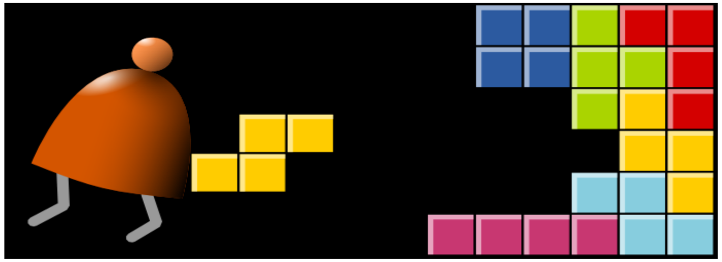
# Machine (Assembly) Language



*Building a Modern Computer From First Principles*

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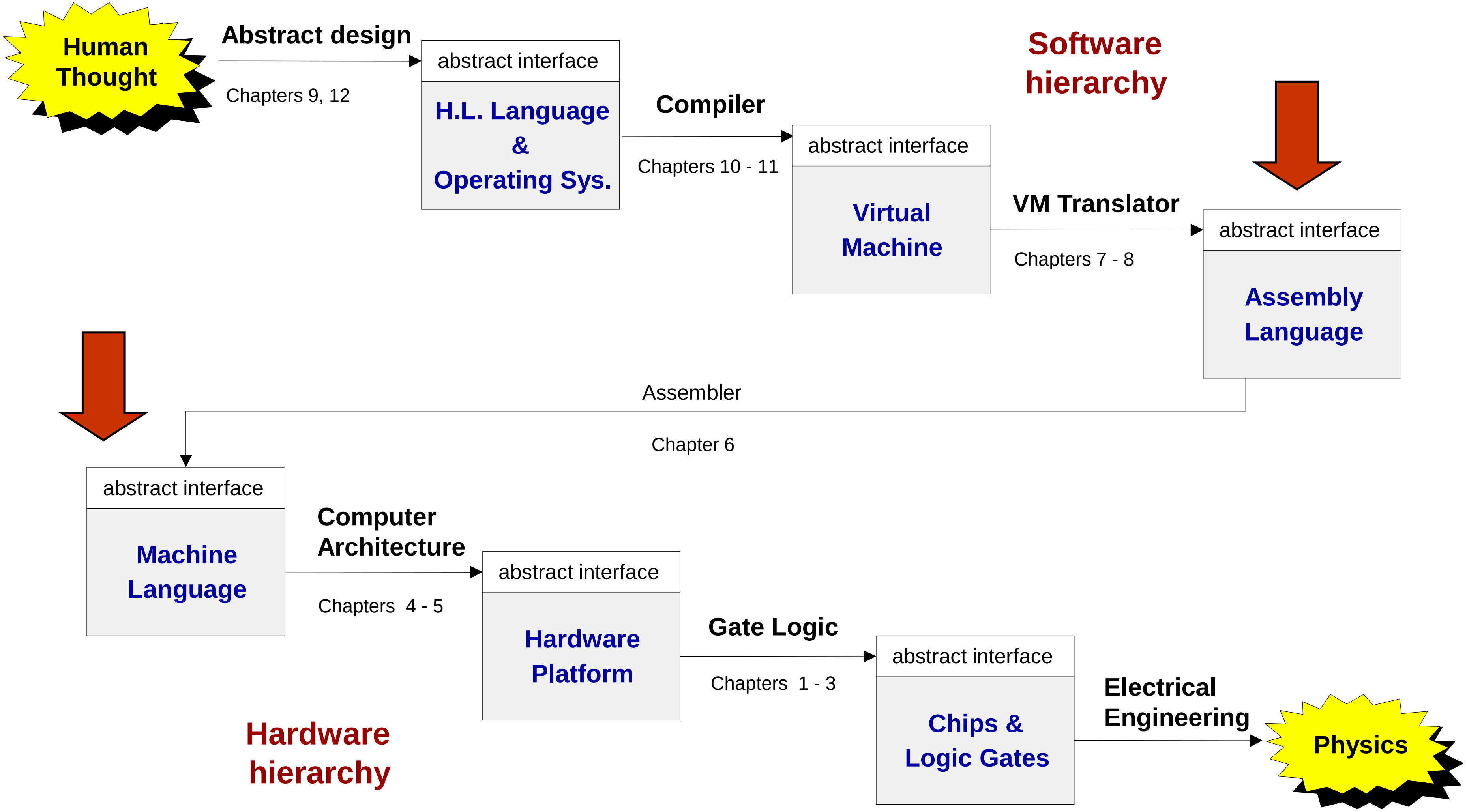
# Where we are at:

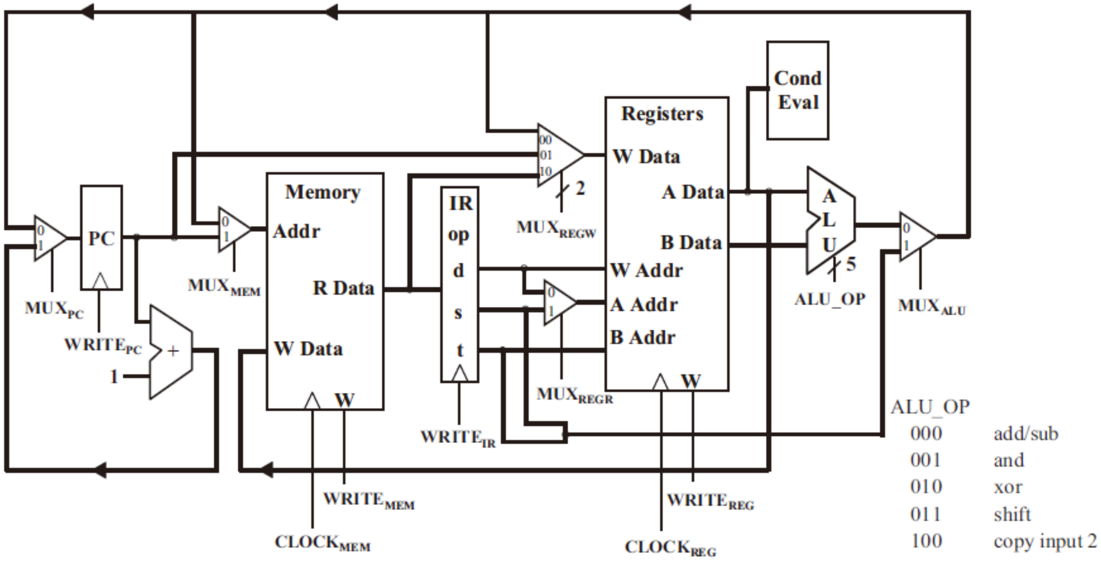


# Machine language

Abstraction – implementation duality:

- Machine language ( = instruction set) can be viewed as a programmer-oriented abstraction of the hardware platform
- The hardware platform can be viewed as a physical means for realizing the machine language abstraction

| # | Operation | Fmt | Pseudocode |
|---|---|---|---|
| 0: | halt | 1 | exit(0) |
| 1: | add | 1 | R[d] ← R[s] + R[t] |
| 2: | subtract | 1 | R[d] ← R[s] - R[t] |
| 3: | and | 1 | R[d] ← R[s] & R[t] |
| 4: | xor | 1 | R[d] ← R[s] ^ R[t] |
| 5: | shift left | 1 | R[d] ← R[s] << R[t] |
| 6: | shift right | 1 | R[d] ← R[s] >> R[t] |
| 7: | load addr | 2 | R[d] ← addr |
| 8: | load | 2 | R[d] ← mem[addr] |
| 9: | store | 2 | mem[addr] ← R[d] |
| A: | load indirect | 1 | R[d] ← mem[R[t]] |
| B: | store indirect | 1 | mem[R[t]] ← R[d] |
| C: | branch zero | 2 | if (R[d] == 0) pc ← addr |
| D: | branch positive | 2 | if (R[d] > 0) pc ← addr |
| E: | jump register | 1 | pc ← R[t] |
| F: | jump and link | 2 | R[d] ← pc; pc ← addr |



| ALU_OP | |
|---|---|
| 000 | add/sub |
| 001 | and |
| 010 | xor |
| 011 | shift |
| 100 | copy input 2 |

# Machine language

## Abstraction – implementation duality:

- Machine language ( = instruction set) can be viewed as a programmer-oriented abstraction of the hardware platform
- The hardware platform can be viewed as a physical means for realizing the machine language abstraction

## Another duality:

- Binary version: 0001 0001 0010 0011 (machine code)
- Symbolic version ADD R1, R2, R3 (assembly)

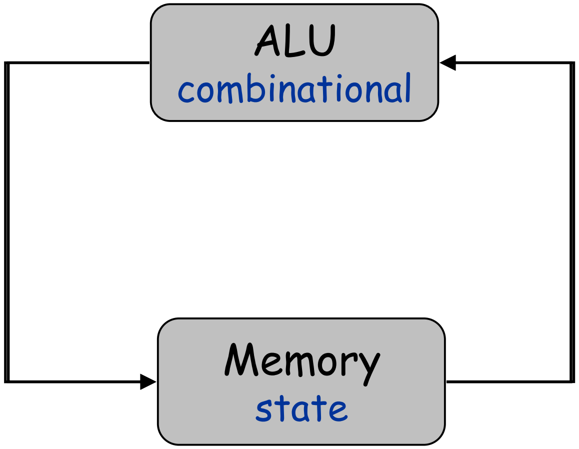
# Machine language

Abstraction – implementation duality:

- Machine language ( = instruction set) can be viewed as a programmer-oriented abstraction of the hardware platform
- The hardware platform can be viewed as a physical means for realizing the machine language abstraction

Another duality:

- Binary version
- Symbolic version



Loose definition:

- Machine language = an agreed-upon formalism for manipulating a *memory* using a *processor* and a set of *registers*
- Same spirit but different syntax across different hardware platforms.

# Lecture plan

- Machine languages at a glance
- The Hack machine language:
  - Symbolic version
  - Binary version
- Perspective

(The assembler will be covered in chapter 6).

# Typical machine language commands (3 types)

- ALU operations
- Memory access operations

  (addressing mode: how to specify operands)

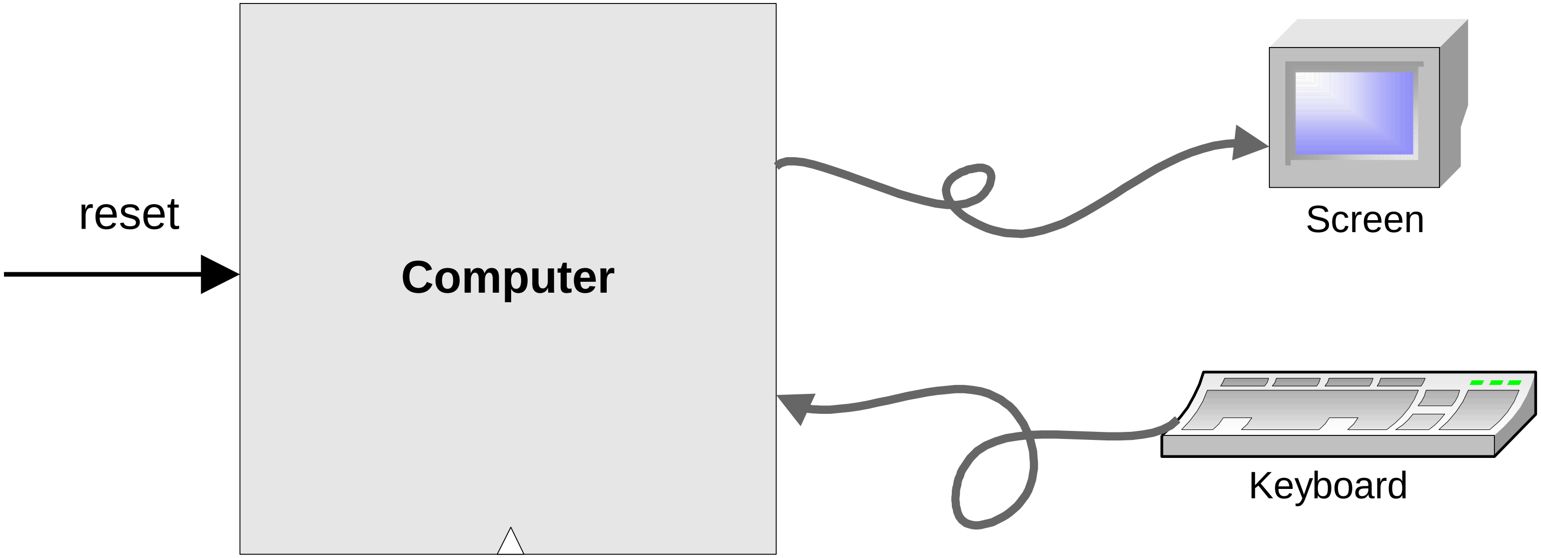
  - Immediate addressing, LDA R1, 67  // R1=67
  - Direct addressing, LD R1, 67 // R1=M[67]
  - Indirect addressing, LDI R1, R2 // R1=M[R2]
- Flow control operations

# Typical machine language commands (a small sample)

```
// In what follows R1,R2,R3 are registers, PC is program counter,
// and addr is some value.

ADD R1,R2,R3       // R1 ← R2 + R3

ADDI R1,R2,addr    // R1 ← R2 + addr

AND R1,R1,R2       // R1 ← R1 and R2 (bit-wise)

JMP addr           // PC ← addr

JEQ R1,R2,addr     // IF R1 == R2 THEN PC ← addr ELSE PC++

LOAD R1, addr      // R1 ← RAM[addr]

STORE R1, addr     // RAM[addr] ← R1

NOP                // Do nothing

// Etc. - some 50-300 command variants
```

# The Hack computer

A 16-bit machine consisting of the following elements:

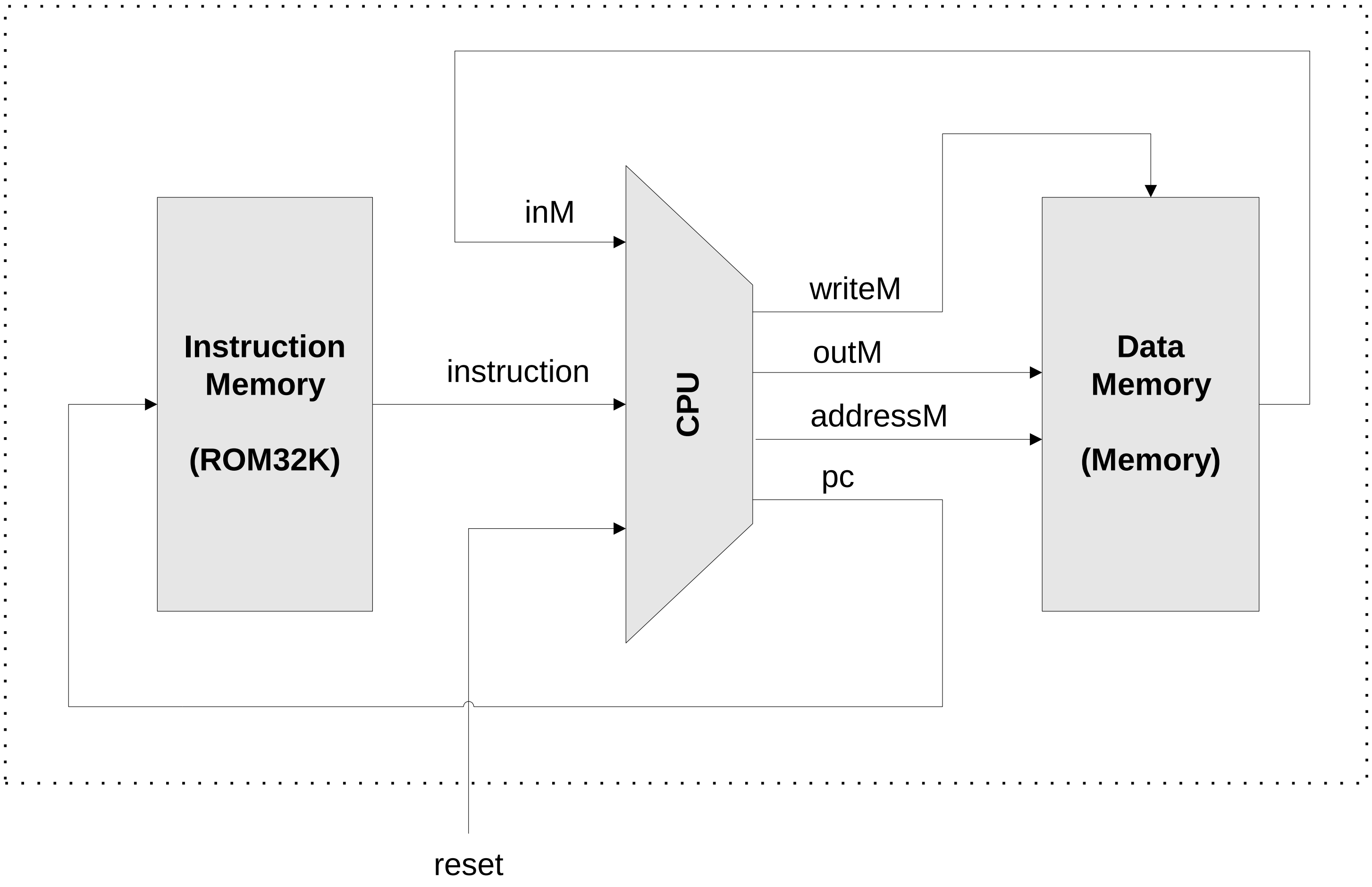


# The Hack computer

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

# The Hack computer

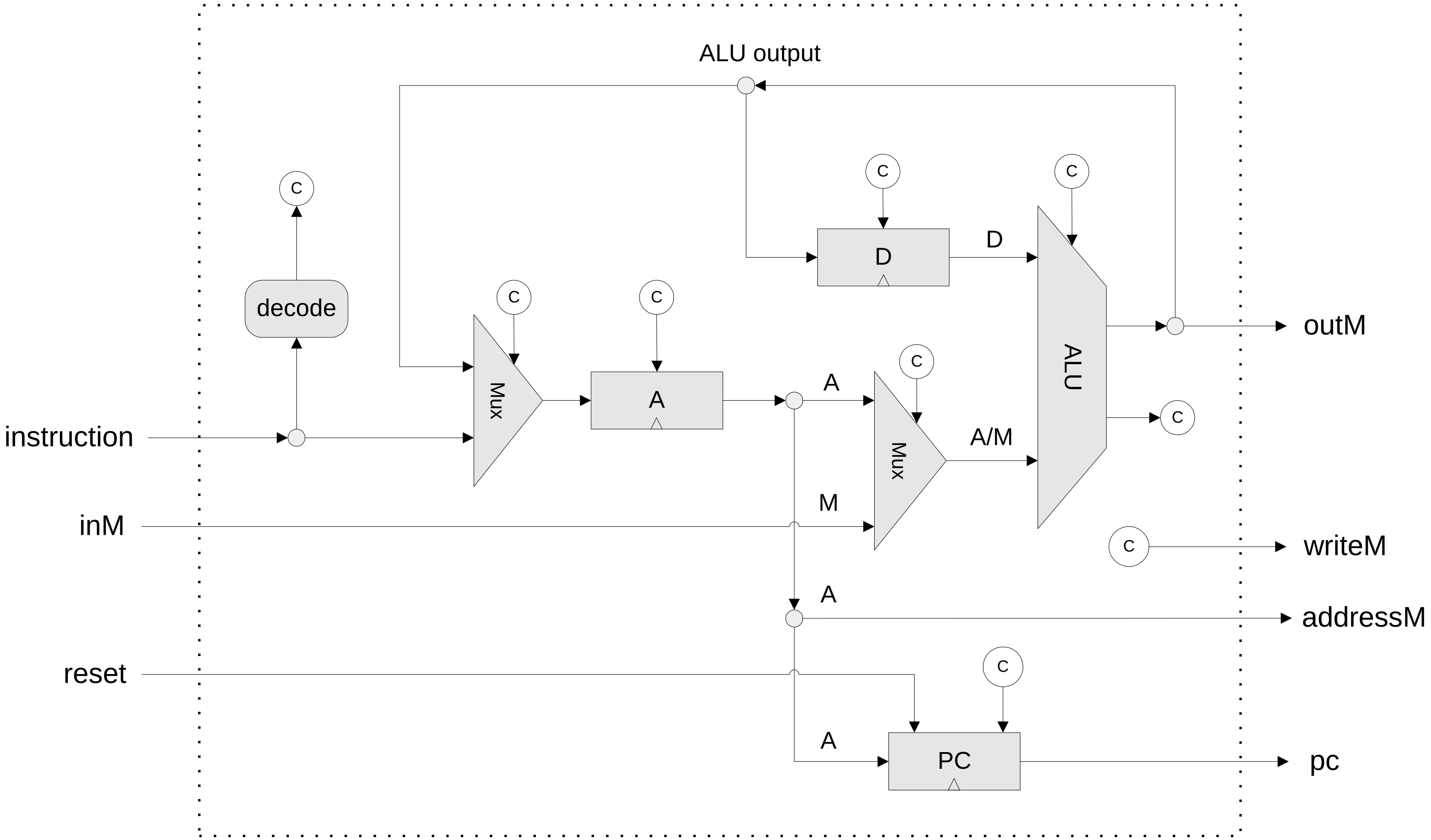
A 16-bit machine consisting of the following elements:



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

# The Hack computer (CPU)

A 16-bit machine consisting of the following elements:



# The Hack computer

A 16-bit machine consisting of the following elements:

Data memory: **RAM** – an addressable sequence of registers

Instruction memory: **ROM** – an addressable sequence of registers

Registers: **D**, **A**, **M**, where **M** stands for **RAM[A]**

Processing: **ALU**, capable of computing various functions

Program counter: **PC**, holding an address

Control: The **ROM** is loaded with a sequence of 16-bit instructions, one per memory location, beginning at address 0. Fetch-execute cycle: later

Instruction set: Two instructions: A-instruction, C-instruction.

# The A-instruction

```
@value        // A ← value
```

Where *value* is either a number or a symbol referring to some number.

Why A-instruction?

In TOY, we store address in the instruction (fmt #2). But, it is impossible to pack a 15-bit address into a 16-bit instruction. So, we have the A-instruction for setting addresses if needed.

Example:

```
@21
```

Effect:

- Sets the *A* register to 21
- RAM[21] becomes the selected RAM register *M*

# The A-instruction

```
@value        // A ← value
```

Used for:

- Entering a constant value
  ( **A** = **value**)

Coding example:

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

- Selecting a RAM location
  ( **register** = **RAM[A]**)

```
@17     // A = 17
D = M   // D = RAM[17]
M = -1  // RAM[17]=-1
```

- Selecting a ROM location
  ( **PC** = **A** )

```
@17     // A = 17
JMP     // fetch the instruction
        // stored in ROM[17]
```

# The C-instruction

***dest* = *comp* ; *jump***

Both dest and jump are optional.

First, we compute something.

Next, optionally, we can store the result, or use it to jump to somewhere to continue the program execution.

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

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

Compare to zero. If the condition holds, jump to ROM[A]

# The C-instruction

***dest* = *comp* ; *jump***

- Computes the value of comp
- Stores the result in dest
- If (the condition jump compares to zero is true), goto the instruction at ROM[A].

# The C-instruction

*dest = comp ; jump*

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

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

Example: set the D register to -1

```
D = -1
```

Example: set RAM[300] to the value of the D register minus 1

```
@300
M = D-1
```

Example: if ((D-1) == 0) goto ROM[56]

```
@56
D-1; JEQ
```

# Hack programming reference card

## Hack commands:

A-command: @value // set A to value

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

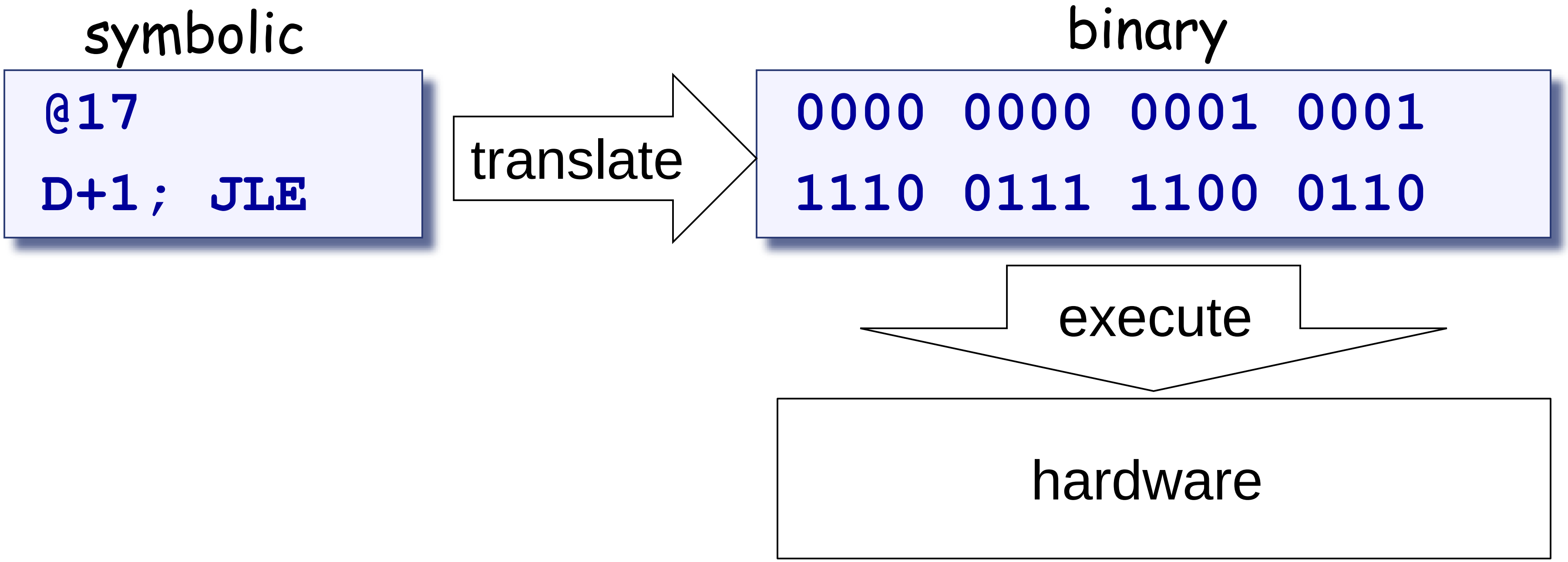
jump = JGT , JEQ , JGE , JLT , JNE , JLE , JMP, or null

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

# The Hack machine language

Two ways to express the same semantics:

- Binary code (machine language)
- Symbolic language (assembly)



symbolic

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

binary

```
0000 0000 0001 0001
1110 0111 1100 0110
```

# 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`

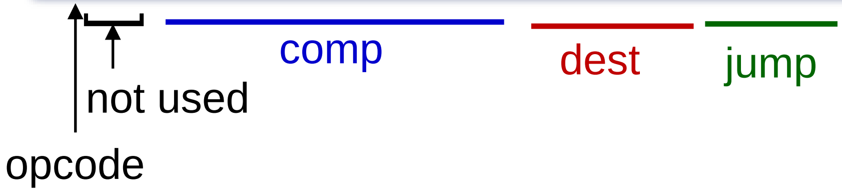
# The C-instruction

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

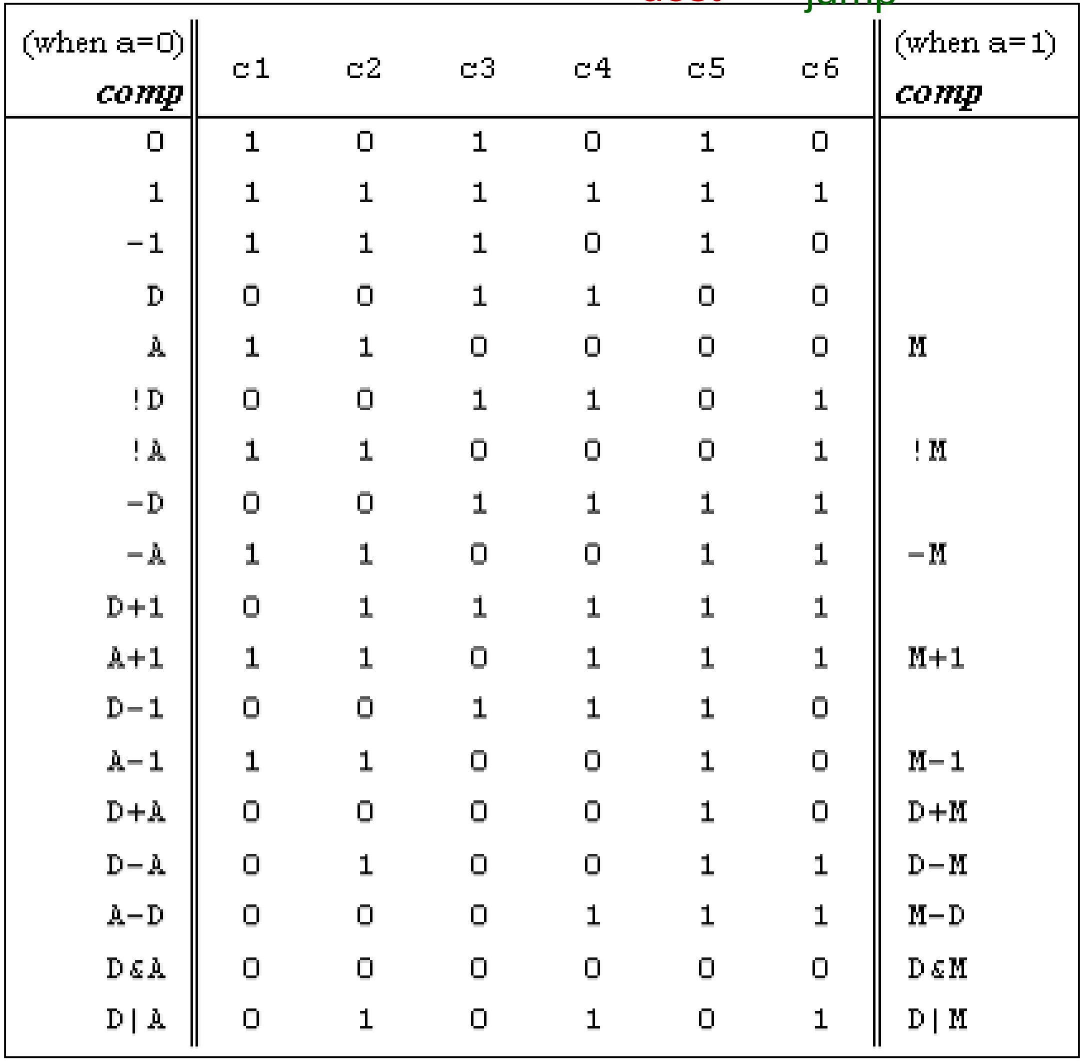
not used

opcode

# The *C*-instruction

$111A\ C_1C_2C_3C_4\ C_5C_6\ D_1D_2\ D_3J_1J_2J_3$

comp dest jump



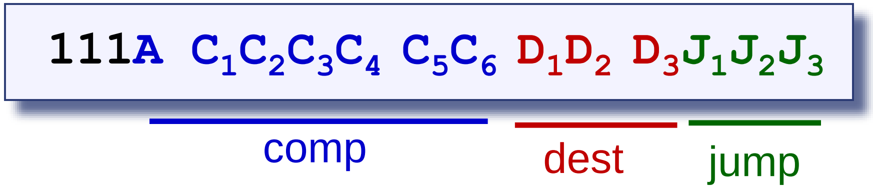
| (when a=0)<br>*comp* | c1 | c2 | c3 | c4 | c5 | c6 | (when a=1)<br>*comp* |
|---|---|---|---|---|---|---|---|
| 0 | 1 | 0 | 1 | 0 | 1 | 0 | |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | |
| -1 | 1 | 1 | 1 | 0 | 1 | 0 | |
| D | 0 | 0 | 1 | 1 | 0 | 0 | |
| A | 1 | 1 | 0 | 0 | 0 | 0 | M |
| !D | 0 | 0 | 1 | 1 | 0 |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

# The *C*-instruction

$$111A\ \underbrace{C_1C_2C_3C_4\ C_5C_6}_{\text{comp}}\ \underbrace{D_1D_2\ D_3}_{\text{dest}}\underbrace{J_1J_2J_3}_{\text{jump}}$$

| | A | D | M | |
|---|---|---|---|---|
| *dest* | *d* | *d* | *d* | 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



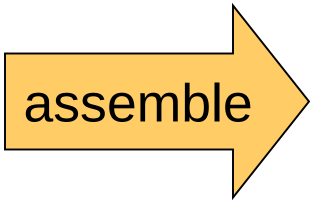
$\mathtt{111A\ C_1C_2C_3C_4\ C_5C_6\ D_1D_2\ D_3J_1J_2J_3}$

| | < | = | > | |
|---|---|---|---|---|
| *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* ≥ 0 jump |
| `JLT` | 1 | 0 | 0 | if *comp* < 0 jump |
| `JNE` | 1 | 0 | 1 | if *comp* ≠ 0 jump |
| `JLE` | 1 | 1 | 0 | if *comp* ≤ 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
```



Hack assembler
or CPU emulator

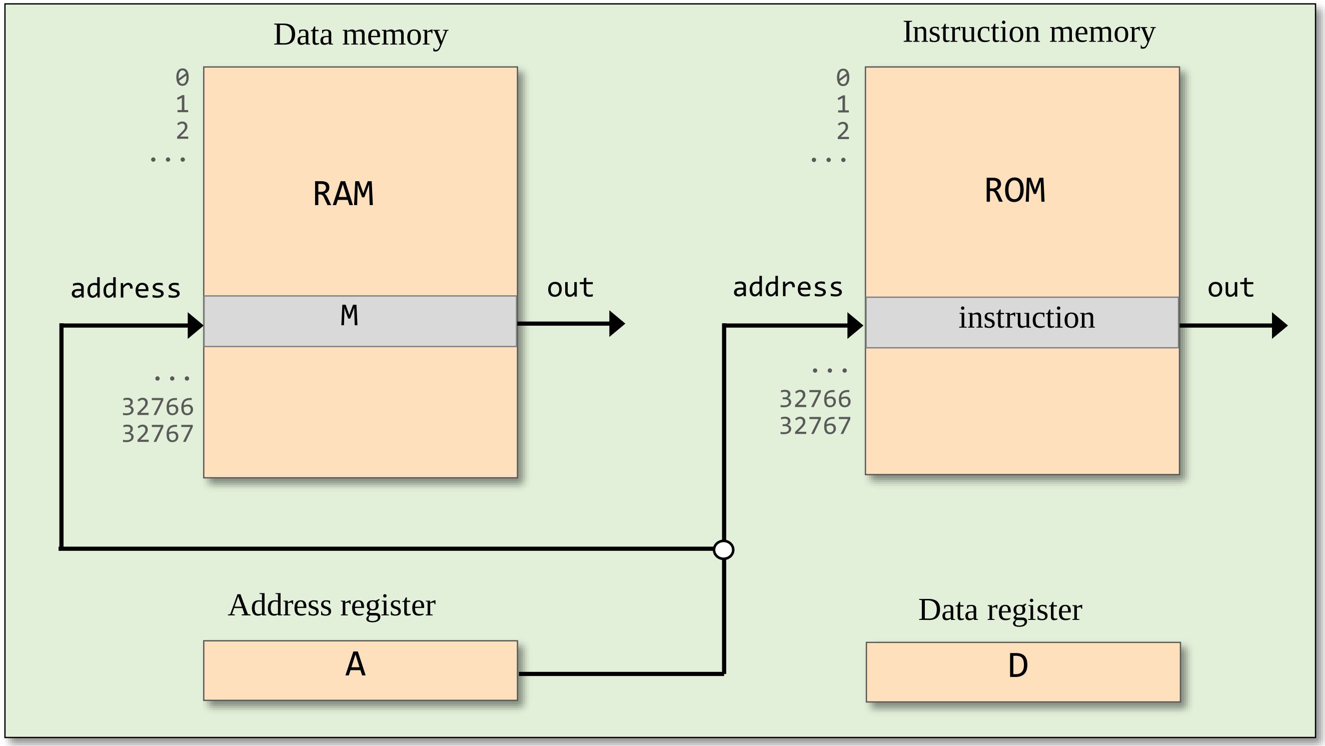
### Target code

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

We will focus on writing the assembly code.

# Working with registers and memory

- D: data register
- A: address/data register
- M: the currently selected memory cell, M=RAM[A]



# Hack programming exercises

Exercise: Implement the following tasks using Hack commands:

1. Set **D** to **A-1**
2. Set both **A** and **D** to **A + 1**
3. Set **D** to **19**
4. D++
5. D=RAM[17]
6. Set **RAM[5034]** to **D - 1**
7. Set **RAM[53]** to **171**
8. Add **1** to **RAM[7]**,
   and store the result in **D**.

# Hack programming exercises

Exercise: Implement the following tasks using Hack commands:

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4. D++
5. D=RAM[17]
6. Set **RAM[5034]** to **D - 1**
7. Set **RAM[53]** to **171**
8. Add **1** to **RAM[7]**, and store the result in **D**.

```
1. D = A-1
2. AD=A+1
3. @19
   D=A
4. D=D+1
5. @17
   D=M
6. @5034
   M=D-1
7. @171
   D=A
   @53
   M=D
8. @7
   D=M+1
```

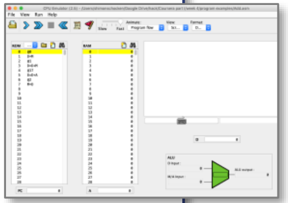
# A simple program: add two numbers (demo)

`Add.asm` (example)

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

// D = RAM[0]
@0
D=M
// D = D + RAM[1]
@1
D=D+M
// RAM[2] = D
@2
M=D
```

Load into the CPU emulator



Binary

```
0000000000000000
1000010010001101
0000000000000001
1010011001100001
0000000000000010
1110010010010011
```

Execute

When loading a symbolic program into the CPU emulator, the emulator translates it into binary code (using a built-in assembler)

# Terminate properly

- To avoid malicious code, you could terminate your program with an infinite loop, such as

```
@6
0; JMP
```

```
00: @0
01: D=M
02: @1
03: D=D+M
04: @2
05: M=D
```

# 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
- SCREEN and KBD : base address of I/O memory maps
- Others: used in the implementation of the Hack Virtual Machine
- Note that Hack assembler is case-sensitive, R5 != r5

# Branching

```
// Program: branch.asm
// if R0>0
//    R1=1
// else
//    R1=0
```

# Branching

```
// Program: branch.asm
// if R0>0
//    R1=1
// else
//    R1=0


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

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

   @R1
   M=0             // R1=0
   @10
   0; JMP          // go to end

   @R1
   M=1             // R1=1

   @10
   0; JMP
```

# Branching

```
// Program: branch.asm
// if R0>0
//    R1=1
// else
//    R1=0


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

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

   @R1
   M=0             // R1=0
   @10
   0; JMP          // go to end

   @R1
   M=1             // R1=1

   @10
   0; JMP
```

# Branching with labels

```
// Program: branch.asm
// if R0>0
//    R1=1
// else
//    R1=0


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

   @POSTIVE
   D; JGT          // If R0>0 goto 8

   @R1
   M=0             // R1=0
   @END
   0; JMP          // go to end
(POSTIVE)
   @R1
   M=1             // R1=1
(END)
   @10
   0; JMP
```

refer a label

declare a label

| | |
|---|---|
| 0 | @0 |
| 1 | D=M |
| 2 | @8 |
| 3 | D;JGT |
| 4 | @1 |
| 5 | M=0 |
| 6 | @10 |
| 7 | 0;JMP |
| 8 | @1 |
| 9 | M=1 |
| 10 | @10 |
| 11 | 0; JMP |
| 12 | |
| 13 | |
| 14 | |
| 15 | |
| 16 | |

# IF logic – Hack style

High level:

```
if condition {
   code block 1
} else {
   code block 2
}
code block 3
```

Hack:

```
   D ← condition
   @IF_TRUE
   D;JEQ
   code block 2
   @END
   0;JMP
(IF_TRUE)
   code block 1
(END)
    code block 3
```

Hack convention:

- ❑ True is represented by -1
- ❑ False is represented by 0

# Coding examples (practice)

Exercise: Implement the following tasks using Hack commands:

1. goto 50
2. if D==0 goto 112
3. if D<9 goto 507
4. if RAM[12] > 0 goto 50
5. if sum>0 goto END
6. if x[i]<=0 goto NEXT.

# Coding examples (practice)

Exercise: Implement the following tasks using Hack commands:

1. goto 50
2. if D==0 goto 112
3. if D<9 goto 507
4. if RAM[12] > 0 goto 50
5. if sum>0 goto END
6. if x[i]<=0 goto NEXT.

```
1. @50
   0; JMP
2. @112
   D; JEQ
3. @9
   D=D-A
   @507
   D; JLT
4. @12
   D=M
   @50
   D; JGT
```

```
5. @sum
   D=M
   @END
   D: JGT
6. @i
   D=M
   @x
   A=D+M
   D=M
   @NEXT
   D; JLE
```

# variables

```
// Program: swap.asm
// temp = R1
// R1 = R0
// R0 = temp
```

# variables

```
// Program: swap.asm
// 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
```

- When a symbol is encountered, the assembler looks up a symbol table
- If it is a new label, assign a number (address of the next available memory cell) to it.
- For this example, temp is assigned with 16.
- If the symbol exists, replace it with the number recorded in the table.
- With symbols and labels, the program is easier to read and debug. Also, it can be relocated.

# Hack program (exercise)

Exercise: Implement the following tasks using Hack commands:

1. `sum = 0`
2. `j = j + 1`
3. `q = sum + 12 – j`
4. `arr[3] = -1`
5. `arr[j] = 0`
6. `arr[j] = 17`

# Hack program (exercise)

Exercise: Implement the following tasks using Hack commands:

```
1.  sum = 0

2.  j = j + 1

3.  q = sum + 12 - j

4.  arr[3] = -1

5.  arr[j] = 0

6.  arr[j] = 17
```

```
1. @sum
   M=0
2. @j
    M=M+1
3. @sum
    D=M
    @12
    D=D+A
    @j
    D=D-M
    @q
    M=D
```

```
4. @arr
   D=M
   @3
   A=D+A
   M=-1
5. @j
   D=M
   @arr
   A=D+M
   M=0
```

```
6. @j
   D=M
   @arr
   D=D+M
   @ptr
   M=D
   @17
   D=A
   @ptr
   A=M
   M=D
```

# WHILE logic – Hack style

High level:

```
while condition {
    code block 1
}
Code block 2
```

Hack:

```
(LOOP)
      D ← condition
      @END
      D;JNE
      code block 1
      @LOOP
      0;JMP
(END)
      code block 2
```

Hack convention:

- True is represented by -1
- False is represented by 0

# Complete program example

C language code:

```
// Adds 1+...+100.
 int i = 1;
 int sum = 0;
 while (i <= 100){
    sum += i;
    i++;
 }
```

Hack assembly convention:

- ❑ Variables: lower-case
- ❑ Labels: upper-case
- ❑ Commands: upper-case

# Complete program example

## Pseudo code:

```
i = 1;
sum = 0;
LOOP:
   if (i>100) goto END
   sum += i;
   i++;
   goto LOOP
END:
```

## Hack assembly convention:

- ❑ Variables: lower-case
- ❑ Labels: upper-case
- ❑ Commands: upper-case

Demo
CPU emulator

## Hack assembly code:

```
// Adds 1+...+100.
      @i      // i refers to some RAM location
      M=1     // i=1
      @sum    // sum refers to some RAM location
      M=0     // sum=0
(LOOP)
      @i
      D=M      // D = i
      @100
      D=D-A    // D = i - 100
      @END
      D;JGT    // If (i-100) > 0 goto END
      @i
      D=M      // D = i
      @sum
      M=D+M    // sum += i
      @i
      M=M+1    // i++
      @LOOP
      0;JMP    // Got LOOP
 (END)
      @END
      0;JMP    // Infinite loop
```

# Example

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

```
Pseudo code:
```

# Example

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

```
Pseudo code:

i = 0

(LOOP)
   if (i-n)>=0 goto END
   arr[i] = -1
   i++
   goto LOOP
(END)
```

# Example

```
// for (i=0; i<n; i++)
//      arr[i] = -1;
   @i
   M=0
(LOOP)
   @i
   D=M
   @n
   D=D-M
   @END
   D; JGE

   @arr
   D=M
   @i
   A=D+M
   M=-1

   @i
   M=M+1

   @LOOP
   0; JMP
(END)
```

```
Pseudo code:

i = 0

(LOOP)
   if (i-n)>=0 goto END
   arr[i] = -1
   i++
   goto LOOP
(END)
```

# Perspective

- Hack is a simple machine language

- User friendly syntax: **D=D+A** instead of **ADD D,D,A**

- Hack is a "½-address machine": any operation that needs to operate on the RAM must be specified using two commands: an **A**-command to address the RAM, and a subsequent **C**-command to operate on it

- A Macro-language can be easily developed
  - D=D+M[XXX] => @XXX followed by D=D+M
  - GOTO YYY => @YYY followed by 0; JMP

- A Hack assembler is needed and will be discusses and developed later in the course.