Sets the `A` register to *value*

<u>Symbolic syntax:</u>

```
@value
```

Example:

```
@21
```

sets `A` to 21

Where *value* is either:

- a non-negative decimal constant ≤ 65535 (=2^{15}-1) or
- a symbol referring to a constant (later)

<u>Binary syntax:</u>

```
0value
```

Example:

```
0000000000010101
```

opcode signifying an A-instruction

sets `A` to 21

Where *value* is a 15-bit binary constant

C-instruction specification

Symbolic syntax: `dest = comp ; jump`

Binary syntax: `1 1 1 a c1 c2 c3 c4 c5 c6 d1 d2 d3 j1 j2 j3`

opcode

not used

comp bits

dest bits

jump bits

C-instruction specification

Symbolic syntax: *dest* = *comp* ; *jump*

Binary syntax: `1 1 1 a c1 c2 c3 c4 c5 c6 d1 d2 d3 j1 j2 j3`

comp		c1	c2	c3	c4	c5	c6
0		1	0	1	0	1	0
1		1	1	1	1	1	1
-1		1	1	1	0	1	0
D		0	0	1	1	0	0
A	M	1	1	0	0	0	0
!D		0	0	1	1	0	1
!A	!M	1	1	0	0	0	1
-D		0	0	1	1	1	1
-A	-M	1	1	0	0	1	1
D+1		0	1	1	1	1	1
A+1	M+1	1	1	0	1	1	1
D-1		0	0	1	1	1	0
A-1	M-1	1	1	0	0	1	0
D+A	D+M	0	0	0	0	1	0
D-A	D-M	0	1	0	0	1	1
A-D	M-D	0	0	0	1	1	1
D&A	D&M	0	0	0	0	0	0
D|A	D|M	0	1	0	1	0	1
a==0	a==1						

C-instruction specification

Symbolic syntax: *dest* = *comp* ; *jump*

Binary syntax: `1 1 1 a c1 c2 c3 c4 c5 c6 d1 d2 d3 j1 j2 j3`

dest	d1 d2 d3	effect: the value is stored in:
null	0 0 0	The value is not stored
M	0 0 1	RAM[A]
D	0 1 0	D register
MD	0 1 1	RAM[A] and D register
A	1 0 0	A register
AM	1 0 1	A register and RAM[A]
AD	1 1 0	A register and D register
AMD	1 1 1	A register, RAM[A], and D register

C-instruction specification

Symbolic syntax: *dest* = *comp* ; *jump*

Binary syntax: `1 1 1 a c1 c2 c3 c4 c5 c6 d1 d2 d3 j1 j2 j3`

jump	j1 j2 J3	effect
`null`	0 0 0	no jump
`JGT`	0 0 1	if `out>0` jump
`JEQ`	0 1 0	if `out=0` jump
`JGE`	0 1 1	if `out≥0` jump
`JLT`	1 0 0	if `out<0` jump
`JNE`	1 0 1	if `out≠0` jump
`JLE`	1 1 0	if `out≤0` jump
`JMP`	1 1 1	unconditional jump

C-instruction specification

Symbolic syntax: *dest* = *comp* ; *jump*

Binary syntax: `1 1 1 a c1 c2 c3 c4 c5 c6 d1 d2 d3 j1 j2 j3`

comp (a==0)	*comp* (a==1)	c1	c2	c3	c4	c5	c6
0		1	0	1	0	1	0
1		1	1	1	1	1	1
-1		1	1	1	0	1	0
D		0	0	1	1	0	0
A	M	1	1	0	0	0	0
!D		0	0	1	1	0	1
!A	!M	1	1	0	0	0	1
-D		0	0	1	1	1	1
-A	-M	1	1	0	0	1	1
D+1		0	1	1	1	1	1
A+1	M+1	1	1	0	1	1	1
D-1		0	0	1	1	1	0
A-1	M-1	1	1	0	0	1	0
D+A	D+M	0	0	0	0	1	0
D-A	D-M	0	1	0	0	1	1
A-D	M-D	0	0	0	1	1	1
D&A	D&M	0	0	0	0	0	0
D|A	D|M	0	1	0	1	0	1
a==0	a==1						

dest	d1	d2	d3	effect: the value is stored in:
null	0	0	0	The value is not stored
M	0	0	1	RAM[A]
D	0	1	0	D register
MD	0	1	1	RAM[A] and D register
A	1	0	0	A register
AM	1	0	1	A register and RAM[A]
AD	1	1	0	A register and D register
AMD	1	1	1	A register, RAM[A], and D register

jump	j1	j2	j3	effect:
null	0	0	0	no jump
JGT	0	0	1	if out > 0 jump
JEQ	0	1	0	if out = 0 jump
JGE	0	1	1	if out ≥ 0 jump
JLT	1	0	0	if out < 0 jump
JNE	1	0	1	if out ≠ 0 jump
JLE	1	1	0	if out ≤ 0 jump
JMP	1	1	1	Unconditional jump

Examples:

Symbolic: `MD=D+1`

Binary: `1110011111011000`

C-instruction specification

Symbolic syntax: *dest* = *comp* ; *jump*

Binary syntax: 1 1 1 a c1 c2 c3 c4 c5 c6 d1 d2 d3 j1 j2 j3

comp (a==0)	*comp* (a==1)	c1	c2	c3	c4	c5	c6
0		1	0	1	0	1	0
1		1	1	1	1	1	1
-1		1	1	1	0	1	0
D		0	0	1	1	0	0
A	M	1	1	0	0	0	0
!D		0	0	1	1	0	1
!A	!M	1	1	0	0	0	1
-D		0	0	1	1	1	1
-A	-M	1	1	0	0	1	1
D+1		0	1	1	1	1	1
A+1	M+1	1	1	0	1	1	1
D-1		0	0	1	1	1	0
A-1	M-1	1	1	0	0	1	0
D+A	D+M	0	0	0	0	1	0
D-A	D-M	0	1	0	0	1	1
A-D	M-D	0	0	0	1	1	1
D&A	D&M	0	0	0	0	0	0
D|A	D|M	0	1	0	1	0	1
a==0	a==1						

dest	d1	d2	d3	effect: the value is stored in:
null	0	0	0	The value is not stored
M	0	0	1	RAM[A]
D	0	1	0	D register
MD	0	1	1	RAM[A] and D register
A	1	0	0	A register
AM	1	0	1	A register and RAM[A]
AD	1	1	0	A register and D register
AMD	1	1	1	A register, RAM[A], and D register

jump	j1	j2	j3	effect:
null	0	0	0	no jump
JGT	0	0	1	if out > 0 jump
JEQ	0	1	0	if out = 0 jump
JGE	0	1	1	if out ≥ 0 jump
JLT	1	0	0	if out < 0 jump
JNE	1	0	1	if out ≠ 0 jump
JLE	1	1	0	if out ≤ 0 jump
JMP	1	1	1	Unconditional jump

Examples:

Symbolic: M=1

Binary: 1110111111001000

C-instruction specification

Symbolic syntax: *dest* = *comp* ; *jump*

Binary syntax: 1 1 1 a c1 c2 c3 c4 c5 c6 d1 d2 d3 j1 j2 j3

comp (a==0)	*comp* (a==1)	c1	c2	c3	c4	c5	c6
0		1	0	1	0	1	0
1		1	1	1	1	1	1
-1		1	1	1	0	1	0
D		0	0	1	1	0	0
A	M	1	1	0	0	0	0
!D		0	0	1	1	0	1
!A	!M	1	1	0	0	0	1
-D		0	0	1	1	1	1
-A	-M	1	1	0	0	1	1
D+1		0	1	1	1	1	1
A+1	M+1	1	1	0	1	1	1
D-1		0	0	1	1	1	0
A-1	M-1	1	1	0	0	1	0
D+A	D+M	0	0	0	0	1	0
D-A	D-M	0	1	0	0	1	1
A-D	M-D	0	0	0	1	1	1
D&A	D&M	0	0	0	0	0	0
D|A	D|M	0	1	0	1	0	1
a==0	a==1						

dest	d1	d2	d3	effect: the value is stored in:
null	0	0	0	The value is not stored
M	0	0	1	RAM[A]
D	0	1	0	D register
MD	0	1	1	RAM[A] and D register
A	1	0	0	A register
AM	1	0	1	A register and RAM[A]
AD	1	1	0	A register and D register
AMD	1	1	1	A register, RAM[A], and D register

jump	j1	j2	j3	effect:
null	0	0	0	no jump
JGT	0	0	1	if out > 0 jump
JEQ	0	1	0	if out = 0 jump
JGE	0	1	1	if out ≥ 0 jump
JLT	1	0	0	if out < 0 jump
JNE	1	0	1	if out ≠ 0 jump
JLE	1	1	0	if out ≤ 0 jump
JMP	1	1	1	Unconditional jump

Examples:

Symbolic: D+1;JLE

Binary: 1110011111000110

Hack program

Symbolic code

```
// Computes RAM[1] = 1+...+RAM[0]
// Usage: put a number in RAM[0]
@16   // RAM[16] represents i
M=1   // i = 1
@17   // RAM[17] represents sum
M=0   // sum = 0

@16
D=M
@0
D=D-M
@17    // if i>RAM[0] goto 17
D;JGT

@16
D=M
@17
M=D+M  // sum += i
@16
M=M+1  // i++
@4     // goto 4 (loop)
0;JMP

@17
D=M
@1
M=D    // RAM[1] = sum
@21    // program's end
0;JMP  // infinite loop
```

Observations:

- Hack program:
  a sequence of Hack instructions
- White space is permitted
- Comments are welcome
- There are better ways to write symbolic Hack programs; stay tuned.

No need to understand ...
we'll review the code later in the lecture.

Hack programs: symbolic and binary

Symbolic code

```
// Computes RAM[1] = 1+...+RAM[0]
// Usage: put a number in RAM[0]
@16    // RAM[16] represents i
M=1    // i = 1
@17    // RAM[17] represents sum
M=0    // sum = 0

@16
D=M
@0
D=D-M
@17     // if i>RAM[0] goto 17
D;JGT

@16
D=M
@17
M=D+M   // sum += i
@16
M=M+1   // i++
@4      // goto 4 (loop)
0;JMP

@17
D=M
@1
M=D     // RAM[1] = sum
@21     // program's end
0;JMP   // infinite loop
```

translate

Binary code

```
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
0000000000010001
1110001100000001
0000000000010000
1111110000010000
0000000000010001
1111000010001000
0000000000010000
1111110111001000
0000000000000100
1110101010000111
0000000000010001
1111110000010000
0000000000000001
1110001100001000
0000000000010101
1110101010000111
```

execute

Machine Language: lecture plan

- ✓ Machine languages
- ✓ Basic elements
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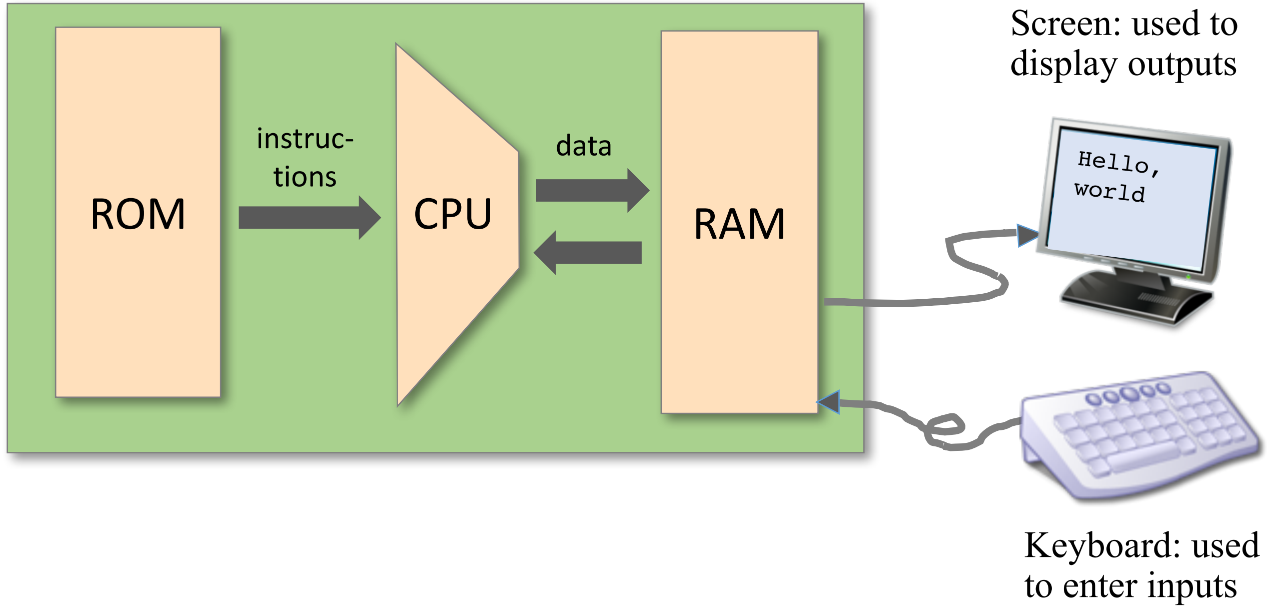
- ✓ The Hack language specification
- ➡ Input / Output
- Hack programming
- Project 4 overview

Input / output



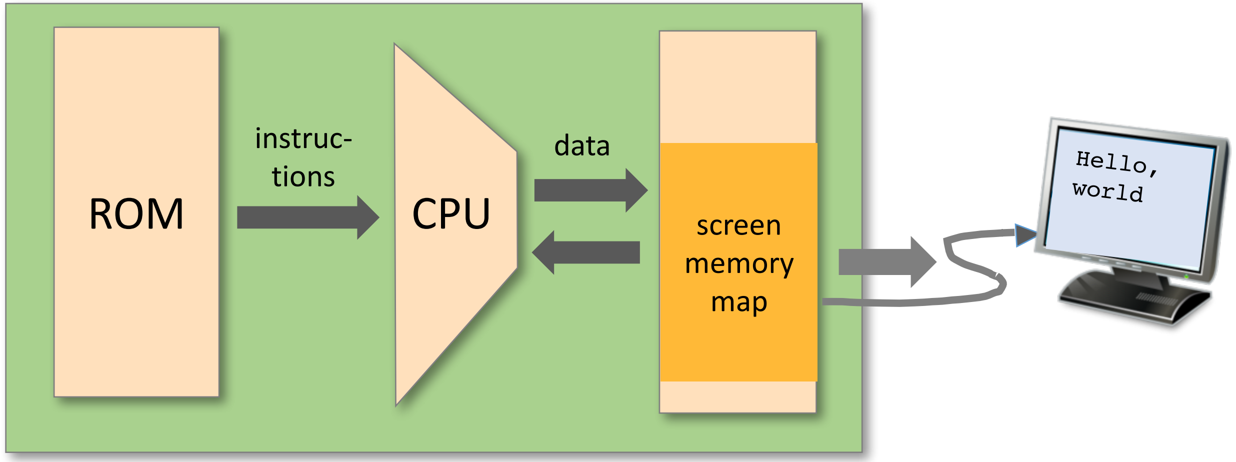
I/O handling (high-level):

Software libraries enabling text, graphics, audio, video, etc.

I/O handling (low-level):

Bits manipulation.

Memory mapped output



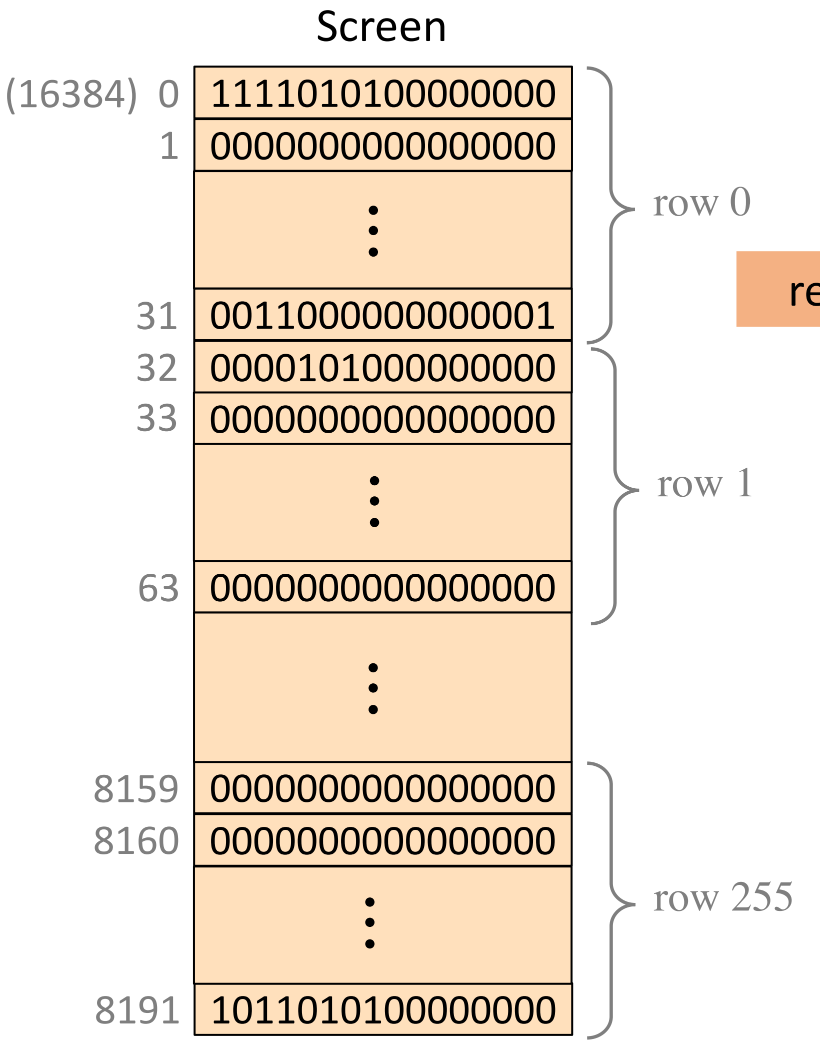
Memory mapped output

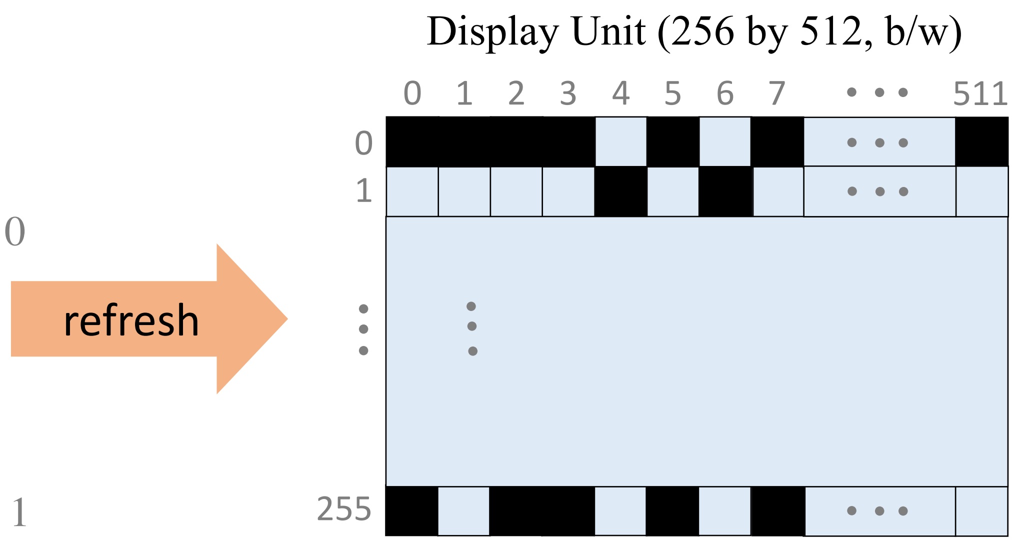
A designated memory area, dedicated to manage a display unit

The physical display is continuously *refreshed* from the memory map, many times per second

Output is effected by writing code that manipulates the screen memory map.

Memory mapped output





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

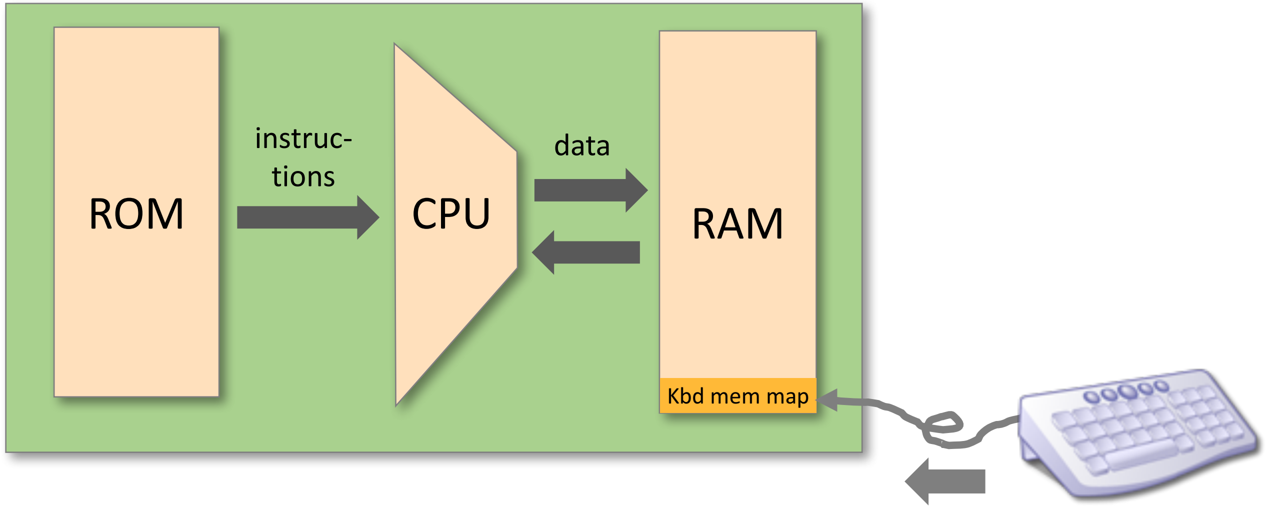
(1) *word* = RAM[16384 + 32**row* + *col*/16]

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

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

Memory mapped output

Input

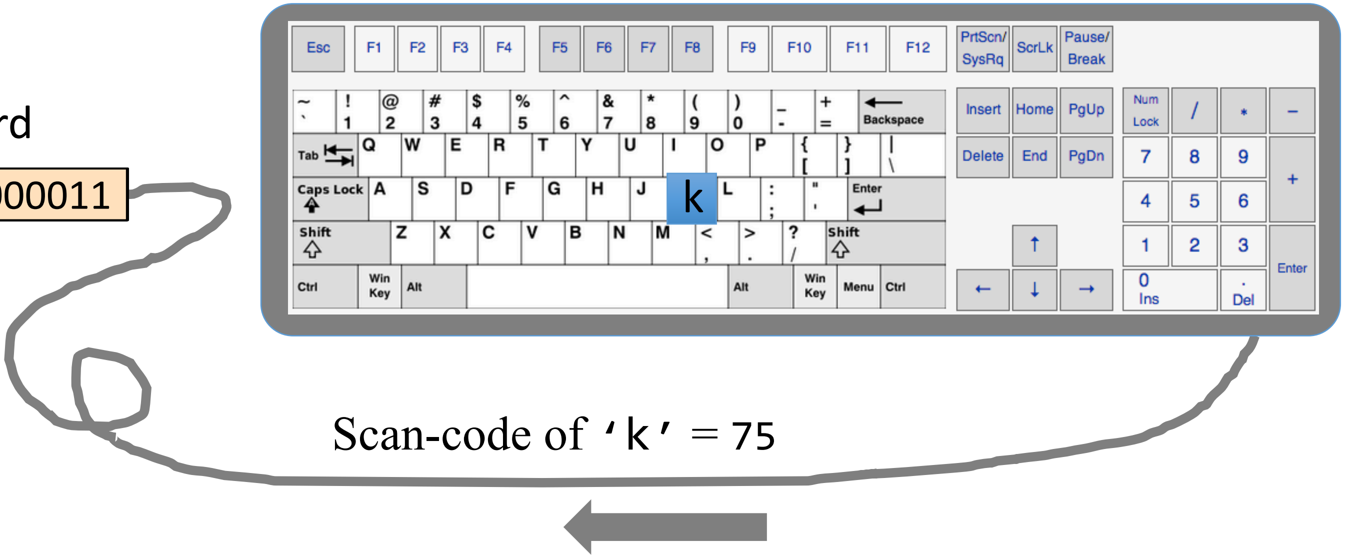


The physical keyboard is associated with a *keyboard memory map*.

Memory mapped input

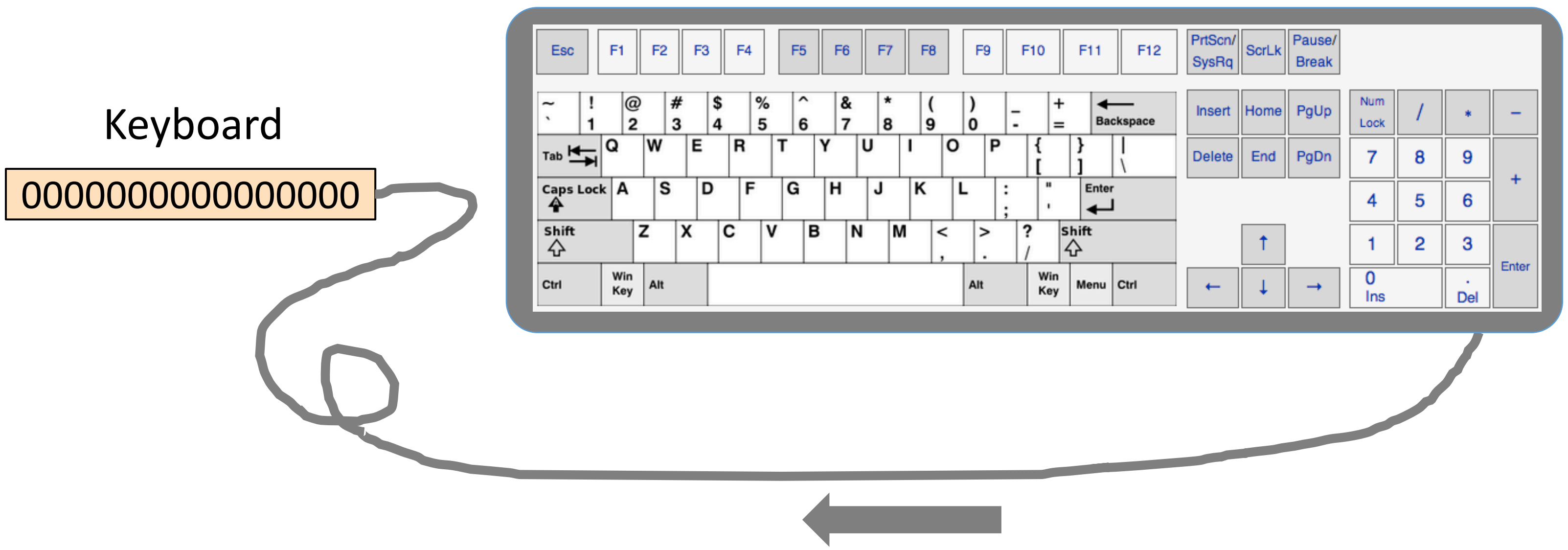
Keyboard

0000000010000011



When a key is pressed on the keyboard, the key’s *scan code* appears in the *keyboard memory map*

Memory mapped input



When no key is pressed, the resulting code is `0`.

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

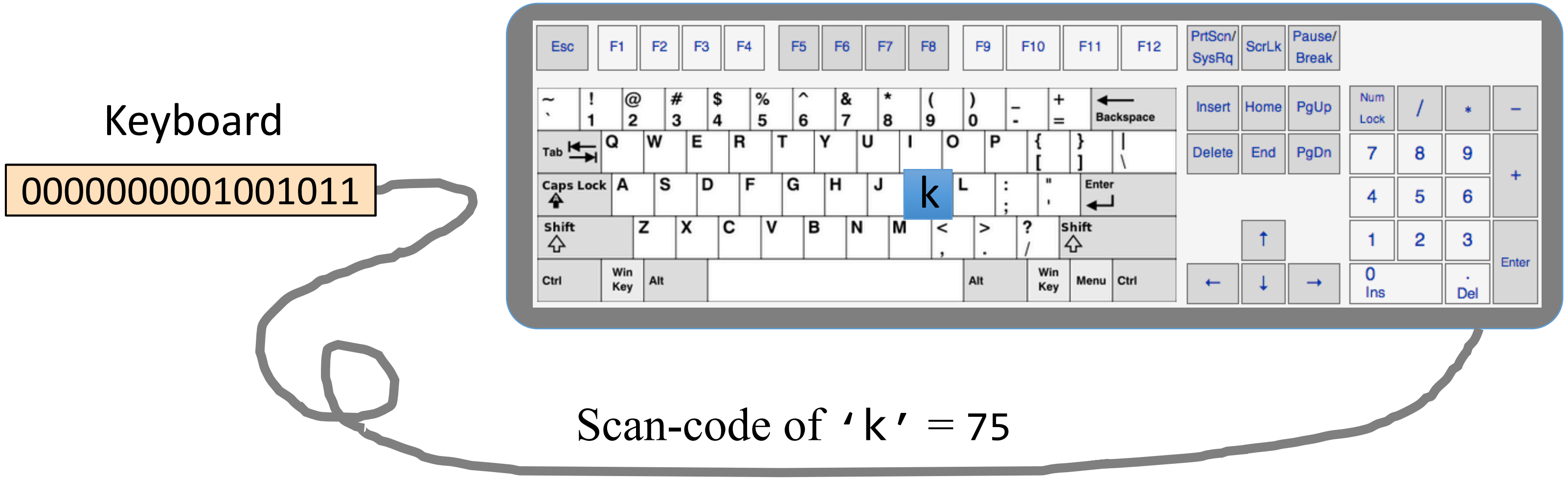
[	91
/	92
]	93
^	94
_	95
`	96

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

Handling the keyboard



To check which key is currently pressed:

- Probe the contents of the `Keyboard` chip
- In the Hack computer: probe the contents of `RAM[24576]`.

Handling the keyboard

Machine Language: lecture plan

- ✓ Machine languages
- ✓ Basic elements
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- Project 4 overview

Machine Language: lecture plan

✓ Machine languages

✓ Basic elements

✓ The Hack computer and machine language

✓ The Hack language specification

✓ Input / Output

- Hack programming
  - ➡ Part 1: registers and memory
  - ❑ Part 2: branching, variables, iteration
  - ❑ Part 3: pointers, input/output
- Project 4 overview

Hack assembly language (overview)

A-instruction:

```
@value    // A = value
```

where *value* is either a constant or a symbol referring to such a constant

C-instruction:

```
dest = comp ; jump
```

(both *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` refers to `RAM[A]`)

jump =

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

Semantics:

- Computes the value of *comp*
- Stores the result in *dest*
- If the Boolean expression (*comp jump* `0`) is true, jumps to execute the instruction at `ROM[A]`

Hack assembler

Assembly program

```
// Program: Flip.asm
// flips the values of
// RAM[0] and RAM[1]
   @R1
   D=M
   @temp
   M=D     // temp = R1

   @R0
   D=M
   @R1
   M=D     // R1 = R0

   @temp
   D=M
   @R0
   M=D     // R0 = temp

(END)
   @END
   0;JMP
```

Hack assembler

Binary code

```
0000000000000001
1111110000010000
0000000000010000
1110001100001000
0000000000000000
1111110000010000
0000000000000001
1110001100001000
0000000000010000
1111110000010000
0000000000000000
1110001100001000
0000000000001100
1110101010000111
```

load & execute

We'll develop a Hack assembler later in the course.

CPU Emulator

Assembly program

```
// Program: Flip.asm
// flips the values of
// RAM[0] and RAM[1]
   @R1
   D=M
   @temp
   M=D    // temp = R1

   @R0
   D=M
   @R1
   M=D    // R1 = R0

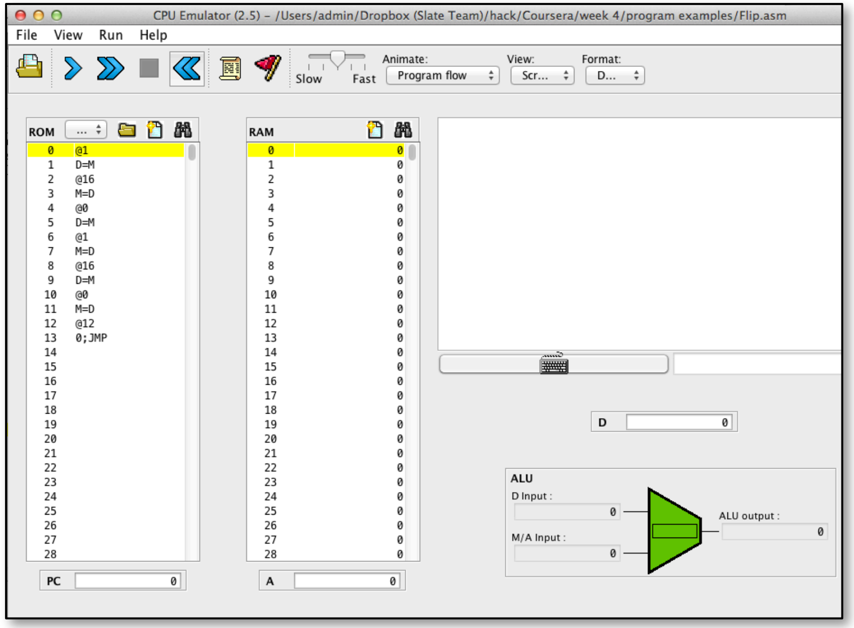
   @temp
   D=M
   @R0
   M=D    // R0 = temp

(END)
   @END
   0;JMP
```

load

(the simulator software translates from symbolic to binary as it loads)

CPU Emulator



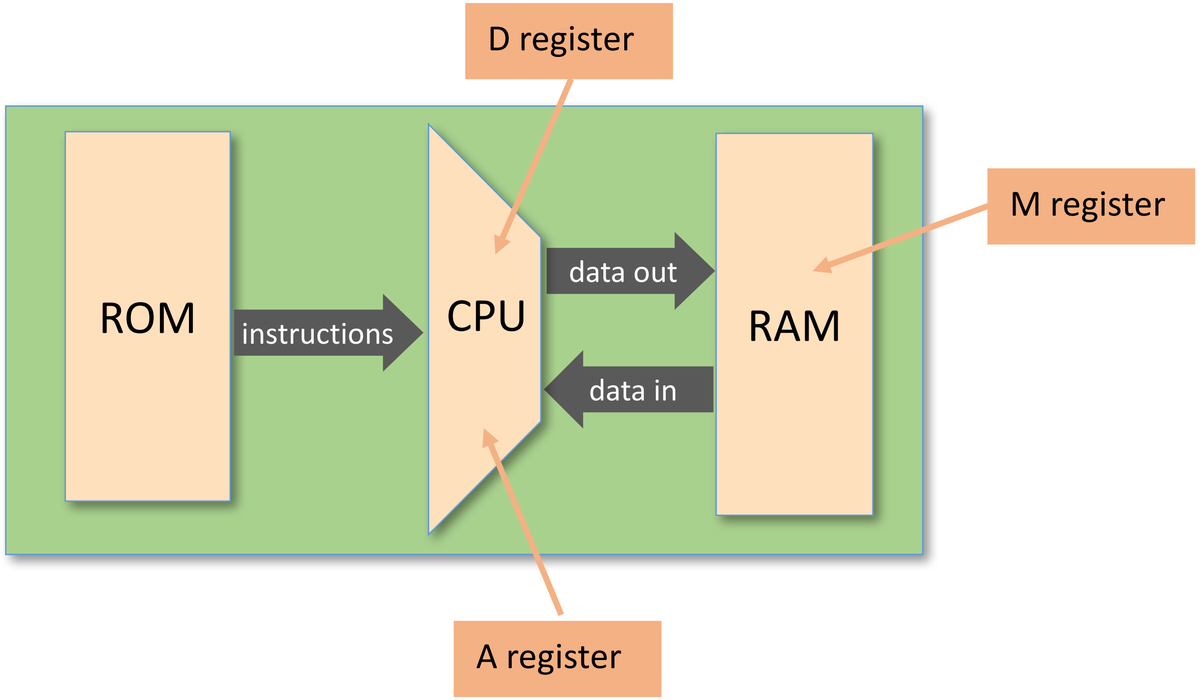
- A software tool
- Convenient for debugging and executing symbolic Hack programs.

Registers and memory

D: data register

A: address / data register

M: the currently selected memory register: M = RAM[A]



Registers and memory

D: data register

A: address / data register

M: the currently selected memory register: M = RAM[A]

Typical operations:

```
// D=10
@10
D=A


// D++
D=D+1


// D=RAM[17]
@17
D=M


// RAM[17]=D
@17
M=D
```

```
// RAM[17]=10
@10
D=A
@17
M=D


// RAM[5] = RAM[3]
@3
D=M
@5
M=D
```

Program example: add two numbers

Hack assembly code

```
  // Program: Add2.asm
  // Computes: RAM[2] = RAM[0] + RAM[1]
  // Usage: put values in RAM[0], RAM[1]

0 @0
1 D=M    // D = RAM[0]

2 @1
3 D=D+M  // D = D + RAM[1]

4 @2
5 M=D    // RAM[2] = D
```

translate and load

(white space ignored)

Memory (ROM)

0	@0
1	D=M
2	@1
3	D=D+M
4	@2
5	M=D
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	
⋮	
32767	

symbolic view

Program example: add two numbers

Hack assembly code

```
    // Program: Add2.asm
    // Computes: RAM[2] = RAM[0] + RAM[1]
    // Usage: put values in RAM[0], RAM[1]

0   @0
1   D=M   // D = RAM[0]

2   @1
3   D=D+M // D = D + RAM[1]

4   @2
5   M=D   // RAM[2] = D
```

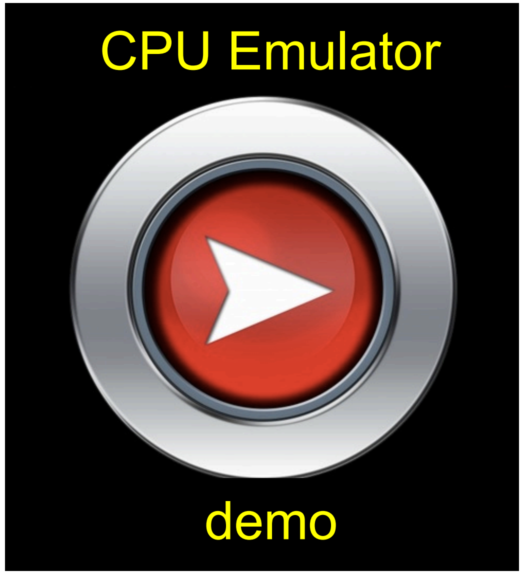
translate and load

Memory (ROM)

0	0000000000000000
1	1111110000010000
2	0000000000000001
3	1111000010010000
4	0000000000000010
5	1110001100001000
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	
⋮	
32767	

binary view

Program example: add two numbers



Terminating a program

Hack assembly code

```
  // Program: Add2.asm
  // Computes: RAM[2] = RAM[0] + RAM[1]
  // Usage: put values in RAM[0], RAM[1]

0 @0
1 D=M    // D = RAM[0]

2 @1
3 D=D+M // D = D + RAM[1]

4 @2
5 M=D    // RAM[2] = D
```

Memory (ROM)

0	@0
1	D=M
2	@1
3	D=D+M
4	@2
5	M=D
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	
	⋮

Terminating a program

Hack assembly code

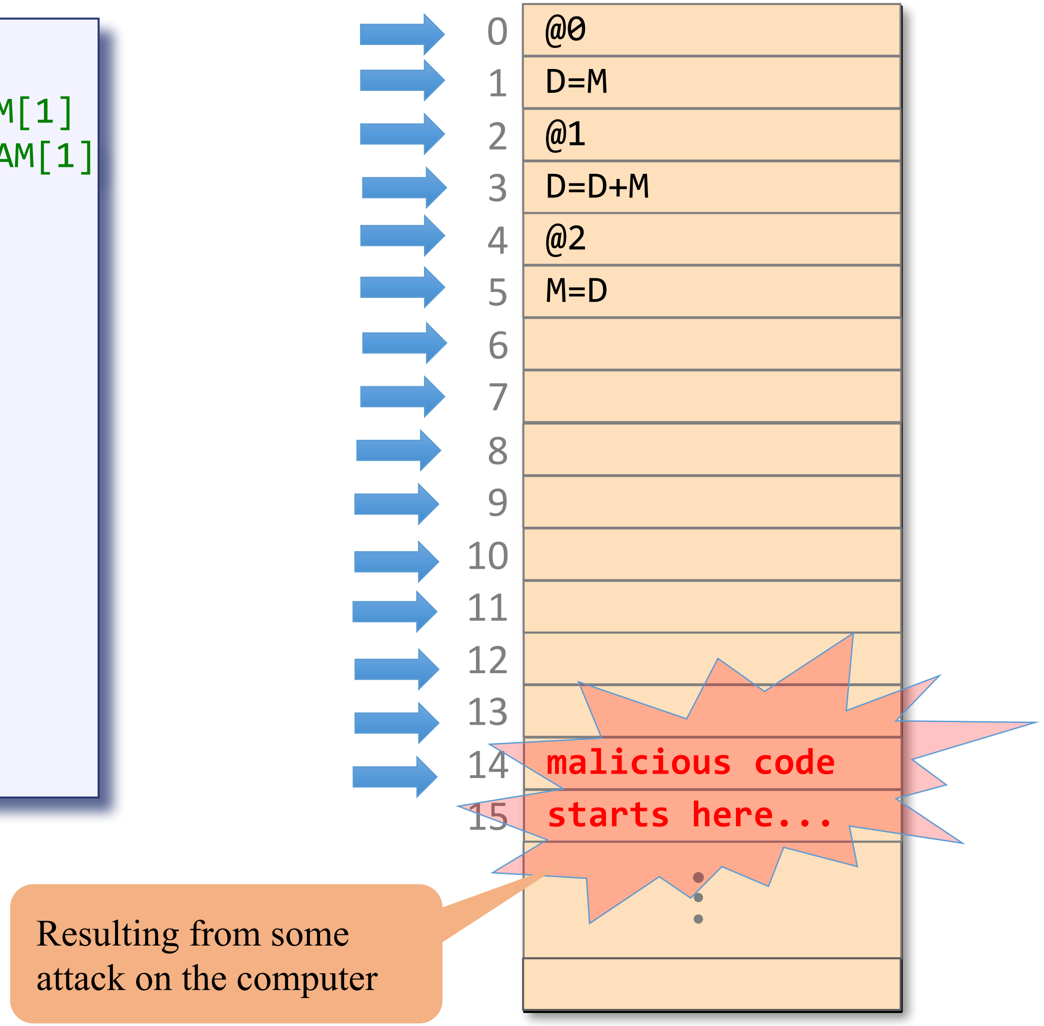
```
// Program: Add2.asm
// Computes: RAM[2] = RAM[0] + RAM[1]
// Usage: put values in RAM[0], RAM[1]

@0
D=M   // D = RAM[0]

@1
D=D+M // D = D + RAM[1]

@2
M=D   // RAM[2] = D
```

Memory (ROM)



Terminating a program

Hack assembly code

```
  // Program: Add2.asm
  // Computes: RAM[2] = RAM[0] + RAM[1]
  // Usage: put values in RAM[0], RAM[1]

0 @0
1 D=M    // D = RAM[0]

2 @1
3 D=D+M // D = D + RAM[1]

4 @2
5 M=D    // RAM[2] = D

6 @6
7 0;JMP
```

- Jump to instruction number A (which happens to be 6)
- `0`: syntax convention for `jmp` instructions

Best practice:

To terminate a program safely, end it with an infinite loop.

Memory (ROM)

0	@0
1	D=M
2	@1
3	D=D+M
4	@2
5	M=D
6	@6
7	0;JMP
8	
9	
10	
11	
12	
13	
14	
15	
	⋮

Built-in symbols

The Hack assembly language features *built-in symbols*:

symbol	value
R0	0
R1	1
R2	2
...	...
R15	15

Attention: Hack is case-sensitive! R5 and r5 are different symbols.

These symbols can be used to denote "virtual registers"

Example: suppose we wish to use RAM[5] to represent some variable, say x, and we wish to let x=7

implementation:

```
// let RAM[5] = 7
@7
D=A

@5
M=D
```

better style:

```
// let RAM[5] = 7
@7
D=A

@R5
M=D
```

Built-in symbols

The Hack assembly language features *built-in symbols*:

symbol	value
R0	0
R1	1
R2	2
...	...
R15	15
SCREEN	16384
KBD	24576

symbol	value
SP	0
LCL	1
ARG	2
THIS	3
THAT	4

- `R0`, `R1` ,…, `R15` : "virtual registers", can be used as variables
- `SCREEN` and `KBD` : base addresses of I/O memory maps
- Remaining symbols: used in the implementation of the Hack *virtual machine*, discussed in chapters 7-8.

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- Project 4 overview

Branching

example:

```
   // Program: Signum.asm
   // Computes: if R0>0
   //                R1=1
   //             else
   //                R1=0
   // Usage: put a value in RAM[0],
   //        run and inspect RAM[1].

0     @R0
1     D=M    // D = RAM[0]

2     @8
3     D;JGT  // If R0>0 goto 8

4     @R1
5     M=0    // RAM[1]=0
6     @10
7     0;JMP  // goto end

8     @R1
9     M=1    // R1=1

10    @10
11    0;JMP
```

Branching

example:

```
    // Program: Signum.asm
    // Computes: if R0>0
    //              R1=1
    //           else
    //              R1=0
    // Usage: put a value in RAM[0],
    //        run and inspect RAM[1].

0      @R0
1      D=M     // D = RAM[0]

2      @8
3      D;JGT   // If R0>0 goto 8

4      @R1
5      M=0     // RAM[1]=0
6      @10
7      0;JMP   // goto end

8      @R1
9      M=1     // R1=1

10     @10
11     0;JMP
```

cryptic code

"Instead of imagining that our main task as programmers is to instruct a computer what to do, let us concentrate rather on explaining to human beings what we want a computer to do."

– Donald Knuth

Branching

example:

```
   // Program: Signum.asm
   // Computes: if R0>0
   //              R1=1
   //           else
   //              R1=0
   // Usage: put a value in RAM[0],
   //        run and inspect RAM[1].

0      @R0
1      D=M     // D = RAM[0]

2      @POSITIVE
3      D;JGT   // If R0>0 goto 8

4      @R1
5      M=0     // RAM[1]=0
6      @10
7      0;JMP   // goto end

   (POSITIVE)
8      @R1
9      M=1     // R1=1

   (END)
10     @END
11     0;JMP
```

referring to a label

declaring a label

Labels

example:

```
    // Program: Signum.asm
    // Computes: if R0>0
    //              R1=1
    //           else
    //              R1=0
    // Usage: put a value in RAM[0],
    //        run and inspect RAM[1].

0      @R0
1      D=M     // D = RAM[0]

2      @POSITIVE
3      D;JGT   // If R0>0 goto 8

4      @R1
5      M=0     // RAM[1]=0
6      @10
7      0;JMP   // goto end

    (POSITIVE)
8      @R1
9      M=1     // R1=1

    (END)
10     @END
11     0;JMP
```

referring to a label

declaring a label

resolving labels

Label resolution rules:

- Label declarations generate no code
- Each reference to a label is replaced with a reference to the instruction number following that label's declaration.

Memory

0	@0
1	D=M
2	@8 // @POSITIVE
3	D;JGT
4	@1
5	M=0
6	@10 // @END
7	0;JMP
8	@1
9	M=1
10	@10 // @END
11	0;JMP
12	
13	
14	
15	
⋮	
32767	

Labels

example:

```
   // Program: Signum.asm
   // Computes: if R0>0
   //              R1=1
   //           else
   //              R1=0
   // Usage: put a value in RAM[0],
   //        run and inspect RAM[1].

0     @R0
1     D=M    // D = RAM[0]

2     @POSITIVE
3     D;JGT  // If R0>0 goto 8

4     @R1
5     M=0    // RAM[1]=0
6     @10
7     0;JMP  // goto end

   (POSITIVE)
8     @R1
9     M=1    // R1=1

   (END)
10    @END
11    0;JMP
```

referring to a label

declaring a label

resolving labels

Memory

0	@0
1	D=M
2	@8 // @POSITIVE
3	D;JGT
4	@1
5	M=0
6	@10 // @END
7	0;JMP
8	@1
9	M=1
10	@10 // @END
11	0;JMP
12	
13	
14	
15	
⋮	
32767	

Implications:

- Instruction numbers no longer needed in symbolic programming
- The symbolic code becomes *relocatable*.

Variables

Variable usage example:

```
// Program: Flip.asm
// flips the values of
// RAM[0] and RAM[1]

// temp = R1
// R1 = R0
// R0 = temp

   @R1
   D=M
   @temp
   M=D    // temp = R1

   @R0
   D=M
   @R1
   M=D    // R1 = R0

   @temp
   D=M
   @R0
   M=D    // R0 = temp

(END)
   @END
   0;JMP
```

Variables

Variable usage example:

```
// Program: Flip.asm
// flips the values of
// RAM[0] and RAM[1]

// temp = R1
// R1 = R0
// R0 = temp

   @R1
   D=M
   @temp
   M=D     // temp = R1

   @R0
   D=M
   @R1
   M=D     // R1 = R0

   @temp
   D=M
   @R0
   M=D     // R0 = temp

(END)
   @END
   0;JMP
```

symbol used for the first time

symbol used again

resolving symbols

Symbol resolution rules:

- A reference to a symbol that has no corresponding label declaration is treated as a reference to a variable
- If the reference @*symbol* occurs in the program for first time, *symbol* is allocated to address 16 onward (say *n*), and the generated code is @*n*
- All subsequencet @*symbol* commands are translated into @*n*

In other words: variables are allocated to `RAM[16]` onward.

Memory

0	@1
1	D=M
2	@16 // @temp
3	M=D
4	@0
5	D=M
6	@1
7	M=D
8	@16 // @temp
9	D=M
10	@0
11	M=D
12	@12
13	0;JMP
14	
15	
	⋮
32767	

Variables

Variable usage example:

```
// Program: Flip.asm
// flips the values of
// RAM[0] and RAM[1]

// temp = R1
// R1 = R0
// R0 = temp

   @R1
   D=M
   @temp
   M=D    // temp = R1

   @R0
   D=M
   @R1
   M=D    // R1 = R0

   @temp
   D=M
   @R0
   M=D    // R0 = temp

(END)
   @END
   0;JMP
```

resolving symbols

Implications:

symbolic code is easy to read and debug

Memory

0	@1
1	D=M
2	@16 // @temp
3	M=D
4	@0
5	D=M
6	@1
7	M=D
8	@16 // @temp
9	D=M
10	@0
11	M=D
12	@12
13	0;JMP
14	
15	
⋮	
32767	

Iterative processing

pseudo code

```
// Computes RAM[1] = 1+2+ ... +RAM[0]

   n = R0
   i = 1
   sum = 0

LOOP:
   if i > n goto STOP
   sum = sum + i
   i = i + 1
   goto LOOP

STOP:
   R1 = sum
```

Iterative processing

pseudo code

```
// Computes RAM[1] = 1+2+ ... +RAM[0]

   n = R0
   i = 1
   sum = 0

   ...
```

assembly code

```
// Program: Sum1toN.asm
// Computes RAM[1] = 1+2+ ... +n
// Usage: put a number (n) in RAM[0]

   @R0
   D=M
   @n
   M=D   // n = R0

   @i
   M=1   // i = 1

   @sum
   M=0   // sum = 0
   ...
```

Memory

0	@0
1	D=M
2	@16 // @n
3	M=D
4	@17 // @i
5	M=1
6	@18 // @sum
7	M=0
8	...
9	
10	
11	
12	
13	
14	
15	
	⋮
32767	

Variables are allocated to consecutive RAM locations from address 16 onward

Iterative processing

pseudo code

```
// Computes RAM[1] = 1+2+ ... +RAM[0]

   n = R0
   i = 1
   sum = 0

   ...
```

Iterative processing

pseudo code

```
// Computes RAM[1] = 1+2+ ... +RAM[0]

   n = R0
   i = 1
   sum = 0

LOOP:
   if i > n goto STOP
   sum = sum + i
   i = i + 1
   goto LOOP

STOP:
   R1 = sum
```

assembly program

```
// Computes RAM[1] = 1+2+ ... +n
// Usage: put a number (n) in RAM[0]
   @R0
   D=M
   @n
   M=D    // n = R0
   @i
   M=1    // i = 1
   @sum
   M=0    // sum = 0
(LOOP)
   @i
   D=M
   @n
   D=D-M
   @STOP
   D;JGT   // if i > n goto STOP
   @sum
   D=M
   @i
   D=D+M
   @sum
   M=D     // sum = sum + i
   @i
   M=M+1   // i = i + 1
   @LOOP
   0;JMP
(STOP)
   @sum
   D=M
   @R1
   M=D     // RAM[1] = sum
(END)
   @END
   0;JMP
```

Program execution

assembly program

```
// Computes RAM[1] = 1+2+ ... +n
// Usage: put a number (n) in RAM[0]
   @R0
   D=M
   @n
   M=D   // n = R0
   @i
   M=1   // i = 1
   @sum
   M=0   // sum = 0
(LOOP)
   @i
   D=M
   @n
   D=D-M
   @STOP
   D;JGT  // if i > n goto STOP
   @sum
   D=M
   @i
   D=D+M
   @sum
   M=D    // sum = sum + i
   @i
   M=M+1  // i = i + 1
   @LOOP
   0;JMP
(STOP)
   @sum
   D=M
   @R1
   M=D    // RAM[1] = sum
(END)
   @END
   0;JMP
```

iterations

	0	1	2	3	...
RAM[0]:	3				
n:	3				
i:	1	2	3	4	...
sum:	0	1	3	6	...

Writing assembly programs

assembly program

```
// Computes RAM[1] = 1+2+ ... +n
// Usage: put a number (n) in RAM[0]
   @R0
   D=M
   @n
   M=D   // n = R0
   @i
   M=1   // i = 1
   @sum
   M=0   // sum = 0
(LOOP)
   @i
   D=M
   @n
   D=D-M
   @STOP
   D;JGT  // if i > n goto STOP
   @sum
   D=M
   @i
   D=D+M
   @sum
   M=D    // sum = sum + i
   @i
   M=M+1  // i = i + 1
   @LOOP
   0;JMP
(STOP)
   @sum
   D=M
   @R1
   M=D    // RAM[1] = sum
(END)
   @END
   0;JMP
```

Best practice:

- **Design** the program using pseudo code
- **Write** the program in assembly language
- **Test** the program (on paper) using a variable-value trace table

Machine Language: lecture plan

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  - ➡ Part 3: pointers, input/output
- Project 4 overview

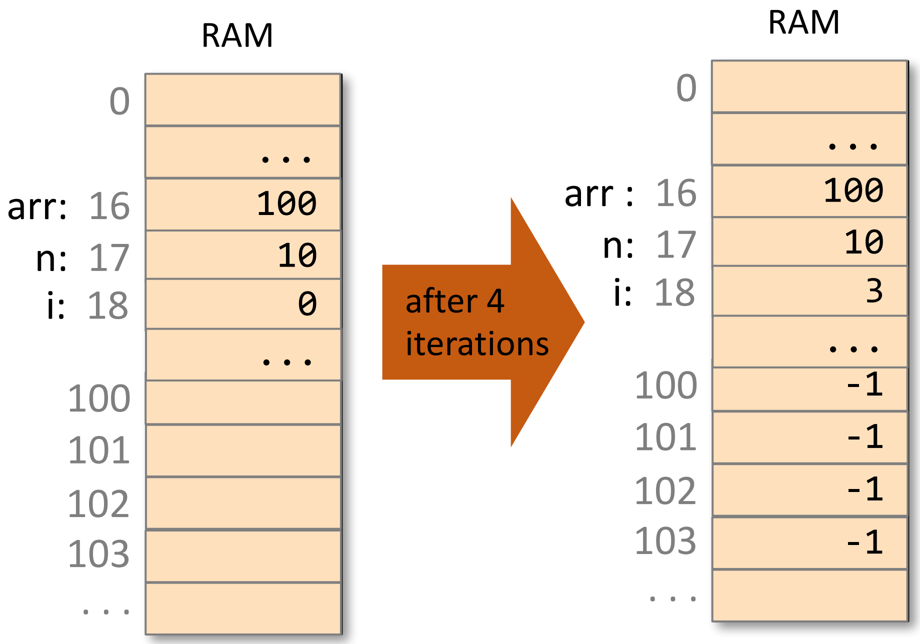
Pointers

Example:

```
// for (i=0; i<n; i++) {
//       arr[i] = -1
// }
```

<u>Observations:</u>

- The array is implemented as a block of memory registers
- In order to access these memory registers one after the other, we need a variable that holds the current address
- Variables that represent addresses are called <u>pointers</u>
- There is nothing special about pointer variables, except that their values are interpreted as addresses.



Pointers

Example:

```
// for (i=0; i<n; i++) {
//      arr[i] = -1
// }

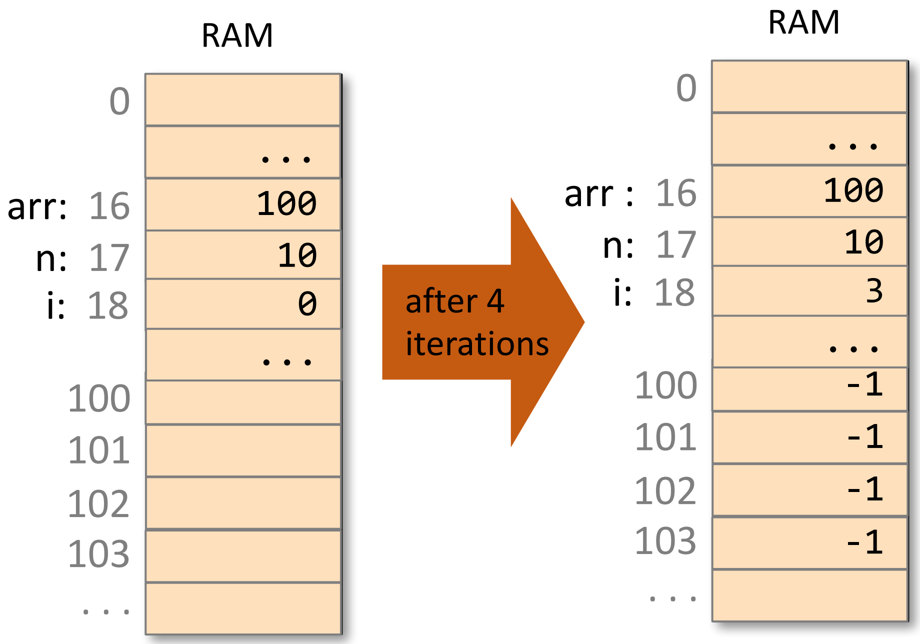
   // Suppose that arr=100 and n=10

   // Let arr = 100
   @100
   D=A
   @arr
   M=D

   // Let n = 10
   @10
   D=A
   @n
   M=D

   // Let i = 0
   @i
   M=0

   // Loop code continues
   // in next slide...
```

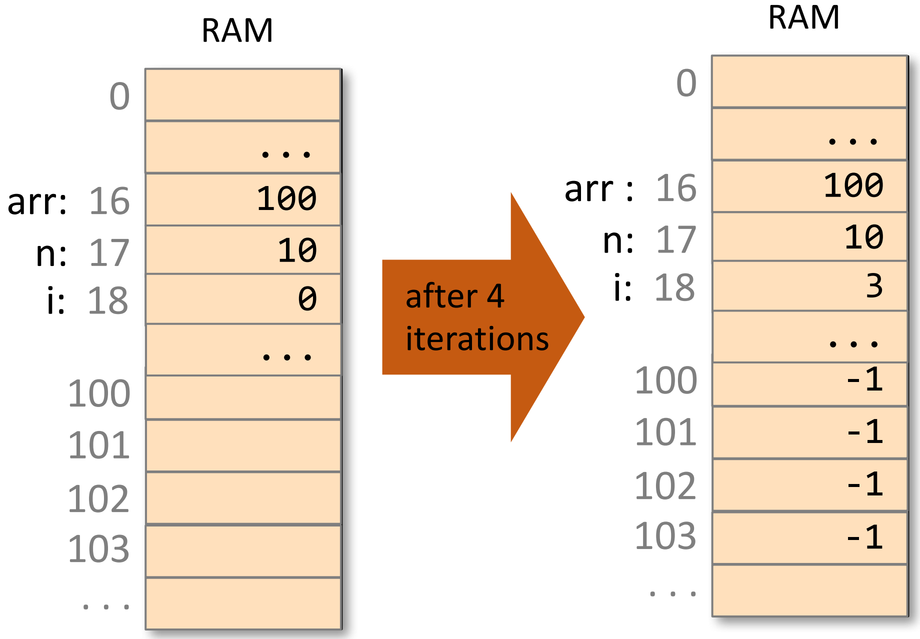


Pointers

Example:

```
(LOOP)
   // if (i==n) goto END
   @i
   D=M
   @n
   D=D-M
   @END
   D;JEQ

   // RAM[arr+i] = -1
   @arr
   D=M
   @i
   A=D+M
   M=-1
```



Pointers

Example:

```
(LOOP)
   // if (i==n) goto END
   @i
   D=M
   @n
   D=D-M
   @END
   D;JEQ

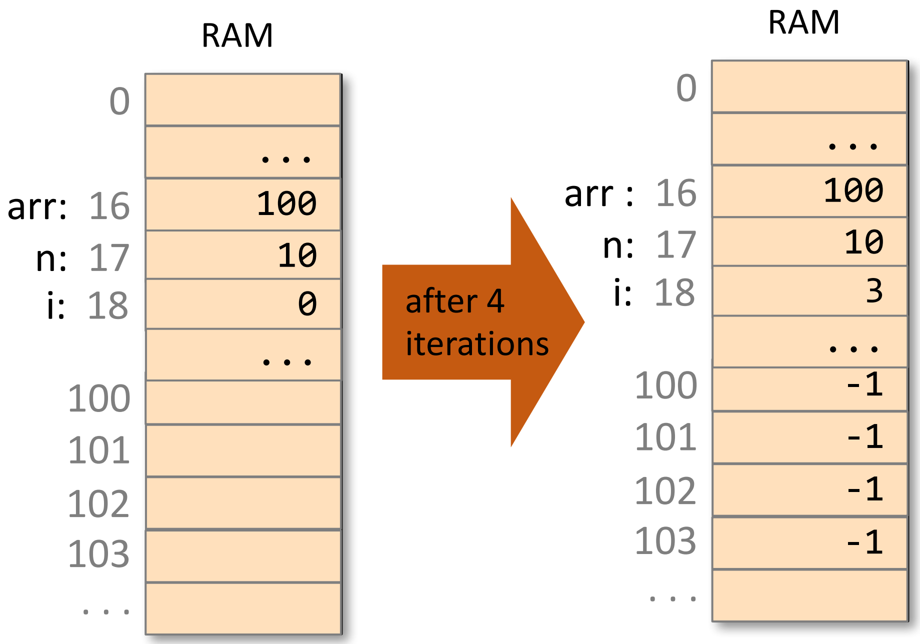
   // RAM[arr+i] = -1
   @arr
   D=M
   @i
   A=D+M
   M=-1

   // i++
   @i
   M=M+1

   @LOOP
   0;JMP

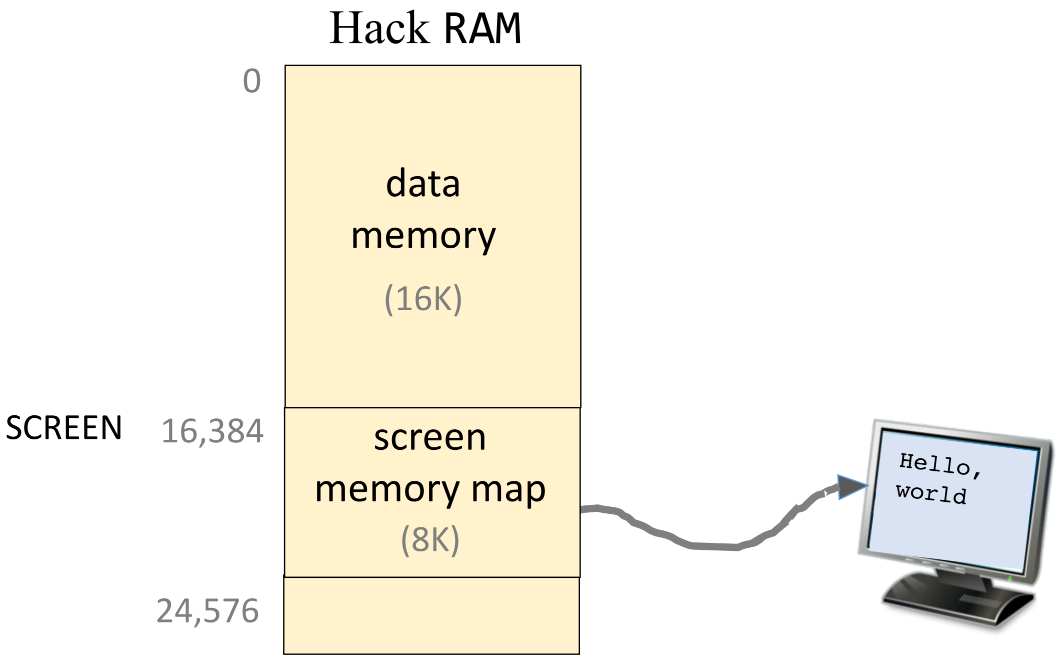
(END)
   @END
   0;JMP
```

typical pointer manipulation



- Pointers: Variables that store memory addresses (like `arr`)
- Pointers in Hack: Whenever we have to access memory using a pointer, we need an instruction like `A` = *expression*
- Semantics: "set the address register to some value".

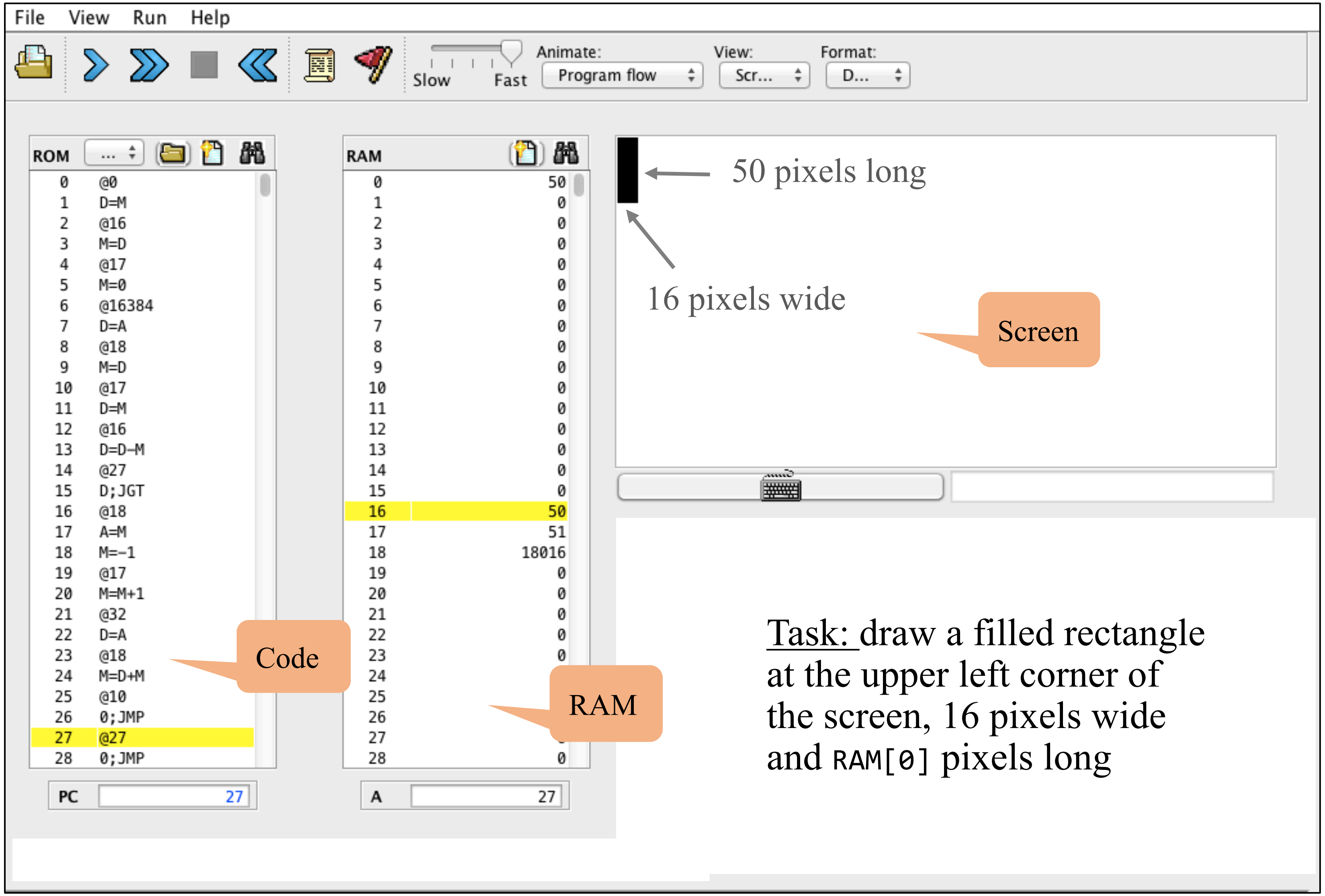
Output



<u>Hack language convention:</u>

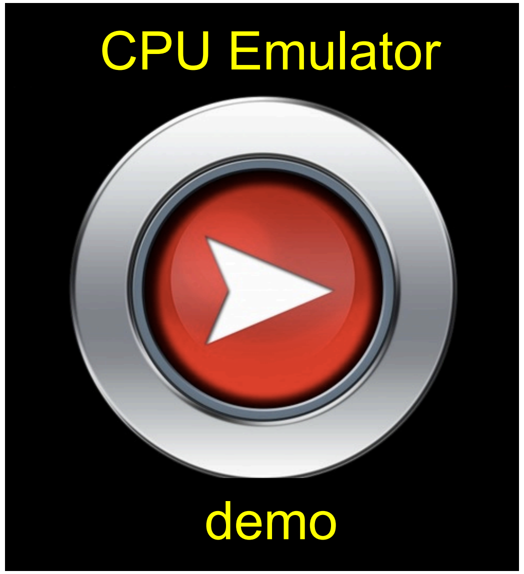
- `SCREEN`: base address of the screen memory map

Handling the screen (example)



Task: draw a filled rectangle at the upper left corner of the screen, 16 pixels wide and `RAM[0]` pixels long

Handling the screen (example)



Handling the screen (example)

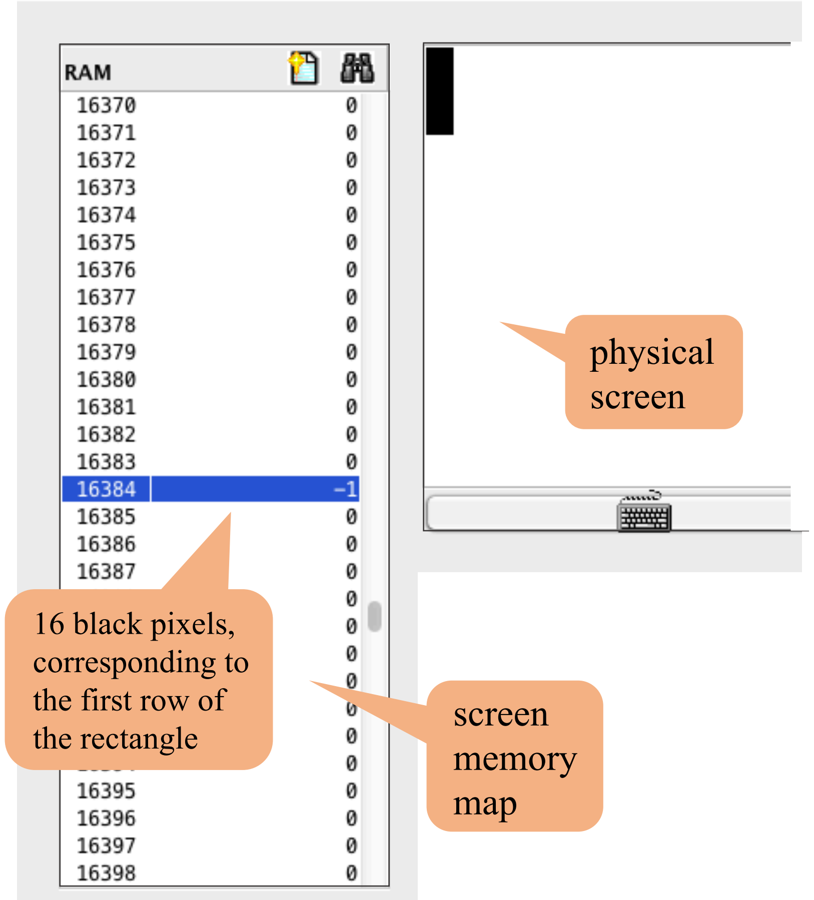
Pseudo code

```
// for (i=0; i<n; i++) {
//      draw 16 black pixels at the
//      beginning of row i
// }

addr = SCREEN
n = RAM[0]
i = 0

LOOP:
   if i > n goto END
   RAM[addr] = -1  // 1111111111111111
   // advances to the next row
   addr = addr + 32
   i = i + 1
   goto LOOP

END:
   goto END
```



Handling the screen (example)

Assembly code

```
// Program: Rectangle.asm
// Draws a filled rectangle at the
// screen's top left corner, with
// width of 16 pixels and height of
// RAM[0] pixels.
// Usage: put a non-negative number
// (rectangle's height) in RAM[0].

   @SCREEN
   D=A
   @addr
   M=D  // addr = 16384
        // (screen's base address)
   @0
   D=M
   @n
   M=D  // n = RAM[0]

   @i
   M=0  // i = 0
```

(continued)

```
(LOOP)
   @i
   D=M
   @n
   D=D-M
   @END
   D;JGT  // if i>n goto END

   @addr
   A=M
   M=-1   // RAM[addr]=1111111111111111

   @i
   M=M+1  // i = i + 1
   @32
   D=A
   @addr
   M=D+M  // addr = addr + 32
   @LOOP
   0;JMP  // goto LOOP

(END)
   @END   // program's end
   0;JMP  // infinite loop
```

Handling the screen (example)

Assembly code

```
// Program: Rectangle.asm
// Draws a filled rectangle at the
// screen's top left corner, with
// width of 16 pixels and height of
// RAM[0] pixels.
// Usage: put a non-negative number
// (rectangle's height) in RAM[0].

   @SCREEN
   D=A
   @addr
   M=D  // addr = 16384
        // (screen’s base address)
   @0
   D=M
   @n
   M=D  // n = RAM[0]

   @i
   M=0  // i = 0
```

(continued)

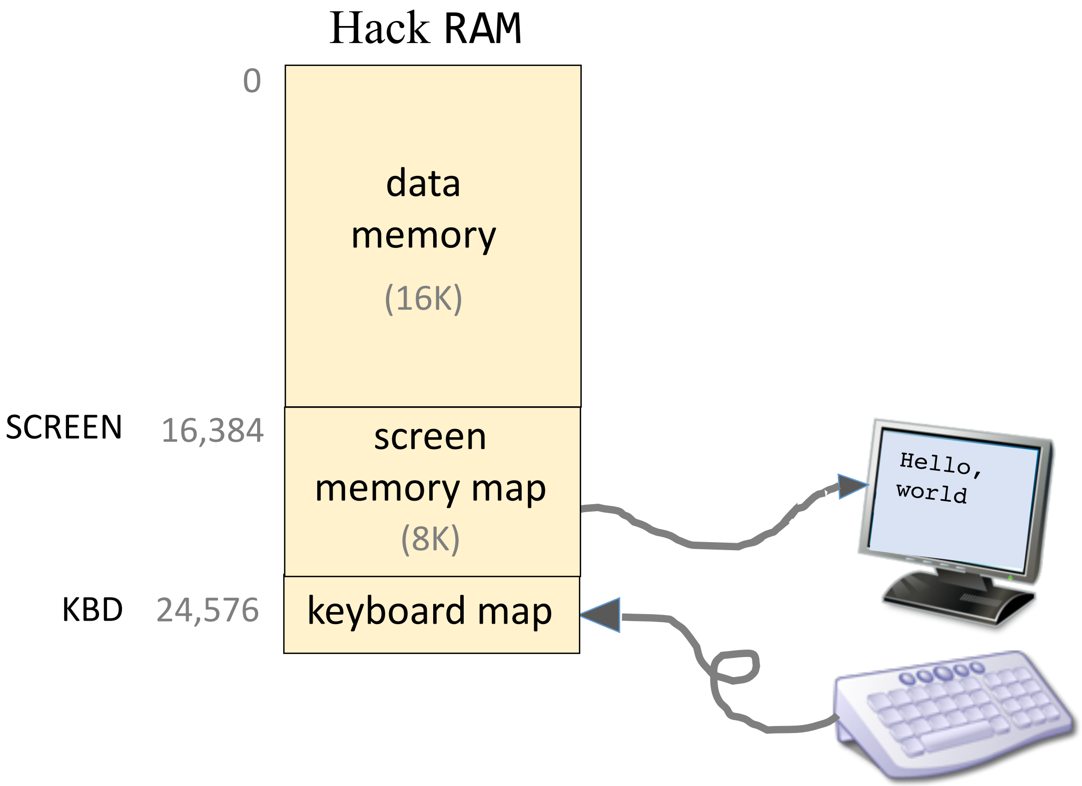
```
(LOOP)
   @i
   D=M
   @n
   D=D-M
   @END
   D;JGT  // if i>n goto END

   @addr
   A=M
   M=-1   // RAM[addr]=1111111111111111

   @i
   M=M+1  // i = i + 1
   @32
   D=A
   @addr
   M=D+M  // addr = addr + 32
   @LOOP
   0;JMP  // goto LOOP

(END)
   @END   // program’s end
   0;JMP  // infinite loop
```

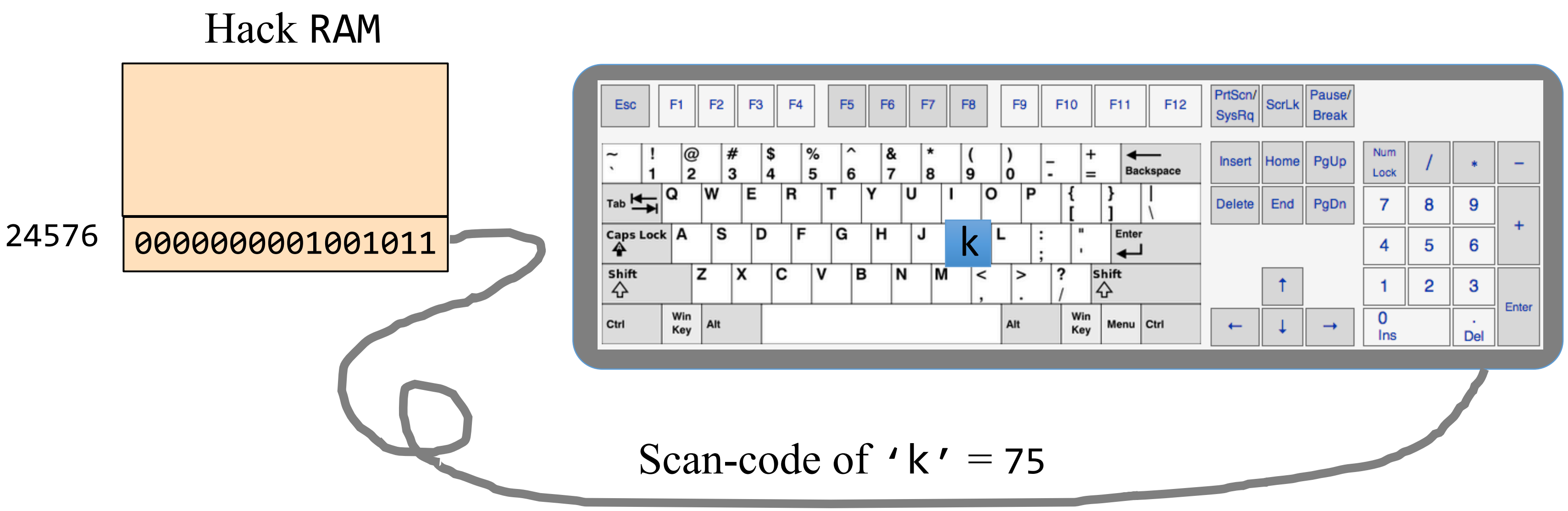
Input



<u>Hack language convention:</u>

- `SCREEN`: base address of the screen memory map
- `KBD`: address of the keyboard memory map

Handling the keyboard



<u>To check which key is currently pressed:</u>

- Read the contents of `RAM[24576]` (address `KBD`)
- If the register contains `0`, no key is pressed
- Otherwise, the register contains the scan code of the currently pressed key.

End notes

High level code

```
for (i=0; i<n; i++) {
     arr[i] = -1
}
```

Compiler

Machine language

```
   ...
   @i
    M=0
(LOOP)
    @i
    D=M
    @n
    D=D-M
    @END
    D;JEQ
    @arr
    D=M
    @i
    A=D+M
    M=-1
    @i
    M=M+1
    @LOOP
    0;JMP
(END)
    @END
    0;JMP
```

<u>Low-level programming is:</u>

- Low level
- Profound
- Subtle
- Efficient (or not)
- Intellectually challenging.

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In a Nutshell

Project objectives

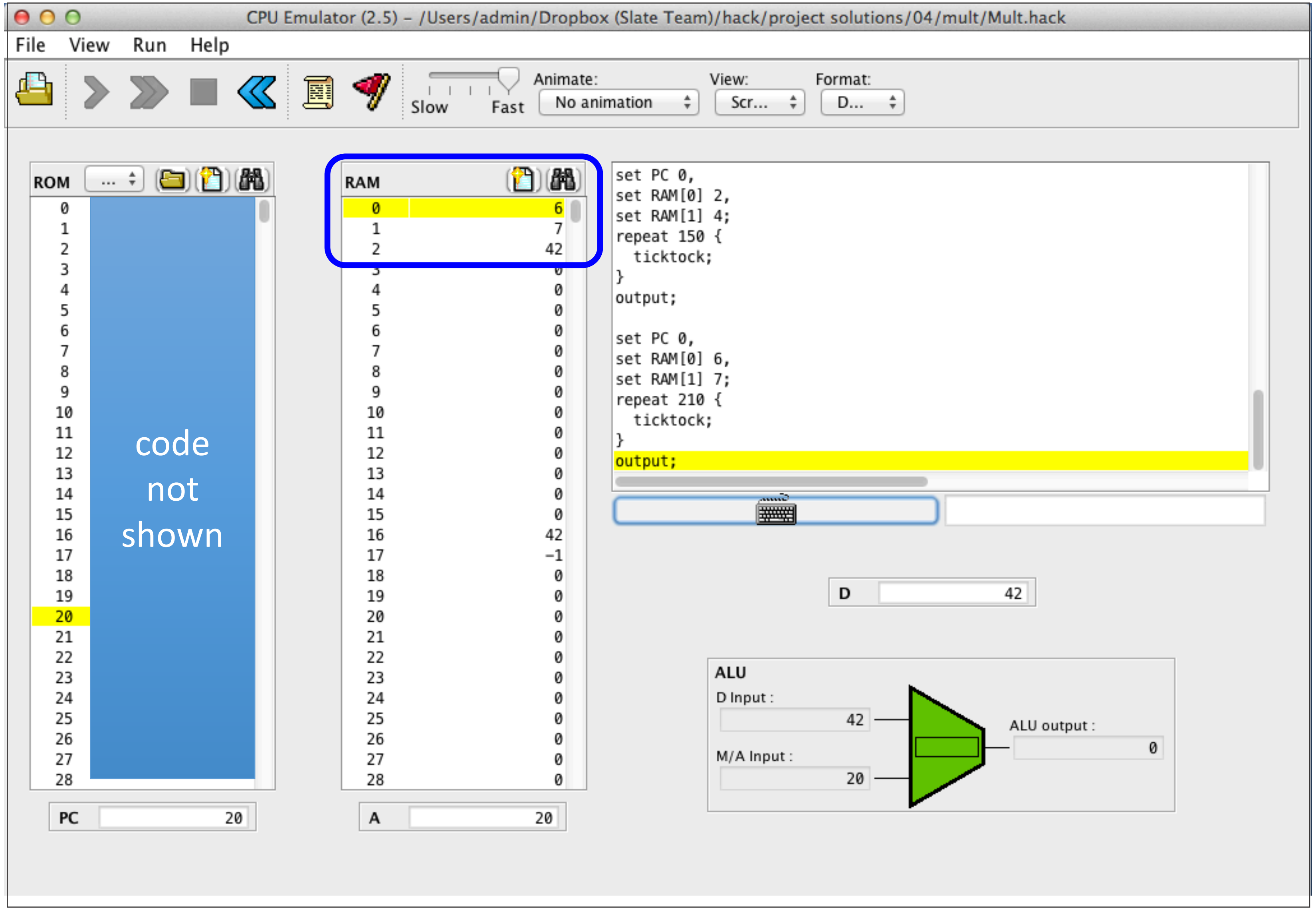
Have a taste of:

- low-level programming
- Hack assembly language
- Hack hardware

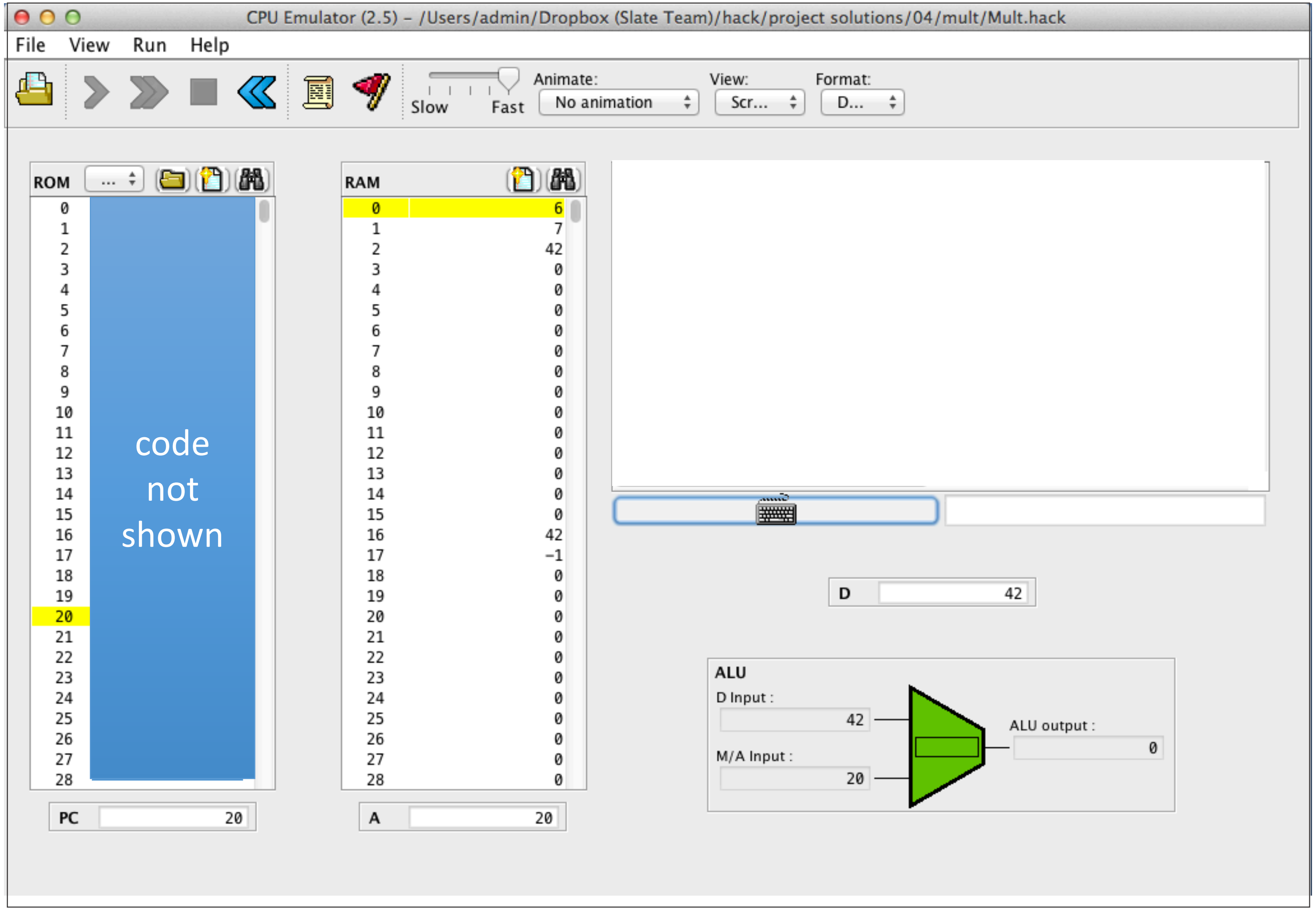
Tasks

- Write a simple algebraic program
- Write a simple interactive program.

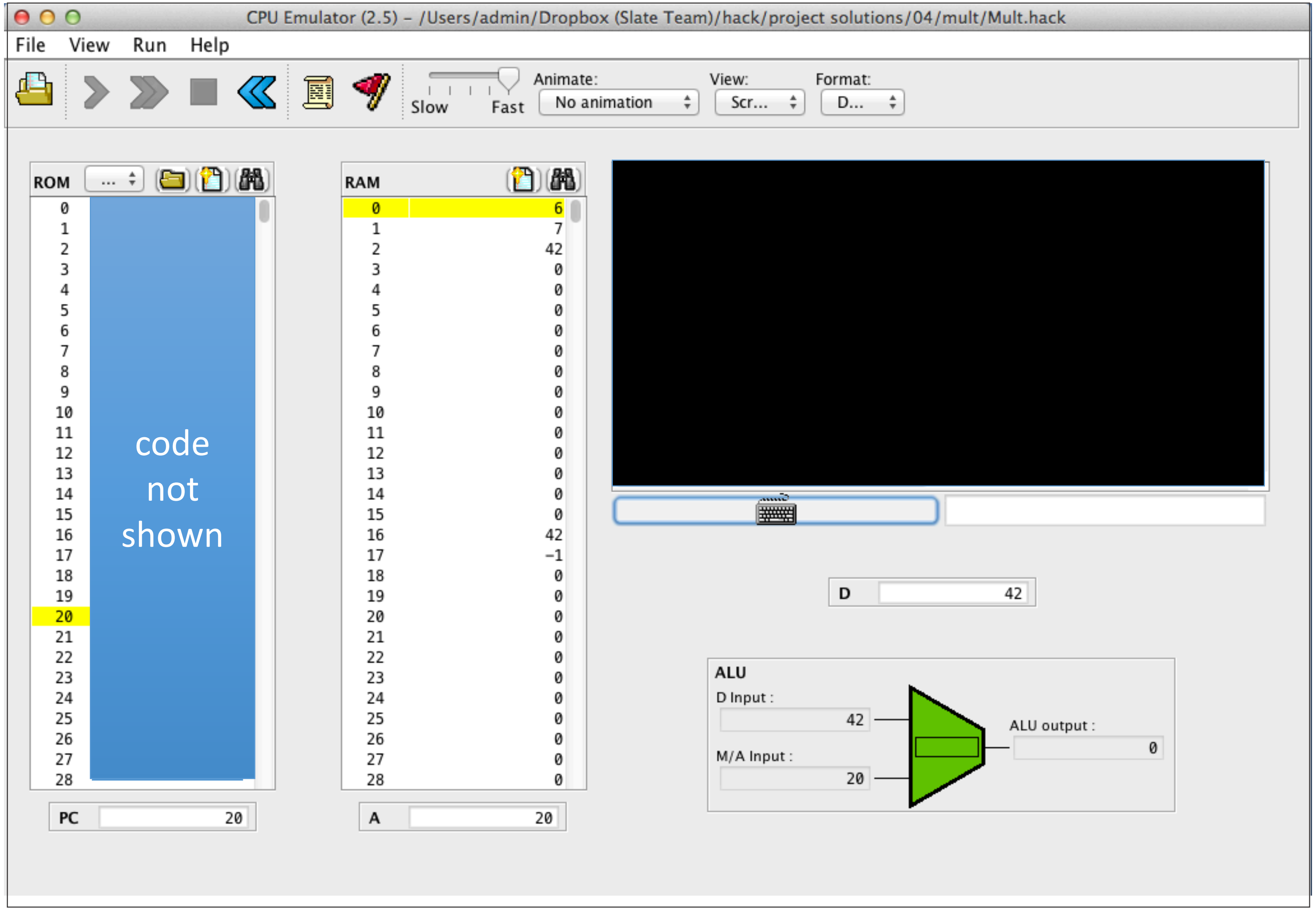
Mult: a program performing R2 = R0 * R1



`Fill`: a simple interactive program



`Fill`: a simple interactive program



`Fill`: a simple interactive program

Implementation strategy

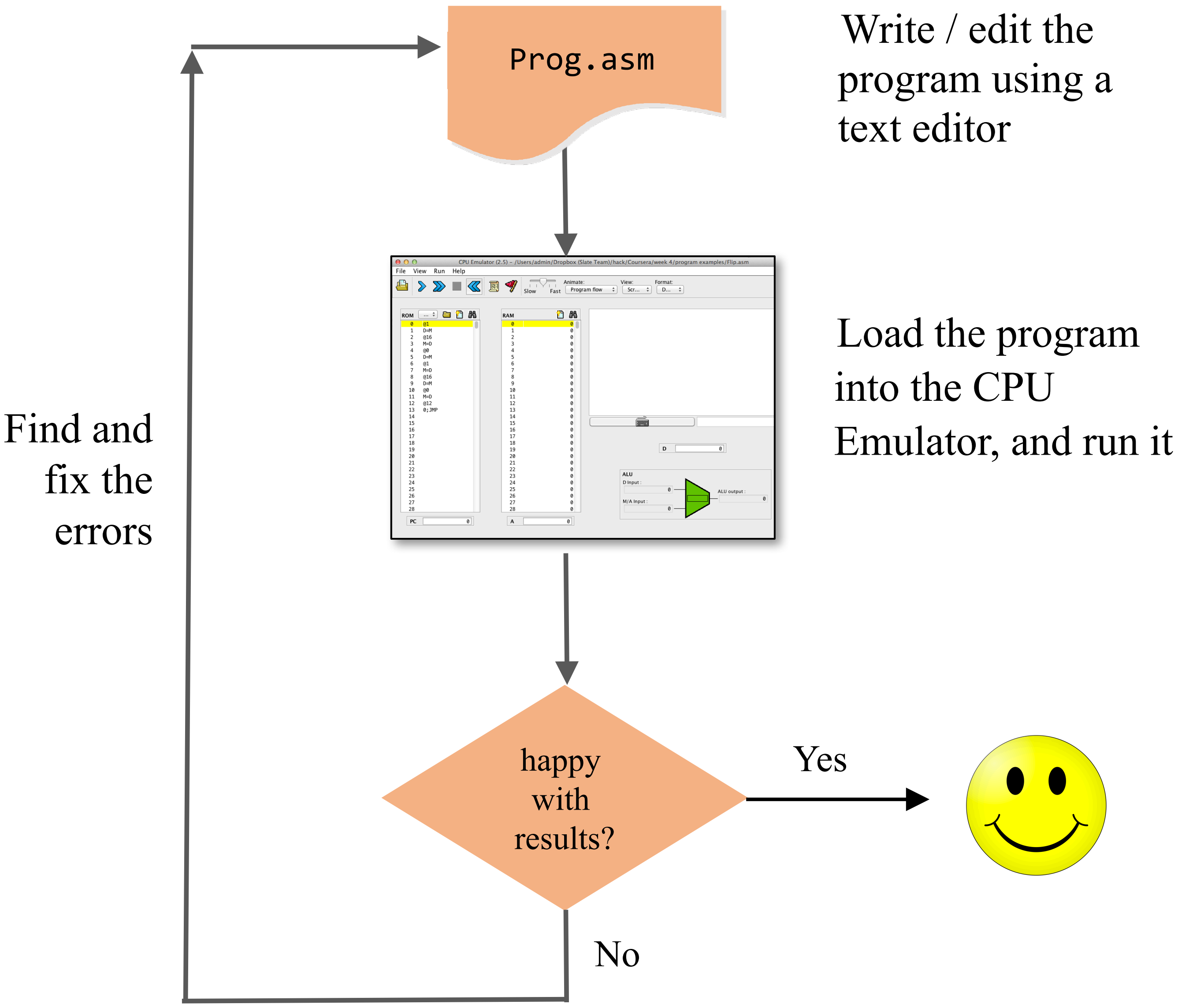
- Listen to the keyboard
- To blacken / clear the screen, write code that fills the entire screen memory map with either “white” or “black” pixels

  (Accessing the memory requires working with pointers)

Testing

- Select “no animation”
- Manual testing (no test scripts).

Program development process



Best practice

Well-written low-level code is

- Short
- Efficient
- Elegant
- Self-describing

Technical tips

- Use symbolic variables and labels
- Use sensible variable and label names
- Variables: lower-case
- Labels: upper-case
- Use indentation
- Start with pseudo code.

Project 4 resources

From NAND to Tetris

Building a Modern Computer From First Principles

- Home
- Prerequisites
- Syllabus
- Course
- Book
- Software
- Terms
- Papers
- Talks
- Cool Stuff
- About
- Team
- Q&A

Project 4: Machine Language Programming

Background

Each hardware platform is designed to execute a certain machine language, expressed using agreed-upon binary codes. Writing programs directly in binary code is a possible, yet an unnecessary, tedium. Instead, we can write such programs in a low-level symbolic language, called *assembly*, and have them translated into binary code by a program called *assembler*. In this project you will write some low-level assembly programs, and will be forever thankful for high-level languages like C and Java. (Actually, assembly programming can be a lot of fun, if you are in the right mood; it's an excellent brain teaser, and it allows you to control the underlying machine directly and completely.

Objective

To get a taste of low-level programming in machine language, and ... m. In the process of working on this project, you will become familiar w... ic language to machine-language - and you will appreciate visually h... vare platform. These lessons will be learned in the context of writing a... below.

All the necessary project 4 files are available in:
nand2tetris / projects / 04

Programs

Program	Description	Comments / Tests
Mult.asm	**Multiplication:** In the Hack framework, the top 16 RAM words (`RAM[0]` ... `RAM[15]`) are also referred to as the so-called *virtual registers* `R0` ... `R15`. With this terminology in mind, this program computes the value `R0*R1` and stores the result in `R2`.	For the purpose of this program, we assume that `R0>=0`, `R1>=0`, and `R0*R1<32768` (you are welcome to ponder where this value comes from). Your program need not test these conditions, but rather assume that they hold. To test your program, put some values in RAM[0] and RAM[1], run the code, and inspect RAM[2]. The supplied `Mult.tst` script and `Mult.cmp` compare file are deigned to test your program "officially", running it on several representative values supplied by us.

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Chapter 4

Machine Language

These slides support chapter 4 of the book

The Elements of Computing Systems

By Noam Nisan and Shimon Schocken

MIT Press