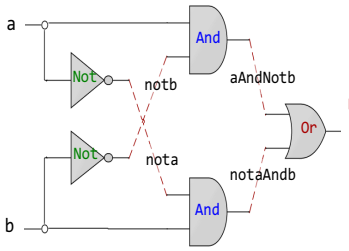
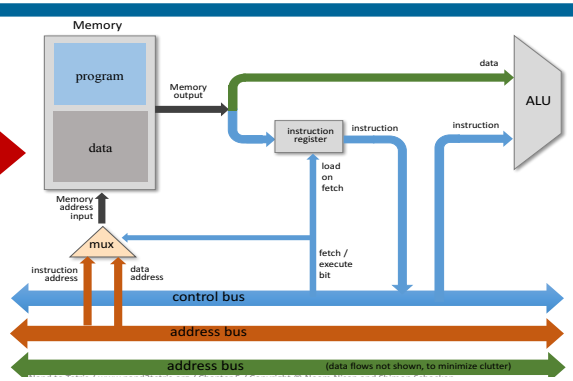
Digital Logic Design




```
CHIP Xor {
  IN a, b;
  OUT out;
  PARTS:
  Not(in=a, out=nota);
  Not(in=b, out=notb);
  And(a=nota, b=b, out=w1);
  And(a=a, b=notb, out=w2);
  Or(a=w1, b=w2, out=out);
}
```




```
@R1
D=M
@temp
M=D
```

```
0000000000000001
1111110000010000
0000000000010000
1110001100001000
```

Lecture # 22

Hack Machine Language

```
#include<stdio.h>
#include<stdlib.h>
int main(){
  printf("Learning is fun with Arif\n");
  exit(0);
}
```

```
global main
SECTION .data
   msg: db "Learning is fun with Arif", 0Ah, 0h
   len_msg: equ $ - msg
SECTION .text
   main:
      mov rax,1
      mov rdi,1
      mov rsi,msg
      mov rdx,len_msg
      syscall
      mov rax,60
      mov rdi,0
      syscall
```

```
0:  b8 01 00 00 00
5:  bf 01 00 00 00
a:  48 be 00 00 00 00 00
11: 00 00 00
14: ba 1b 00 00 00
19: 0f 05
1b: b8 3c 00 00 00
20: bf 00 00 00 00
25: 0f 05
```

Slides of first half of the course are adapted from:
https://www.nand2tetris.org
Download s/w tools required for first half of the course from the following link:
https://drive.google.com/file/d/0B9c0BdDJz6XpZUh3X2dPR1o0MUE/view

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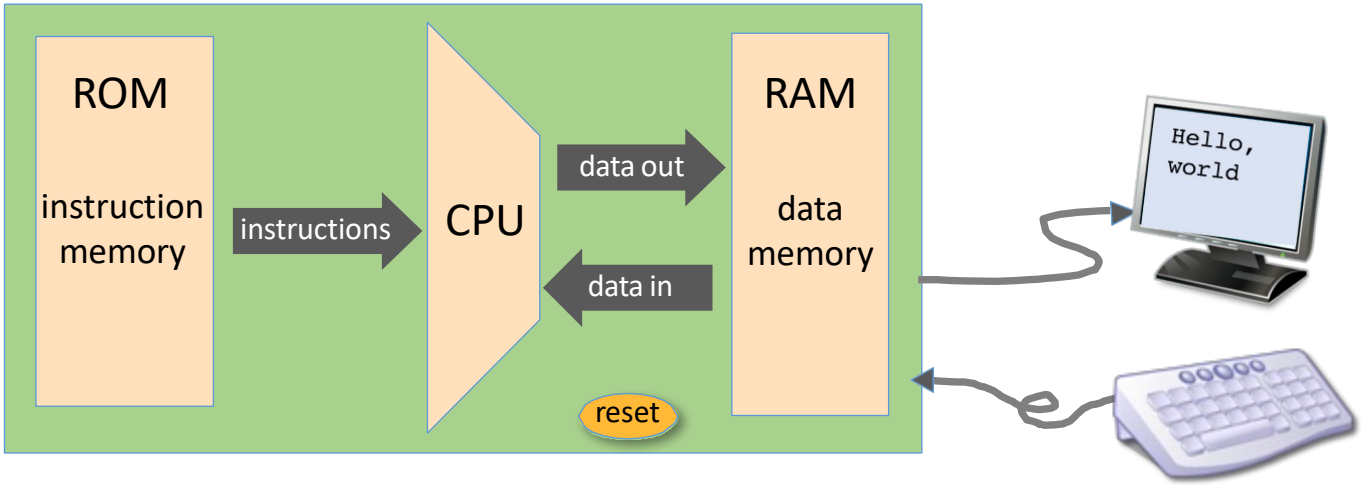
Today's Agenda

- Hack Computer Machine Language
- Review of h/w of Hack Computer
- Software of Hack Computer
  - A Instruction
  - C Instruction
  - Examples
- Binary Code Format of Hack Computer Instruction
  - Encoding of 16 bit A-Instruction
  - Encoding of 16 bit C-Instruction
  - Examples
- A Complete Hack Program: Assembly Language & Machine Code

Hack Computer: Hardware



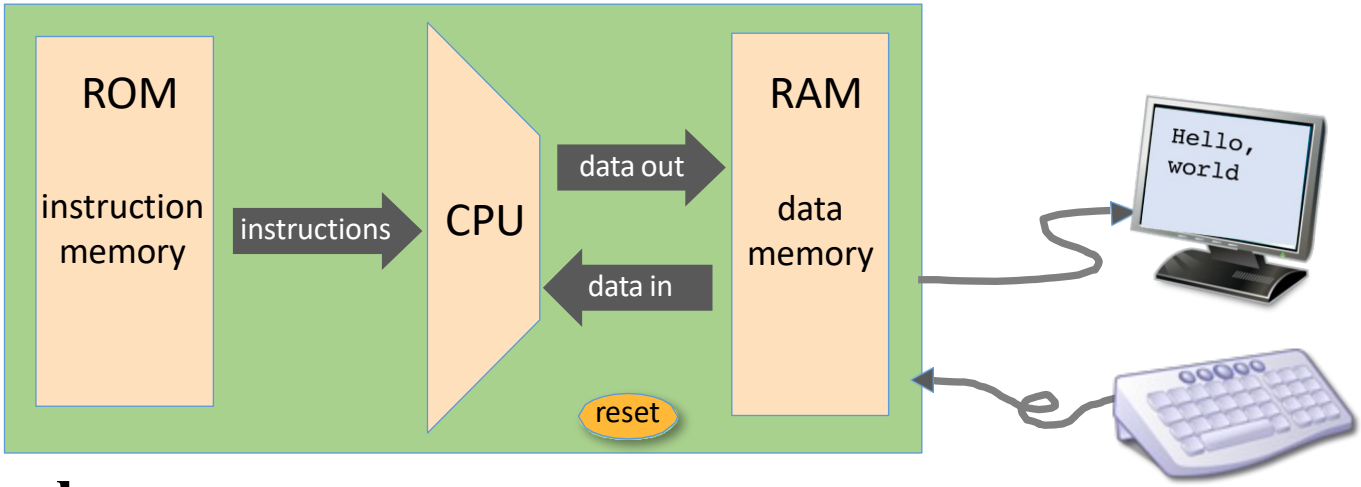
Hack computer is a 16-bit machine consisting of:

- Central Processing Unit (CPU): performs 16-bit instructions
- Data memory (RAM): a sequence of 16-bit registers having 15 bit addr:

  `RAM[0], RAM[1], RAM[2],…`
- Instruction memory (ROM): a sequence of 16-bit registers having 15 bit addr:

  `ROM[0], ROM[1], ROM[2],…`
- Two memory-mapped I/O devices: a screen and a keyboard
- Instruction bus / data bus / address buses

Hack Computer: Software



Hack machine language:

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

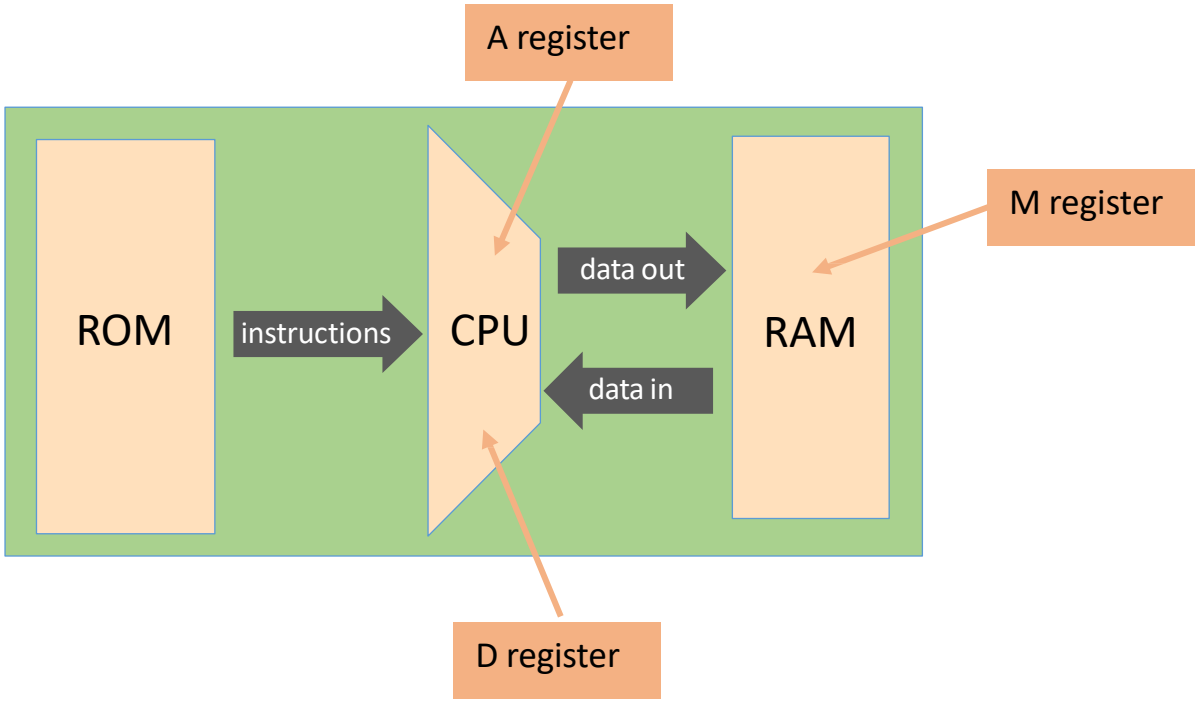
Hack program:

- A sequence of instructions written in the hack machine language

Control:

- The ROM is loaded with a Hack program (16 bit instructions)
- The reset button is pushed
- The program starts running

Hack Computer: Registers



The Hack machine language recognizes three 16-bit registers:

- `D`: used to hold data value
- `A`: used to hold data value / address of the memory
- `M`: represents the currently selected memory register: `M = RAM[A]`

The A-Instruction

The A-instruction is used to set the A register to a 15 bit value

Syntax: `@ value` Where value is either:

- A non-negative decimal constant (<= $2^{15} - 1$) or
- A symbol referring to such a constant

Semantics: Sets the A register to value, so after this

- RAM[A] becomes the selected RAM register
- ROM[A] becomes the selected ROM register

Example:

```
@17   //A =17
```

- Sets the register A to the value of 17
- As a side effect the RAM[17] becomes the selected RAM register

The C Instruction

Syntax: `dest= comp ;jump` (either dest or jump fields may be empty)

comp:

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

dest:

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

jump:

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

Working:

A C instruction can be used in either of the following two ways:

- Store the result at some destination `dest= comp`
- Use the result of the computation to jump `comp ;jump`

Examples: Hack Machine Instructions

The A-instruction:

Syntax: `@value`

The C-instruction:

Syntax: `dest= comp ;jump`

`dest= comp`

`comp ;jump`

comp:

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

dest: `null, M, D, A, MD, AM, AD, AMD`

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

Example 1: Set register D to a value of -1

```
D=-1
```

```
dest= comp
```

Examples: Hack Machine Instructions

The A-instruction:

Syntax: `@value`

The C-instruction:

Syntax: `dest= comp ;jump`

`dest= comp`

`comp ;jump`

comp:

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

dest: `null, M, D, A, MD, AM, AD, AMD`

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

Example 2: Suppose the programmer wants to increment the value of D

```
D=D+1
```

```
dest= comp
```

Examples: Hack Machine Instructions

The A-instruction:

Syntax: `@value`

The C-instruction:

Syntax: `dest= comp ;jump`

`dest= comp`

`comp ;jump`

comp:

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

dest: `null, M, D, A, MD, AM, AD, AMD`

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

Example 3: Suppose the programmer wants to add the contents of D and A-register and place the result in D-register

```
D=D+A
```

```
dest= comp
```

Examples: Hack Machine Instructions

The A-instruction:

Syntax: `@value`

The C-instruction:

Syntax: `dest= comp ;jump`

`dest= comp`

`comp ;jump`

comp:

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

dest: `null, M, D, A, MD, AM, AD, AMD`

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

Example 4: Suppose the programmer wants to store a number 10 in register D

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

```
@value
dest= comp
```

Examples: Hack Machine Instructions

The A-instruction:

Syntax: `@value`

The C-instruction:

Syntax: `dest= comp ;jump`

`dest= comp`

`comp ;jump`

comp:

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

dest: `null, M, D, A, MD, AM, AD, AMD`

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

Example 5: Suppose the programmer wants to write the value of register D at RAM[135]

```
@135   //A =135
M=D
```

```
@value
dest= comp
```

Examples: Hack Machine Instructions

The A-instruction:

Syntax: `@value`

The C-instruction:

Syntax: `dest= comp ;jump`

`dest= comp`

`comp ;jump`

comp:

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

dest:

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

jump:

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

Example 6: Suppose the programmer wants to write the value of register D+1 at RAM[135]

```
@135   //A =135
M=D+1
```

```
@value
dest= comp
```

Examples: Hack Machine Instructions

The A-instruction:

Syntax: `@value`

The C-instruction:

Syntax: `dest= comp ;jump`

`dest= comp`

`comp ;jump`

comp:
```
0, 1, -1, D, A, M, !D, !A, !M, -D, -A, -M,
D+1, A+1, M+1, D-1, A-1, M-1,
D+A, D-A, A-D, D&A, D|A,
D+M, D-M, M-D, D&M, D|M
```

dest: `null, M, D, A, MD, AM, AD, AMD`

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

Example 7: Suppose the programmer wants to read memory contents from address 325 and place them in D register

```
@325   //A =325
D=M //D=M[325]
```

```
@value
dest= comp
```

Examples: Hack Machine Instructions

The A-instruction:

Syntax: `@value`

The C-instruction:

Syntax: `dest= comp ;jump`

`dest= comp`

`comp ;jump`

comp: `0, 1, -1, D, A, M, !D, !A, !M, -D, -A, -M, D+1, A+1, M+1, D-1, A-1, M-1, D+A, D-A, A-D, D&A, D|A, D+M, D-M, M-D, D&M, D|M`

dest: `null, M, D, A, MD, AM, AD, AMD`

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

Example 8: Suppose the programmer wants to do an unconditional jump to ROM[431]

```
@431 //A =431
0;JMP
```

```
@value
comp; jump
```

Examples: Hack Machine Instructions

The A-instruction:

Syntax: `@value`

The C-instruction:

Syntax: `dest= comp ;jump`

`dest= comp`

`comp ;jump`

comp:

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

dest: `null, M, D, A, MD, AM, AD, AMD`

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

Example 9: Suppose the programmer wants to jump to ROM[97], if D-1 == 0

```
@97 //A =97
D-1;JEQ
```

```
@value
comp; jump
```

Examples: Hack Machine Instructions

The A-instruction:

Syntax: `@value`

The C-instruction:

Syntax: `dest= comp ;jump`

`dest= comp`

`comp ;jump`

comp:

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

dest: `null, M, D, A, MD, AM, AD, AMD`

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

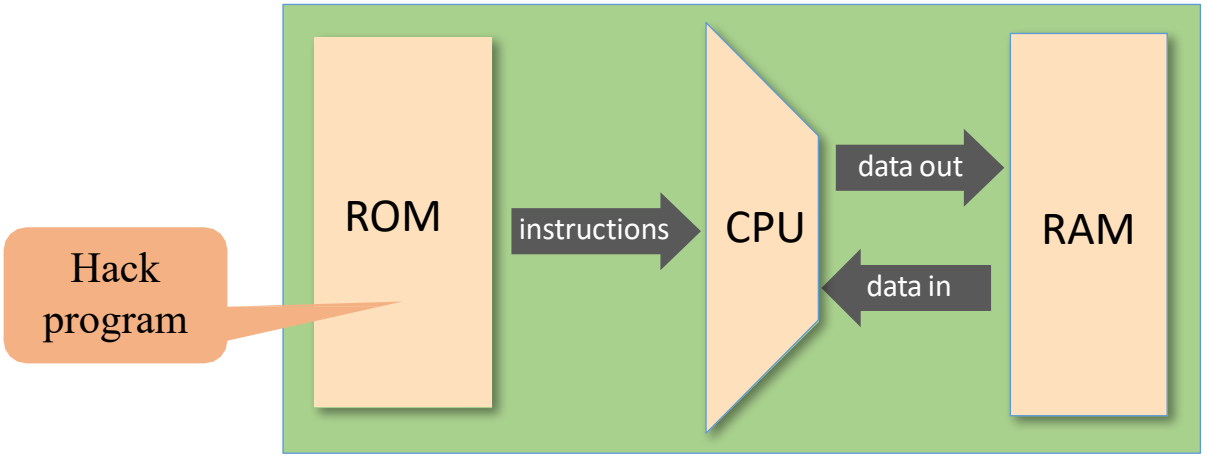
Example 10: Suppose the programmer wants to write constant 54 at RAM[17]

```
//D=54
@54
D=A
//M[17]=D
@17
M=D
```

Hack

Machine Language vs. Symbolic Language

Hack Machine Language



Two ways to express the same semantics:

Symbolic:

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

translate

Binary:

```
0000000000010001
1110011111000110
```

load & execute

Binary Code Format: A-Instruction

- The A-instruction is used to set the A register to a 15 bit value
- The symbolic as well as machine code for the instruction is shown below:

Symbolic Code

```
@23
```

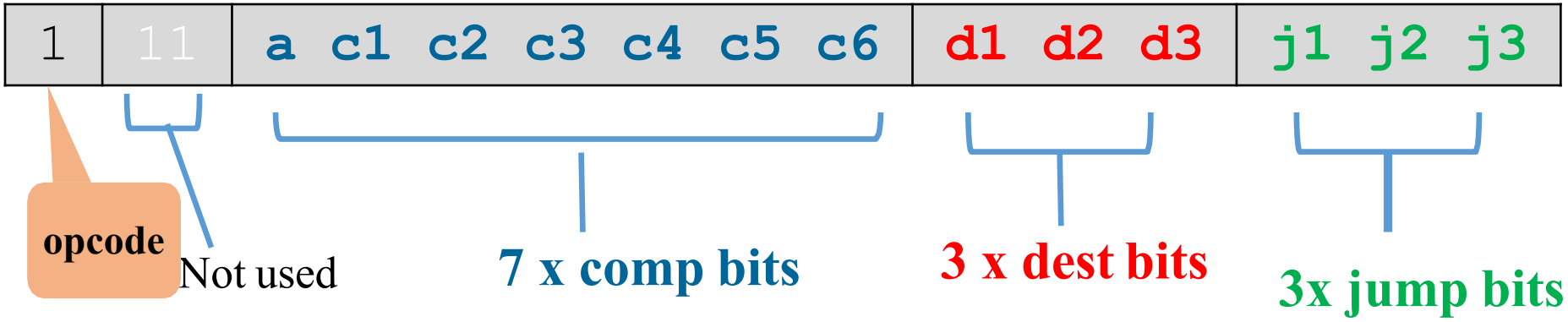
Machine Code

```
0000 0000 0001 0111
```

opcode signifying an A-instruction

Binary Code Format: C-Instruction

```
dest= comp ;jump
```



Binary Code Format: C-Instruction

```
dest= comp ;jump
```

1	11	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						

Binary Code Format: C-Instruction

```
dest= comp ;jump
```

1	11	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

Binary Code Format: C-Instruction

```
dest= comp ;jump
```

1	11	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

Complete Specification of C-Instruction

dest= comp ;jump

1	11	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						

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

Example 1: Symbolic Code to Binary Code

```
dest= comp ;jump
```

1	11	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						

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

Example 1: Suppose the programmer wants to increment the value of D

```
D= D+1
```

```
1 11 0011111 010 000
```

Example 2: Symbolic Code to Binary Code

```
dest= comp ;jump
```

1	11	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						

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

Example 2: Suppose the programmer wants to add the contents of D and A-register and place the result in D-register

```
D=D+A
```

```
1 11 0000010 010 000
```

Example 3: Symbolic Code to Binary Code

dest= comp ;jump

1	11	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						

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

Example 3: Suppose the programmer wants to store a number 10 in register D

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

```
0000000000001010
1  11  0110000  010  000
```

Example 4: Symbolic Code to Binary Code

```
dest= comp ;jump
```

1	11	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						

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

Example 4: Suppose the programmer wants to write the value of register D at RAM[135]

```
@135   //A =135
M=D
```

```
0000000010000111
1  11  0001100  001  000
```

Example 5: Symbolic Code to Binary Code

```
dest= comp ;jump
```

1	11	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						

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

Example 5: Set RAM[64] to the value of D-register +1

```
@64
M= D+1
```

```
0000000001000000
1 11 0011111 001 000
```

Example 6: Symbolic Code to Binary Code

```
dest= comp ;jump
```

1	11	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						

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

Example 6: Suppose the programmer wants to read memory contents from address 25 and place them in D register

```
@25
D=M
```

```
0000000000011001
1  11  1110000  010  000
```

Example 7: Symbolic Code to Binary Code

```
dest= comp ;jump
```

1	11	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						

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

Example 7: Suppose the programmer wants to do an unconditional jump to ROM[31]

```
@31 //A =31
0;JMP
```

```
0000000000011111
1 11 0101010 000 111
```

Example 8: Symbolic Code to Binary Code

```
dest= comp ;jump
```

1	11	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						

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

Example 8: Suppose the programmer wants to jump to ROM[17], if D-1 == 0

```
@17 //A =17
D-1;JEQ
```

```
0000000000010001
1 11 0001110 000 010
```

A Complete Hack Program

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

@17
M=0    // RAM[17] = 0 (sum)

@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 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
- More to come….

No need to understand ... we'll review the code in later part of the course

Hack Program: Assembly & Machine Code

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

@17
M=0    // RAM[17] = 0 (sum)

@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 end
0;JMP // infinite loop
```

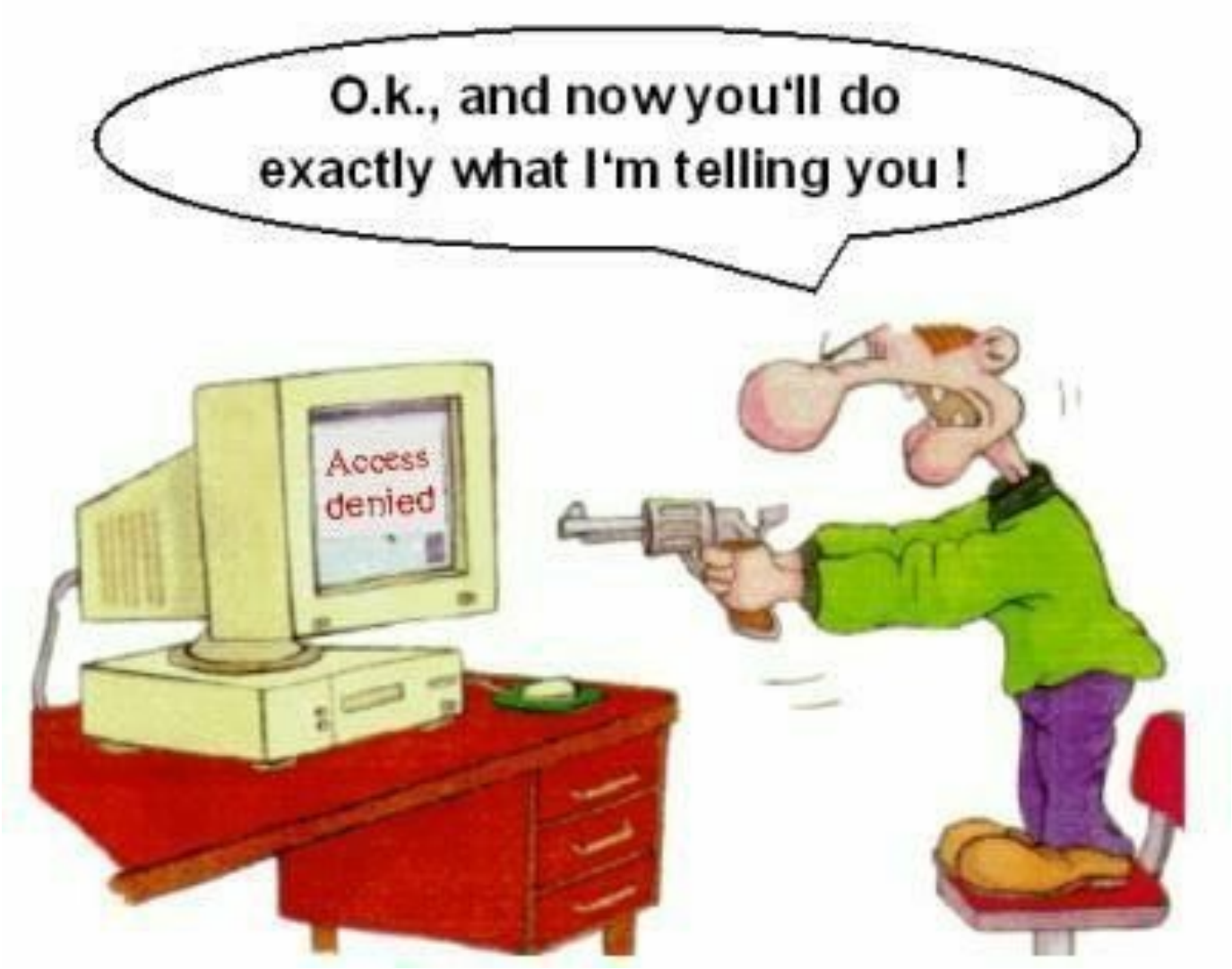
translate

```
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

24 Assembly Instructions mapped to 24 Machine Instructions

Things To Do


O.k., and now you'll do exactly what I'm telling you !
Access denied