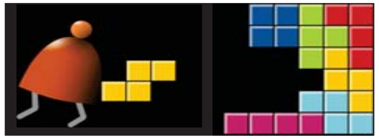
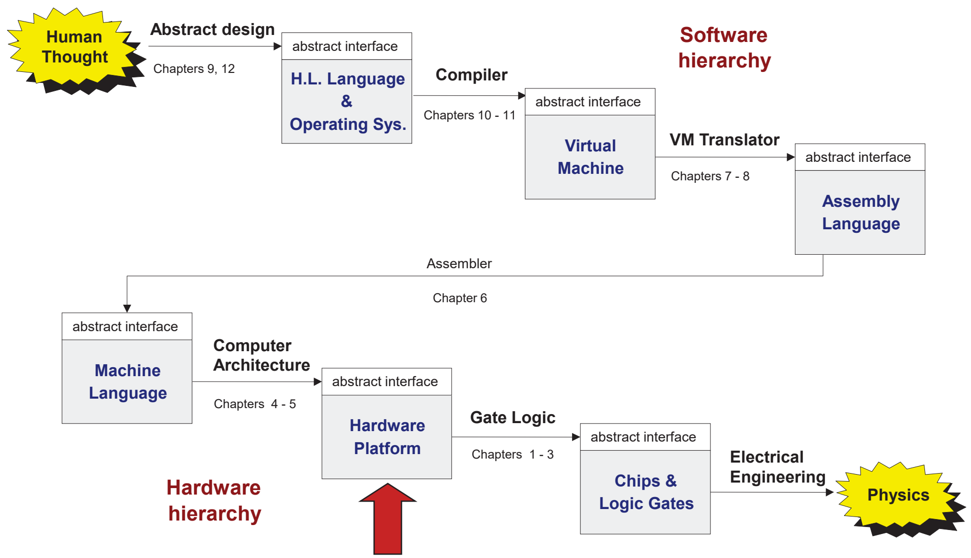
Computer Architecture



Building a Modern Computer From First Principles

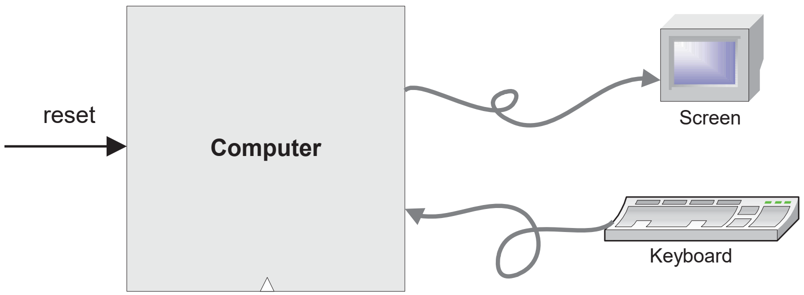
www.nand2tetris.org

Where we are at:



The Hack computer

A 16-bit machine consisting of the following elements:



The program is stored in a ROM.

The A-instruction

symbolic

`@value`

- *value* is a non-negative decimal number <= 2^{15}-1 or
- A symbol referring to such a constant

binary

`0value`

- *value* is a 15-bit binary number

Example

`@21`

`0000 0000 0001 0101`

The C-instruction

symbolic

dest* = *comp* ; *jump

binary

111A $C_1C_2C_3C_4$ C_5C_6 D_1D_2 $D_3J_1J_2J_3$

comp dest jump

not used

opcode

The *C*-instruction

111A $C_1C_2C_3C_4$ C_5C_6 D_1D_2 $D_3J_1J_2J_3$

comp dest jump

<table>
<tr><th>(when a=0)
comp</th><th>c1</th><th>c2</th><th>c3</th><th>c4</th><th>c5</th><th>c6</th><th>(when a=1)
comp</th></tr>
<tr><td>0</td><td>1</td><td>0</td><td>1</td><td>0</td><td>1</td><td>0</td><td></td></tr>
<tr><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td></td></tr>
<tr><td>-1</td><td>1</td><td>1</td><td>1</td><td>0</td><td>1</td><td>0</td><td></td></tr>
<tr><td>D</td><td>0</td><td>0</td><td>1</td><td>1</td><td>0</td><td>0</td><td></td></tr>
<tr><td>A</td><td>1</td><td>1</td><td>0</td><td>0</td><td>0</td><td>0</td><td>M</td></tr>
<tr><td>!D</td><td>0</td><td>0</td><td>1</td><td>1</td><td>0</td><td>1</td><td></td></tr>
<tr><td>!A</td><td>1</td><td>1</td><td>0</td><td>0</td><td>0</td><td>1</td><td>!M</td></tr>
<tr><td>-D</td><td>0</td><td>0</td><td>1</td><td>1</td><td>1</td><td>1</td><td></td></tr>
<tr><td>-A</td><td>1</td><td>1</td><td>0</td><td>0</td><td>1</td><td>1</td><td>-M</td></tr>
<tr><td>D+1</td><td>0</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td></td></tr>
<tr><td>A+1</td><td>1</td><td>1</td><td>0</td><td>1</td><td>1</td><td>1</td><td>M+1</td></tr>
<tr><td>D-1</td><td>0</td><td>0</td><td>1</td><td>1</td><td>1</td><td>0</td><td></td></tr>
<tr><td>A-1</td><td>1</td><td>1</td><td>0</td><td>0</td><td>1</td><td>0</td><td>M-1</td></tr>
<tr><td>D+A</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>0</td><td>D+M</td></tr>
<tr><td>D-A</td><td>0</td><td>1</td><td>0</td><td>0</td><td>1</td><td>1</td><td>D-M</td></tr>
<tr><td>A-D</td><td>0</td><td>0</td><td>0</td><td>1</td><td>1</td><td>1</td><td>M-D</td></tr>
<tr><td>D&A</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>D&M</td></tr>
<tr><td>D|A</td><td>0</td><td>1</td><td>0</td><td>1</td><td>0</td><td>1</td><td>D|M</td></tr>
</table>

The *C*-instruction

111A $C_1C_2C_3C_4$ C_5C_6 D_1D_2 $D_3J_1J_2J_3$

comp dest jump

dest	*d* (A)	*d* (D)	*d* (M)	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
DM	0	1	1	D register and RAM[A]
A	1	0	0	A register
AM	1	0	1	A register and RAM[A]
AD	1	1	0	A register and D register
ADM	1	1	1	A register, D register, and RAM[A]

The *C*-instruction

111A $C_1C_2C_3C_4$ C_5C_6 D_1D_2 $D_3J_1J_2J_3$

comp dest jump

jump	*j* (<)	*j* (=)	*j* (>)	effect:
null	0	0	0	no jump
JGT	0	0	1	if $comp > 0$ jump
JEQ	0	1	0	if $comp = 0$ jump
JGE	0	1	1	if $comp \geq 0$ jump
JLT	1	0	0	if $comp < 0$ jump
JNE	1	0	1	if $comp \neq 0$ jump
JLE	1	1	0	if $comp \leq 0$ jump
JMP	1	1	1	Unconditional jump

Hack assembly/machine language

Source code (example)

```
// Computes 1+...+RAM[0]
// And stored the sum in RAM[1]
    @i
    M=1   // i = 1
    @sum
    M=0   // sum = 0
(LOOP)
    @i    // if i>RAM[0] goto WRITE
    D=M
    @R0
    D=D-M
    @WRITE
    D;JGT
    @i    // sum += i
    D=M
    @sum
    M=D+M
    @i    // i++
    M=M+1
    @LOOP // goto LOOP
    0;JMP
(WRITE)
    @sum
    D=M
    @R1
    M=D  // RAM[1] = the sum
(END)
    @END
    0;JMP
```

assemble

Hack assembler or CPU emulator

Target code

```
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
0000000000010010
1110001100000001
0000000000010000
1111110000010000
0000000000010001
1111000010001000
0000000000010000
1111110111001000
0000000000000100
1110101010000111
0000000000010001
1111110000010000
0000000000000001
1110001100001000
0000000000010110
1110101010000111
```

assembly code v.s. machine code

The Hack computer

- A 16-bit stored program platform
- The *instruction memory* and the *data memory* are physically separate
- Screen: 512 rows by 256 columns, black and white
- Keyboard: standard
- Designed to execute programs written in the Hack machine language
- Can be easily built from the chip-set that we built so far in the course

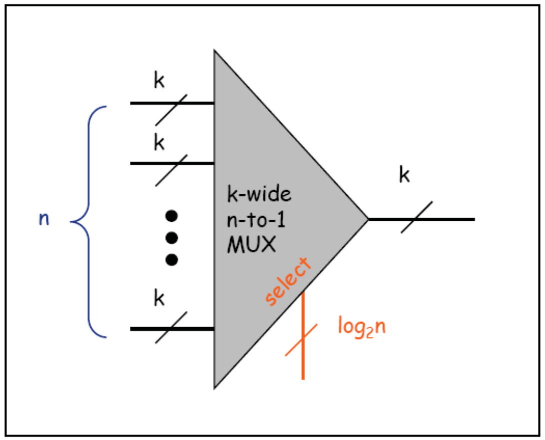
Main parts of the Hack computer:

- Instruction memory (ROM)
- Memory (RAM):
  - Data memory
  - Screen (memory map)
  - Keyboard (memory map)
- CPU
- Computer (the logic that holds everything together).

Multiplexer

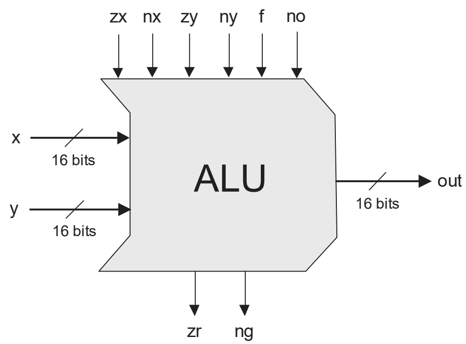
Goal: select from one of n k-bit buses

- Implemented by layering k n-to-1 multiplexer



Interface

Hack ALU



out(x, y, control bits) =

x+y, x-y, y–x,

0, 1, -1,

x, y, -x, -y,

x!, y!,

x+1, y+1, x-1, y-1,

x&y, x|y

Hack ALU

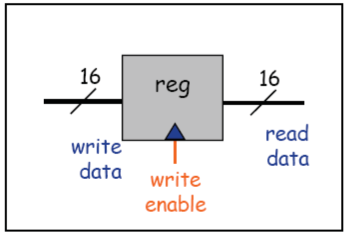
These bits instruct how to preset the x input		These bits instruct how to preset the y input		This bit selects between + / And	This bit inst. how to postset out	Resulting ALU output
zx	nx	zy	ny	f	no	out=
if zx then x=0	if nx then x=!x	if zy then y=0	if ny then y=!y	if f then out=x+y else out=x&y	if no then out=!out	f(x,y)=
1	0	1	0	1	0	0
1	1	1	1	1	1	1
1	1	1	0	1	0	-1
0	0	1	1	0	0	x
1	1	0	0	0	0	y
0	0	1	1	0	1	!x
1	1	0	0	0	1	!y
0	0	1	1	1	1	-x
1	1	0	0	1	1	-y
0	1	1	1	1	1	x+1
1	1	0	1	1	1	y+1
0	0	1	1	1	0	x-1
1	1	0	0	1	0	y-1
0	0	0	0	1	0	x+y
0	1	0	0	1	1	x-y
0	0	0	1	1	1	y-x
0	0	0	0	0	0	x&y
0	1	0	1	0	1	x|y

Registers

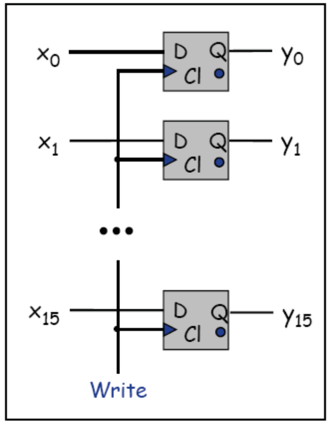
k-bit register.

- Stores k bits.
- Register contents always available on output.
- If write enable is asserted, k input bits get copied into register.

Ex: Program Counter, 16 TOY registers, 256 TOY memory locations.

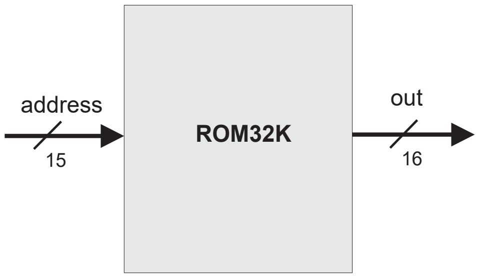


16-bit Register Interface



16-bit Register Implementation

ROM (Instruction memory)



Function:

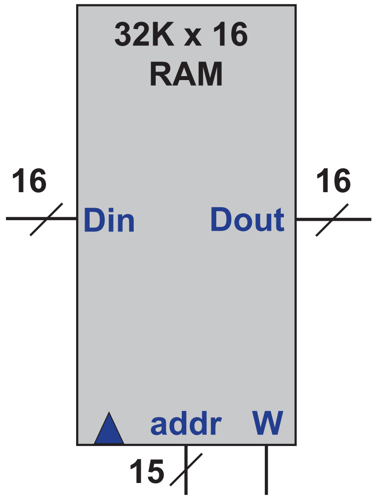
- The ROM is pre-loaded with a program written in the Hack machine language
- The ROM chip always emits a 16-bit number:

```
out = ROM32K[address]
```

- This number is interpreted as the *current instruction*.

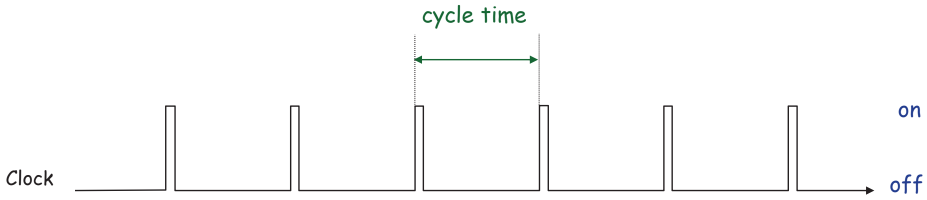
RAM (data memory)

- We will discuss the details for Hack's data memory later.



Clock

- Clock.
  - Fundamental abstraction: regular on-off pulse.
    - on: fetch phase
    - off: execute phase
  - External analog device.
  - Synchronizes operations of different circuit elements.
  - Requirement: clock cycle longer than max switching time.



Design a processor

- How to build a processor (Hack, this time)
  - Develop instruction set architecture (ISA)
    - 16-bit words, two types of machine instructions
  - Determine major components
    - ALU, registers, program counter, memory
  - Determine datapath requirements
    - Flow of bits
  - Analyze how to implement each instruction
    - Determine settings of control signals

Hack programming reference card

Hack commands:

A-command: @value // A<-value; M=RAM[A]

C-command: 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

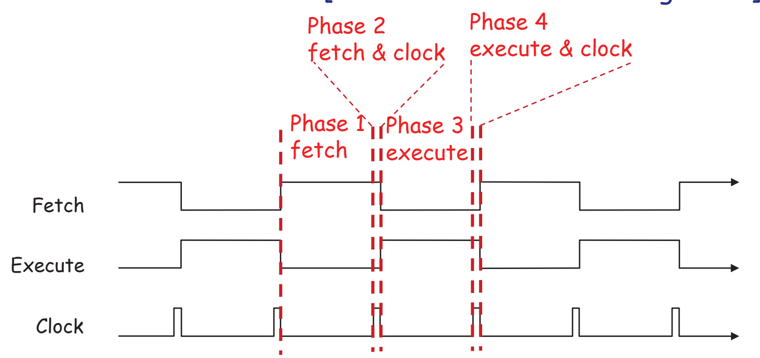
dest = M, D, A, MD, AM, AD, AMD, or null

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

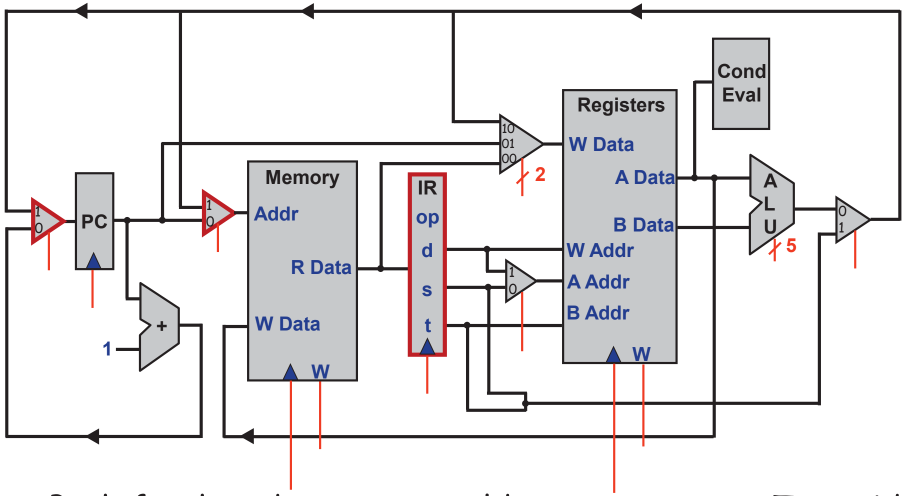
In the command dest = comp; jump, the jump materialzes (PC<-A) if (comp jump 0) is true. For example, in D=D+1,JLT, we jump if D+1 < 0.

Fetch and execute

- In Toy, we have two phases: fetch and execution .
- We use two cycles since fetch and execute phases each access memory and alter program counter.
  - fetch [set memory address from pc]
  - fetch and clock [write instruction to IR]
  - execute [set ALU inputs from registers]
  - execute and clock [write result of ALU to registers]



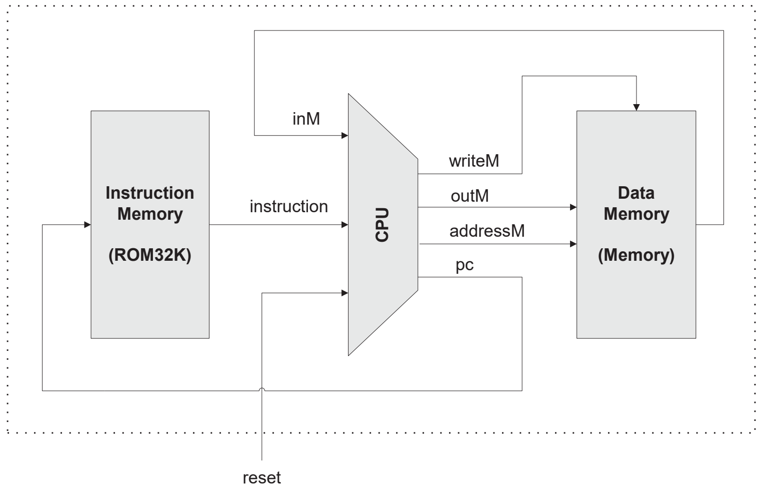
Toy architecture



- Both fetch and execute would access memory. To avoid conflict, we add a MUX. Similar for PC.
- In addition, we need a register IR to store the instruction.

Fetch and execute

- In Hack, we avoid two cycles and IR by using two separate memory chips, one for data and the other for instruction.



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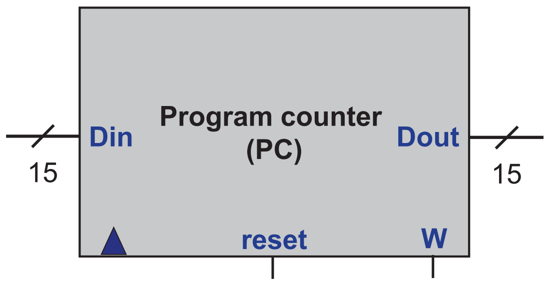
Program counter

- Program counter emits the address of the next instruction.
  - To start/restart the program execution: PC=0
  - No jump: PC++
  - Unconditional jump: PC=A
  - Conditional jump: if (cond.) PC=A else PC++



Note that the design is slightly different from your project #3.

Program counter

if (reset) PC=0

else if (W) PC=Din

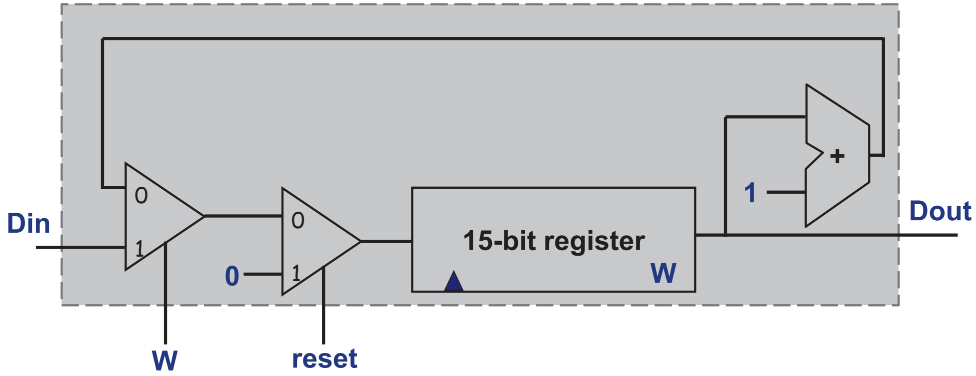
else PC++

Program counter

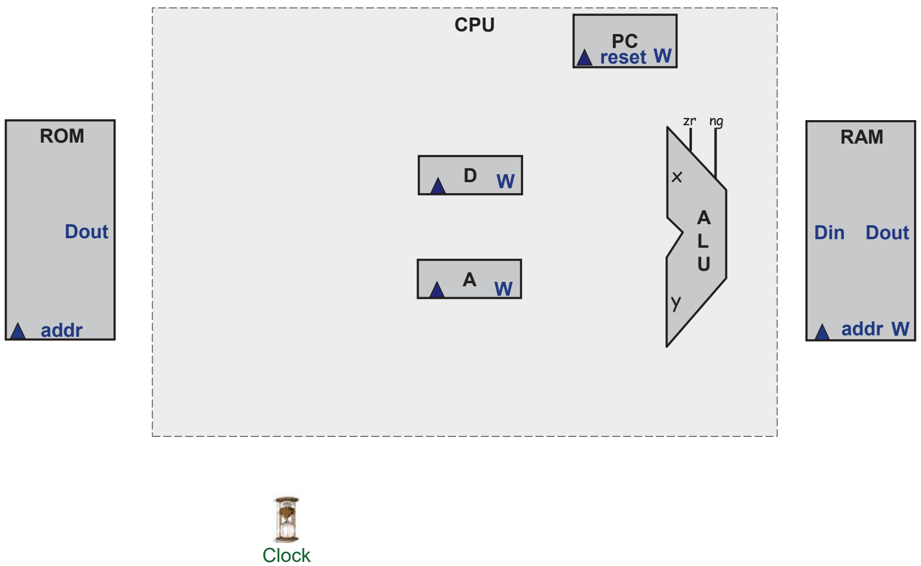
if (reset) PC=0

else if (W) PC=Din

else PC++



Hack architecture (component)



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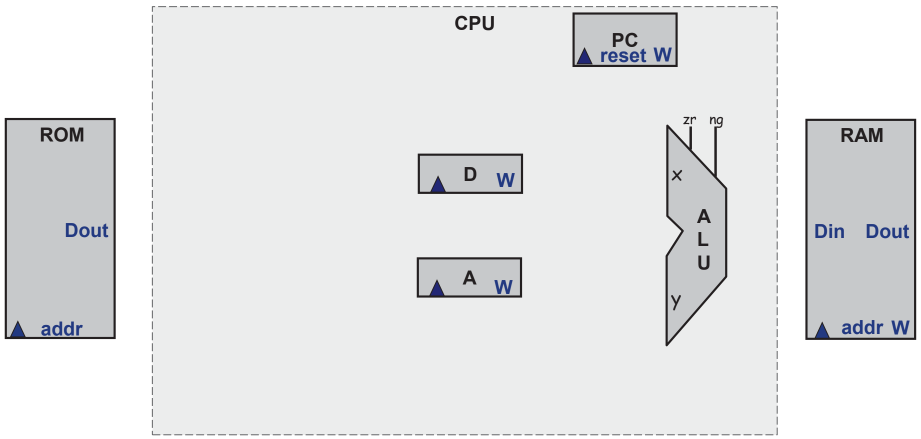
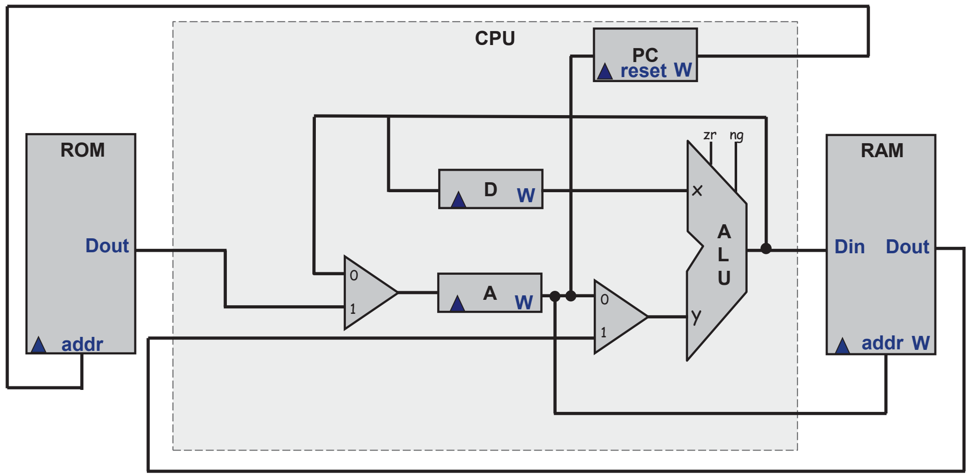
Hack architecture (data path)



Fetch: instruction=ROM[PC]
@value // A<-value; M=RAM[A]
[ADM] = x op y; jump // x=D; y=A or M; if jump then PC<-A

Hack architecture (data path)



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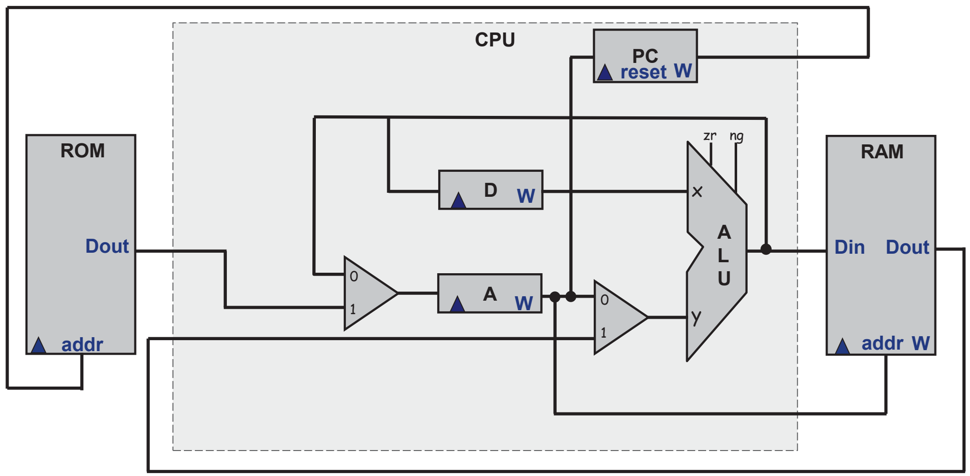
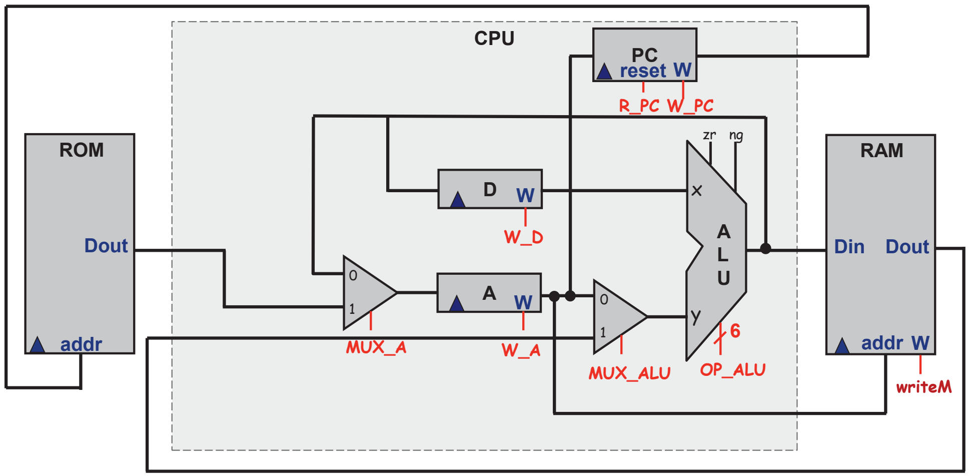
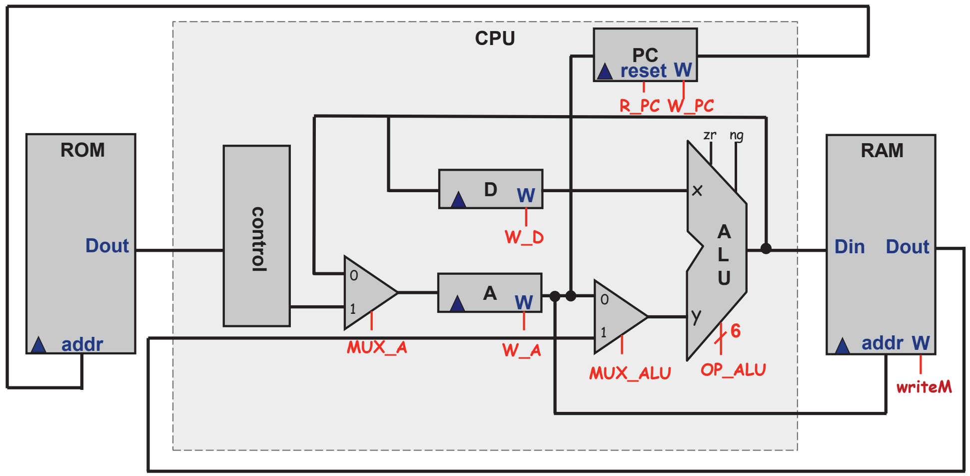


Hack architecture (control)

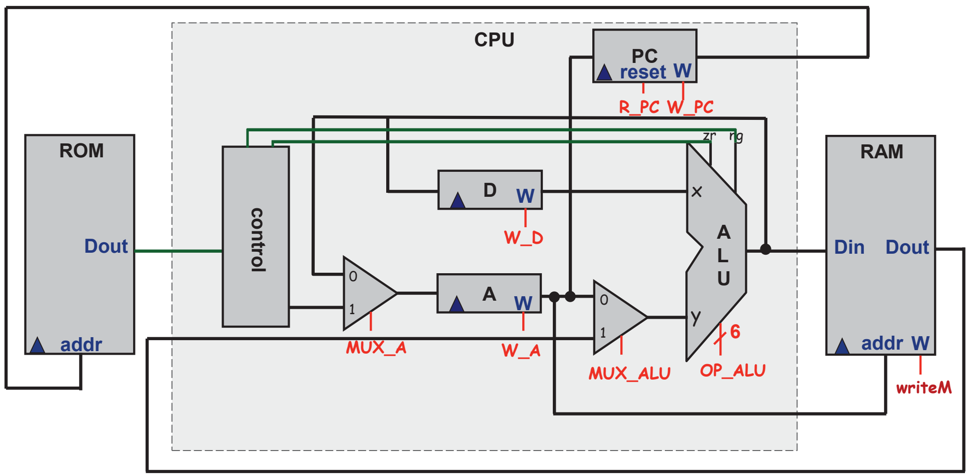


A total of 13 control signals

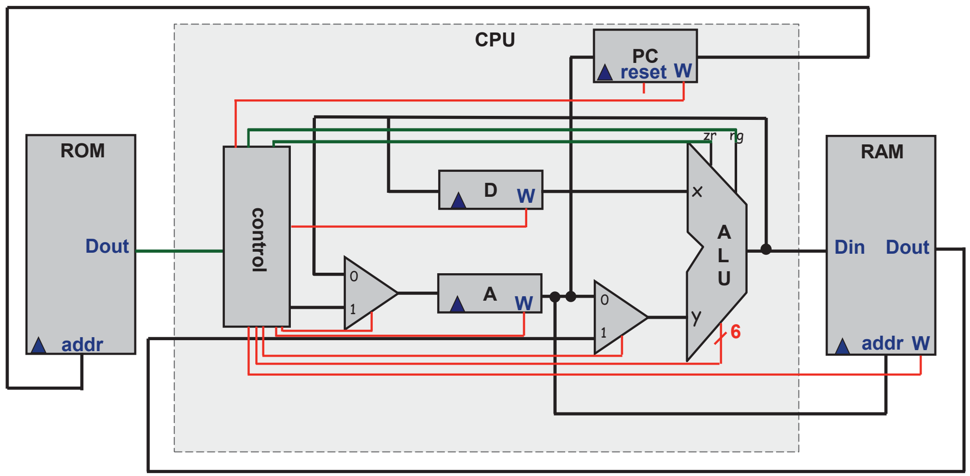
Hack architecture (control)



Hack architecture (control)



Hack architecture (control)



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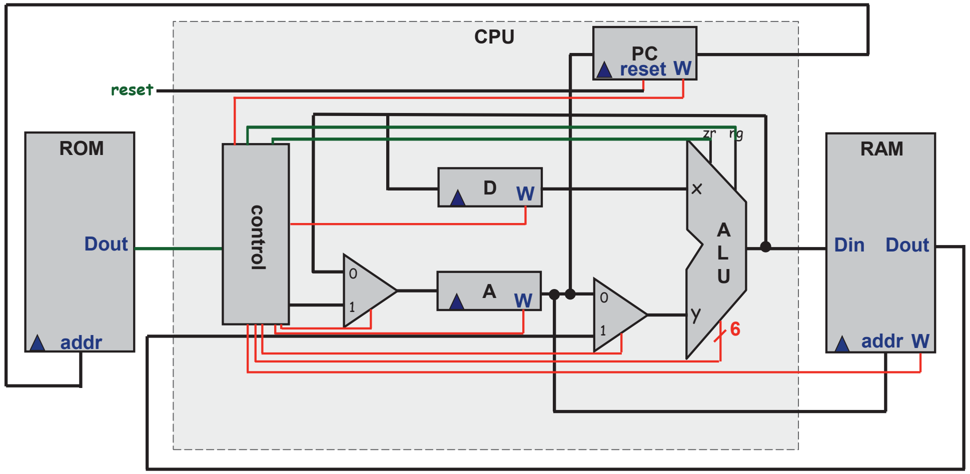
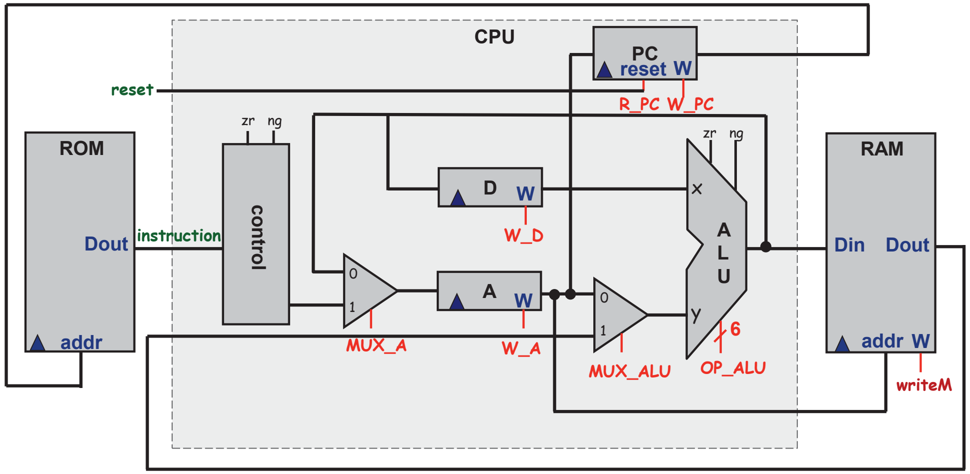


Hack architecture (control)



Hack architecture (control)

- Inputs: instruction, zr, ng
  - instruction

I_{15}	$I_{14..0}$
0	value

111A $C_1C_2C_3C_4$ C_5C_6 D_1D_2 $D_3J_1J_2J_3$

- Outputs:
  - OP_ALU
  - MUX_A
  - MUX_ALU
  - W_A
  - W_D
  - writeM
  - W_PC

Hack architecture (control)

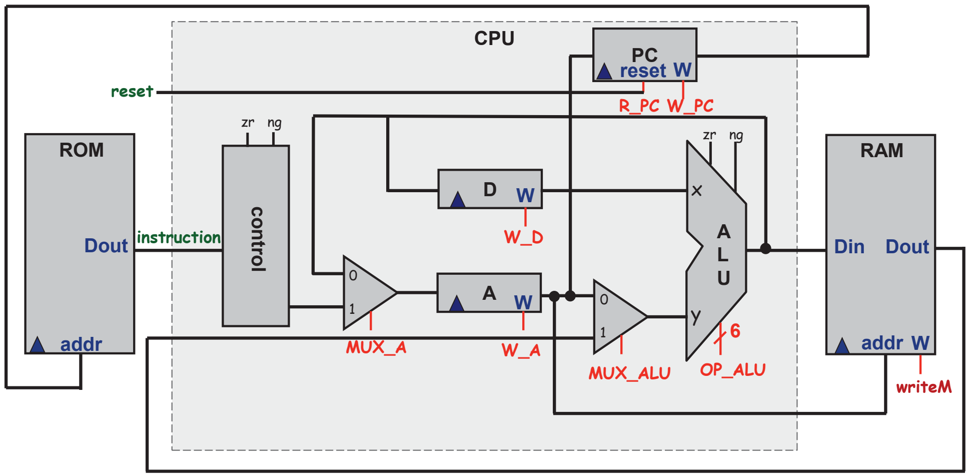
- Inputs: instruction, zr, ng
  - instruction

I_{15}	$I_{14..0}$
0	value

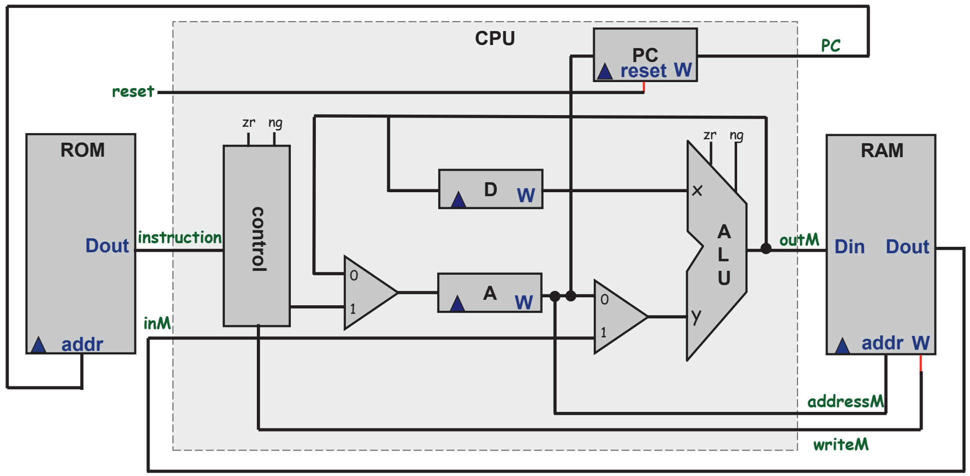
111A $C_1C_2C_3C_4$ C_5C_6 D_1D_2 $D_3J_1J_2J_3$

- Outputs:
  - OP_ALU = $C_1C_2C_3C_4C_5C_6$
  - MUX_A = $\overline{I_{15}}$
  - MUX_ALU = A
  - W_A = (I_{15} & D_1) + $\overline{I_{15}}$
  - W_D = I_{15} & D_2
  - writeM = I_{15} & D_3
  - W_PC = I_{15}& ((J_1&ng) + (J_2&zr) + (J_3&gt)); gt = $\overline{ng}$ & $\overline{zr}$

Hack architecture (trace @10 / D=M+1;JGE)



Hack architecture (CPU interface)



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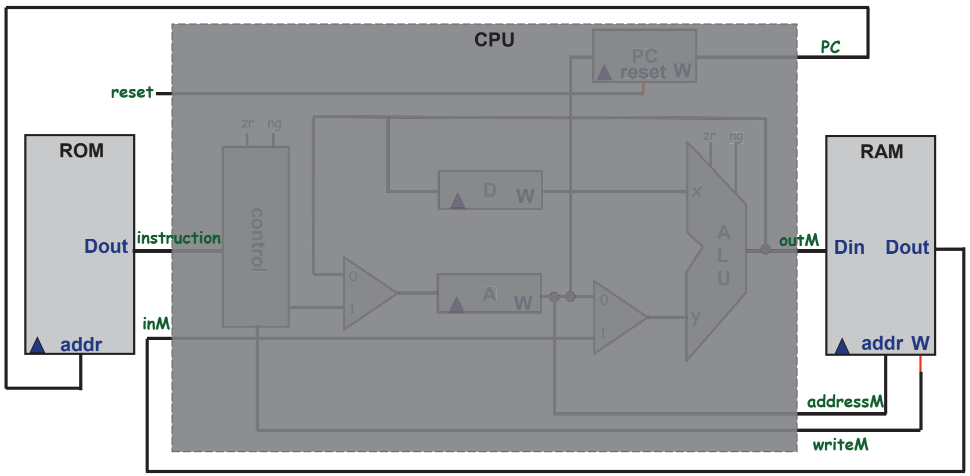
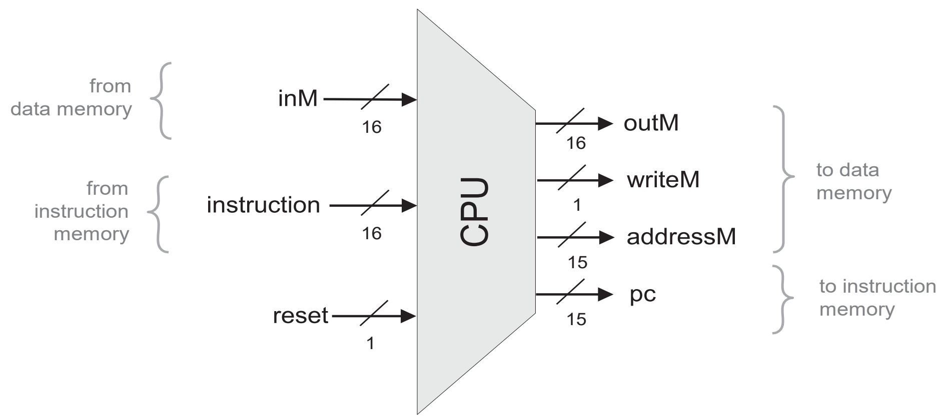
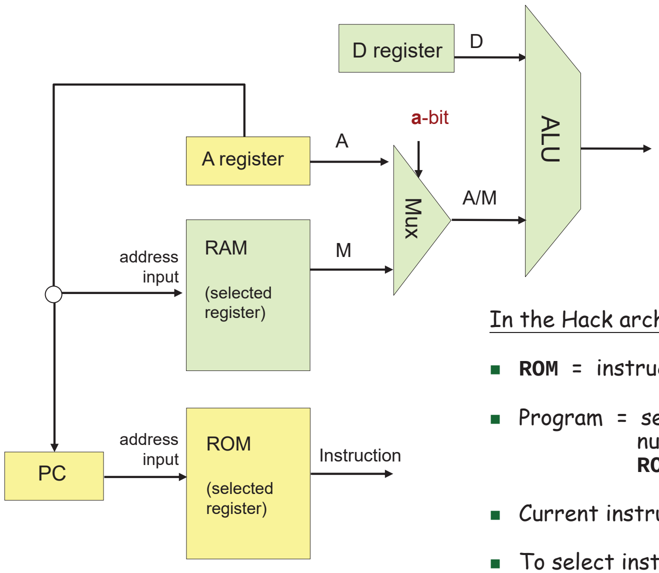


Hack CPU



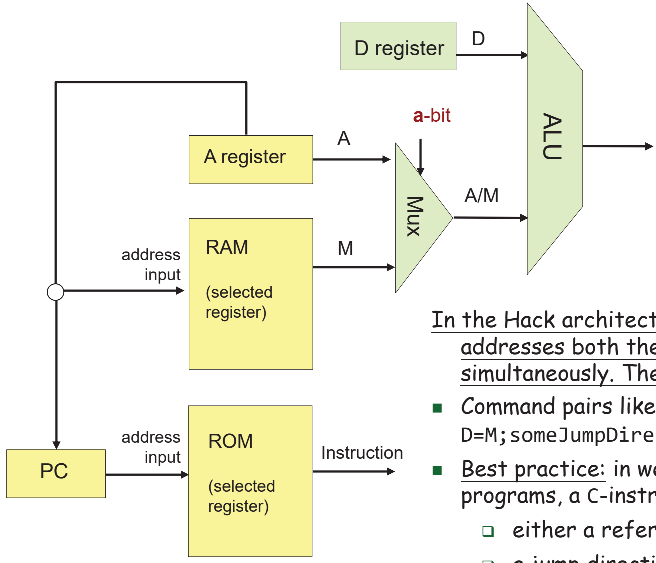
Control (focus on the yellow chips only)



In the Hack architecture:

- **ROM** = instruction memory
- Program = sequence of 16-bit numbers, starting at **ROM[0]**
- Current instruction = **ROM[PC]**
- To select instruction *n* from the **ROM**, we set **A** to *n*, using the instruction @**n**

Side note (focus on the yellow chip parts only)



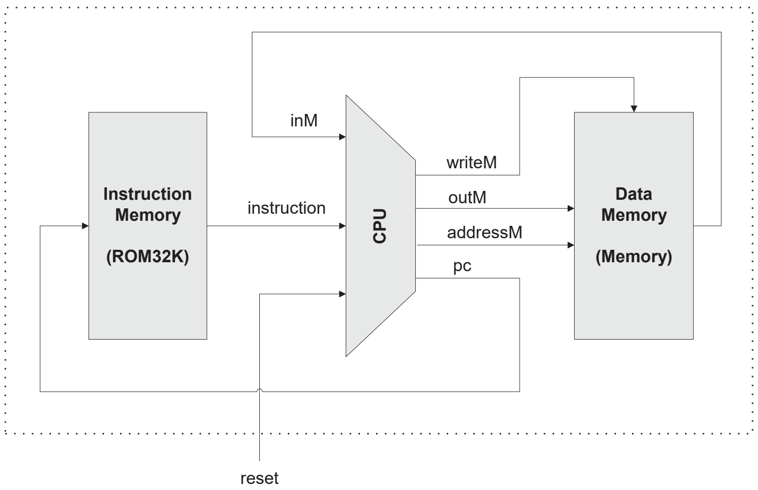
In the Hack architecture, the A register addresses both the RAM and the ROM, simultaneously. Therefore:

- Command pairs like `@addr` followed by `D=M;someJumpDirective` make no sense
- Best practice: in well-written Hack programs, a C-instruction should contain
  - either a reference to M, or
  - a jump directive,

  but not both.

The Hack computer (put together)

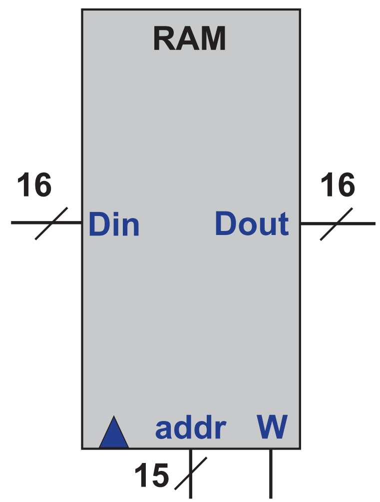
A 16-bit machine consisting of the following elements:



Both memory chips are 16-bit wide and have 15-bit address space.

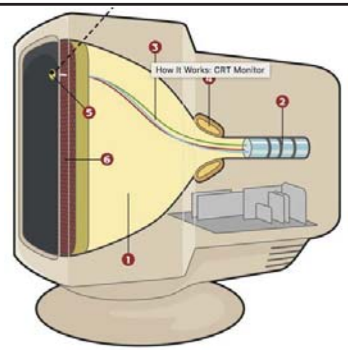
RAM (data memory)

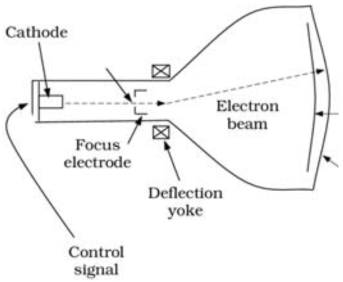
- The RAM used in Hack is different from a normal RAM. It also plays the role for I/O.
- Programmers usually use high-level library for I/O, such as printf, drawline.
- But, at low-level, we usually need to manipulate bits directly for I/O.



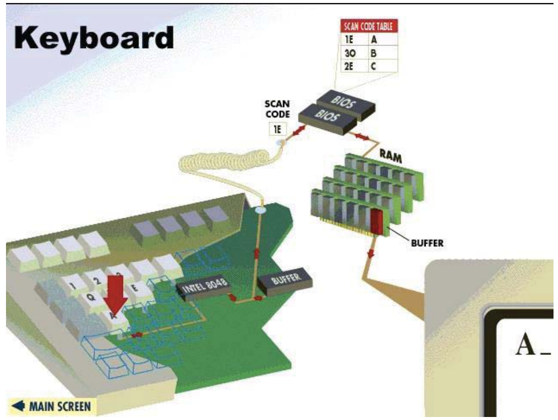
Displays

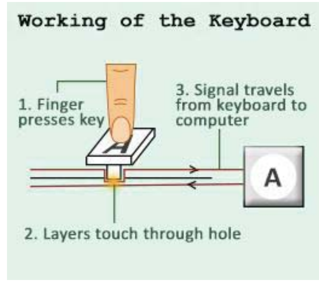
- CRT displays
  - resolution
  - refresh rate

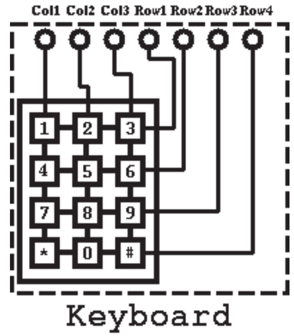





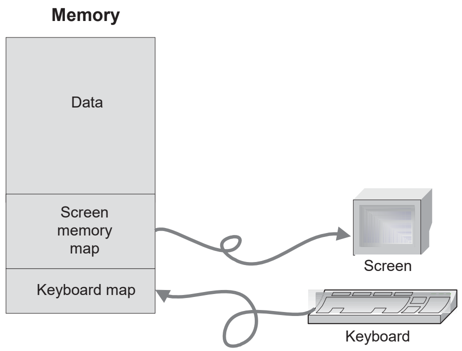
keyboard





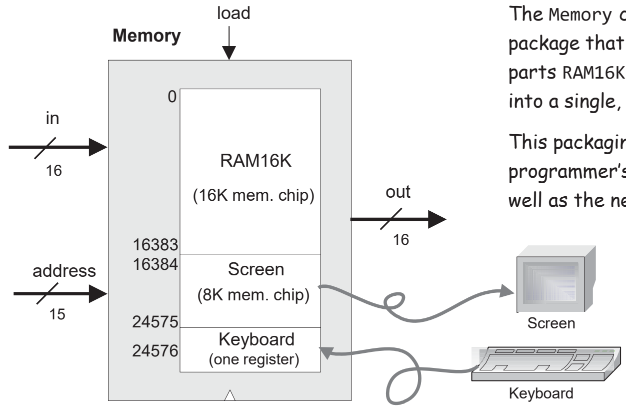
Memory: conceptual / programmer's view



Using the memory:

- To record or recall values (e.g. variables, objects, arrays), use the first 16K words of the memory
- To write to the screen (or read the screen), use the next 8K words of the memory
- To read which key is currently pressed, use the next word of the memory.

Memory: physical implementation



The `Memory` chip is essentially a package that integrates the three chip-parts `RAM16K`, `Screen`, and `Keyboard` into a single, contiguous address space.

This packaging effects the programmer's view of the memory, as well as the necessary I/O side-effects.

Access logic:

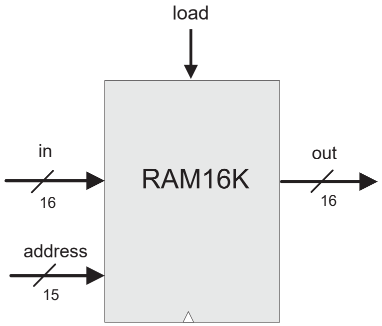
- Access to any address from 0 to 16,383 results in accessing the `RAM16K` chip-part
- Access to any address from 16,384 to 24,575 results in accessing the `Screen` chip-part
- Access to address 24,576 results in accessing the `keyboard` chip-part
- Access to any other address is invalid.

Data memory

Low-level (hardware) read/write logic:

To read RAM[k]: set address to k, probe out

To write RAM[k]=x: set address to k, set in to x, set load to 1, run the clock



High-level (OS) read/write logic:

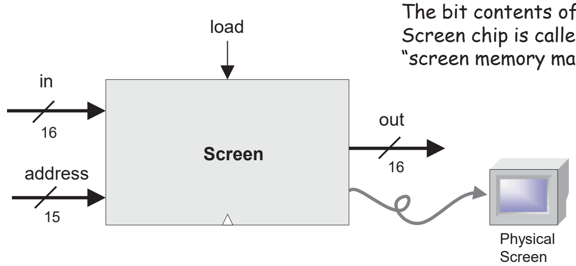
To read RAM[k]: use the OS command out = peek(k)

To write RAM[k]=x: use the OS command poke(k,x)

peek and poke are OS commands whose implementation should effect the same behavior as the low-level commands

More about peek and poke this later in the course, when we'll write the OS.

Screen



The bit contents of the Screen chip is called the "screen memory map"

In the Hack platform, the screen is implemented as an 8K 16-bit RAM chip with a side effect of refreshing.

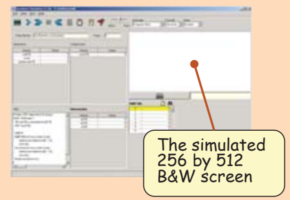
The Screen chip has a basic RAM chip functionality:

- read logic: out = Screen[address]
- write logic: if load then Screen[address] = in

Side effect:

Continuously refreshes a 256 by 512 black-and-white screen device

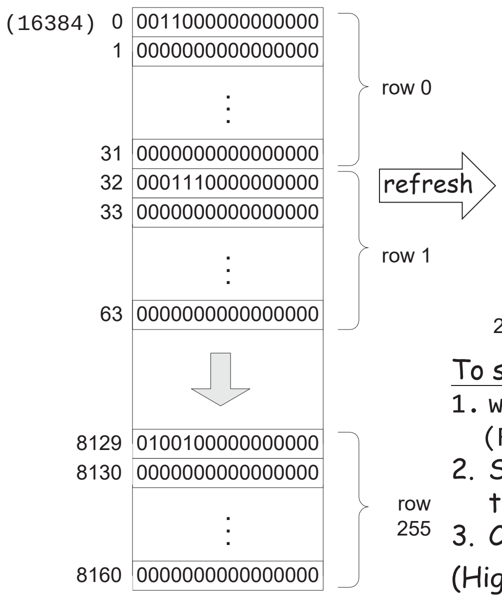
Simulated screen:

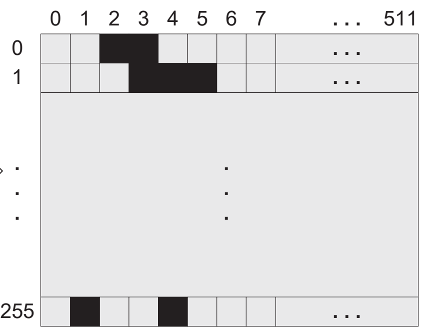


The simulated 256 by 512 B&W screen

When loaded into the hardware simulator, the built-in Screen.hdl chip opens up a screen window; the simulator then refreshes this window from the screen memory map several times each second.

Screen memory map





To set pixel (row,col) black

1. word=Screen[32*row + col/16] (RAM[16384 + 32*row + col/16])
2. Set the (col%16)-th bit of word to 1
3. Commit word to the RAM

(High-level: use the OS command drawPixel(row,col))

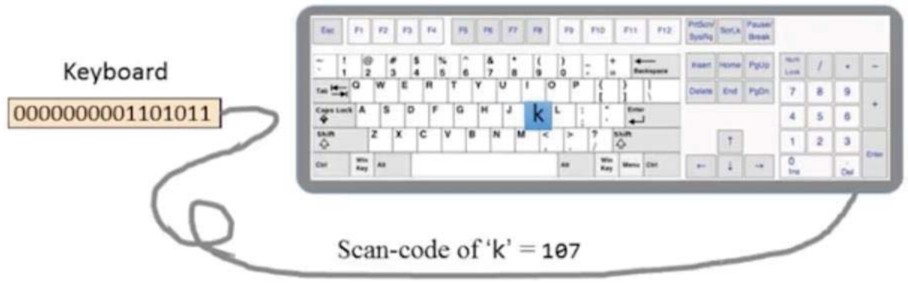
keyboard

- A 16-bit register is used to keep the key stroke.

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

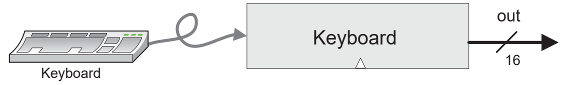
keyboard

- A 16-bit register is used to keep the key stroke.

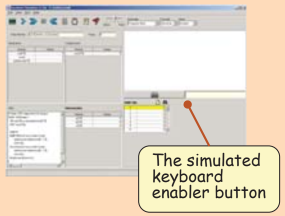


When a key is pressed on the keyboard, the key's scan code appears in the keyboard memory map .

Keyboard



Simulated keyboard:



The keyboard is implemented as a built-in **Keyboard.hdl** chip. When this java chip is loaded into the simulator, it connects to the regular keyboard and pipes the scan-code of the currently pressed key to the keyboard memory map.

Keyboard chip: a single 16-bit register

Input: scan-code (16-bit value) of the currently pressed key, or 0 if no key is pressed

Output: same

Special keys:

Key pressed	Keyboard output	Key pressed	Keyboard output
newline	128	end	135
backspace	129	page up	136
left arrow	130	page down	137
up arrow	131	insert	138
right arrow	132	delete	139
down arrow	133	esc	140
home	134	f1-f12	141-152

How to read the keyboard:

- Low-level (hardware): probe the contents of the `Keyboard` chip
- High-level: use the OS command `keyPressed()` (effects the same operation, discussed later in the course, when we'll write the OS).

Some scan codes

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

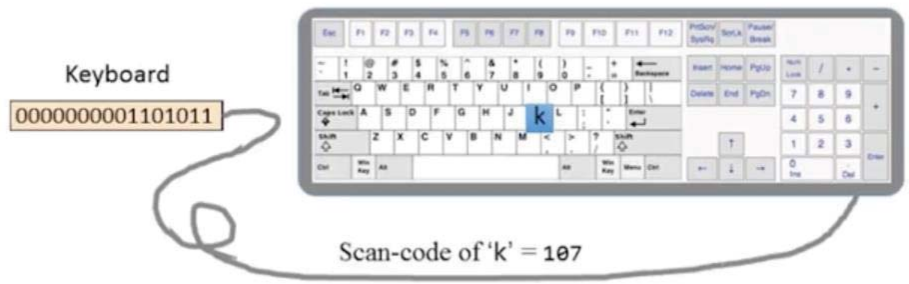
key	code
A	65
B	66
C	…
…	…
Z	90
[	91
/	92
]	93
^	94
_	95
`	96

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

(Subset of Unicode)

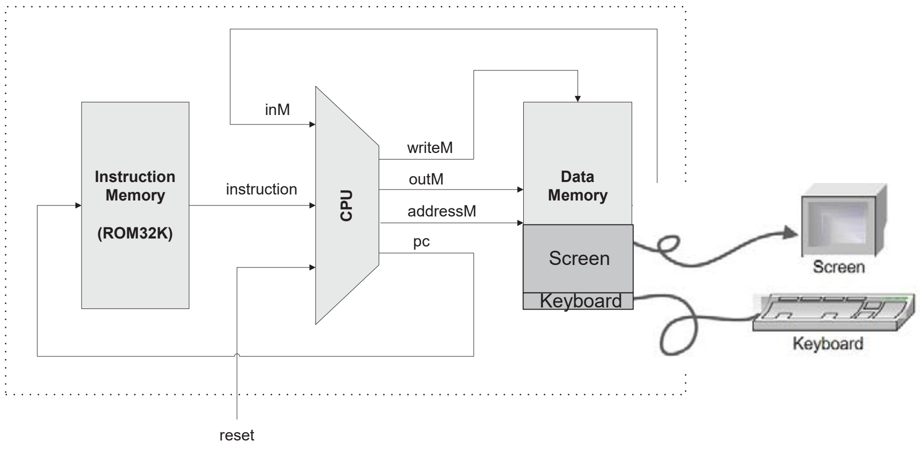
Keyboard memory map



- To check which key is currently pressed:
  - Probe the content of the `Keyboard` chip
  - In the Hack computer, probe the content of `RAM[24576]`
  - If the register contains `0`, no key is pressed.

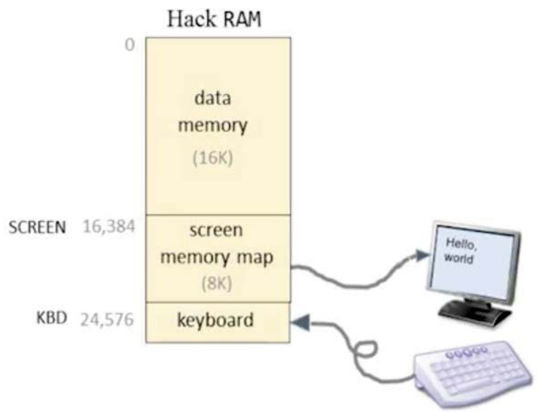
The Hack computer (put together)

A 16-bit machine consisting of the following elements:



Both memory chips are 16-bit wide and have 15-bit address space.

Assembly programming with I/O

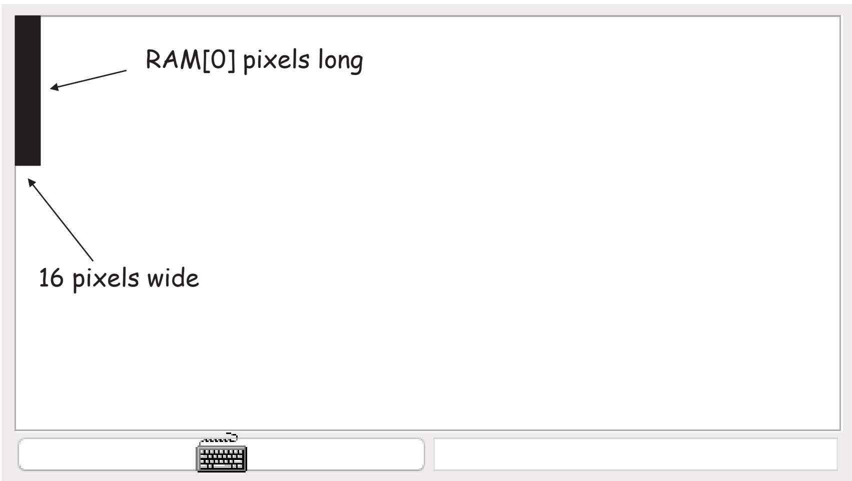


Hack language convention:

- SCREEN: base address of the screen memory map, 16,384.
- KBD: address of the keyboard memory map, 24,576.

Example: draw a rectangle

- Draw a filled rectangle at the upper left corner of the screen, 16 pixels wide and RAM[0] pixels long. (demo)



Example: draw a rectangle (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  // 1111 1111 1111 1111
  addr = addr+32  // advances to the next row
  i++;
  goto LOOP
END:
  goto END
```

Example: draw a rectangle (assembly)

```
    @SCREEN
    D=A
    @addr
    M=D       // addr = SCREEN

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

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

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

LOOP:
  if (i>n) goto END
  RAM[addr] = -1
  addr = addr+32
  i++;
  goto LOOP
END:
  goto END
```


Example: draw a rectangle (assembly)

```
(LOOP)
    @i
    D=M
    @n
    D=D-M
    @END
    D; JGT

    @addr
    A=M
    M=-1
```

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

LOOP:
  if (i>n) goto END
  RAM[addr] = -1
  addr = addr+32
  i++;
  goto LOOP
END:
  goto END
```


Example: draw a rectangle (assembly)

```
(LOOP)
    @i
    D=M
    @n
    D=D-M
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    D; JGT

    @addr
    A=M
    M=-1
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addr = SCREEN
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LOOP:
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  addr = addr+32
  i++;
  goto LOOP
END:
  goto END
```


Example: draw a rectangle (assembly)

```
    @32
    D=A
    @addr
    M=D+M   // addr = addr+32

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

    @LOOP
    0; JMP  // goto LOOP

(END)
    @END
    0; JMP
```

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

LOOP:
  if (i>n) goto END
  RAM[addr] = -1
  addr = addr+32
  i++;
  goto LOOP
END:
  goto END
```

Example: draw a rectangle (assembly)

```
    @32
    D=A
    @addr
    M=D+M   // addr = addr+32

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(END)
    @END
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  goto END
```


Example: draw a rectangle (assembly)

```
    @32
    D=A
    @addr
    M=D+M   // addr = addr+32

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

    @LOOP
    0; JMP  // goto LOOP

(END)
    @END
    0; JMP
```

```
addr = SCREEN
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