Machine Language
Part 2

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Outlines

- Hack assembly programming
  - Registers and memory
  - Branching, variables, iteration
  - Pointers

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:

- Compute the value of *comp*
- Store the result in *dest*
- If the Boolean expression (*comp == 0*) is true, jump 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

Use Mnemonics

We'll develop a Hack assembler later in this module.

CPU emulator

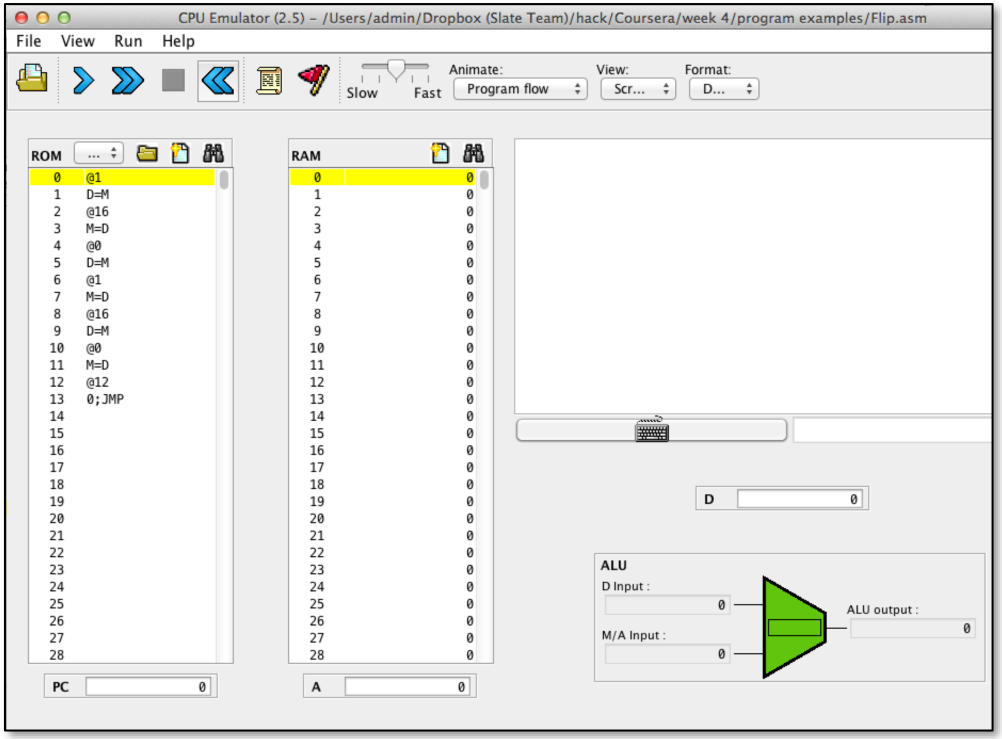
Assembly program

```
// 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 translates from symbolic to binary as it loads)

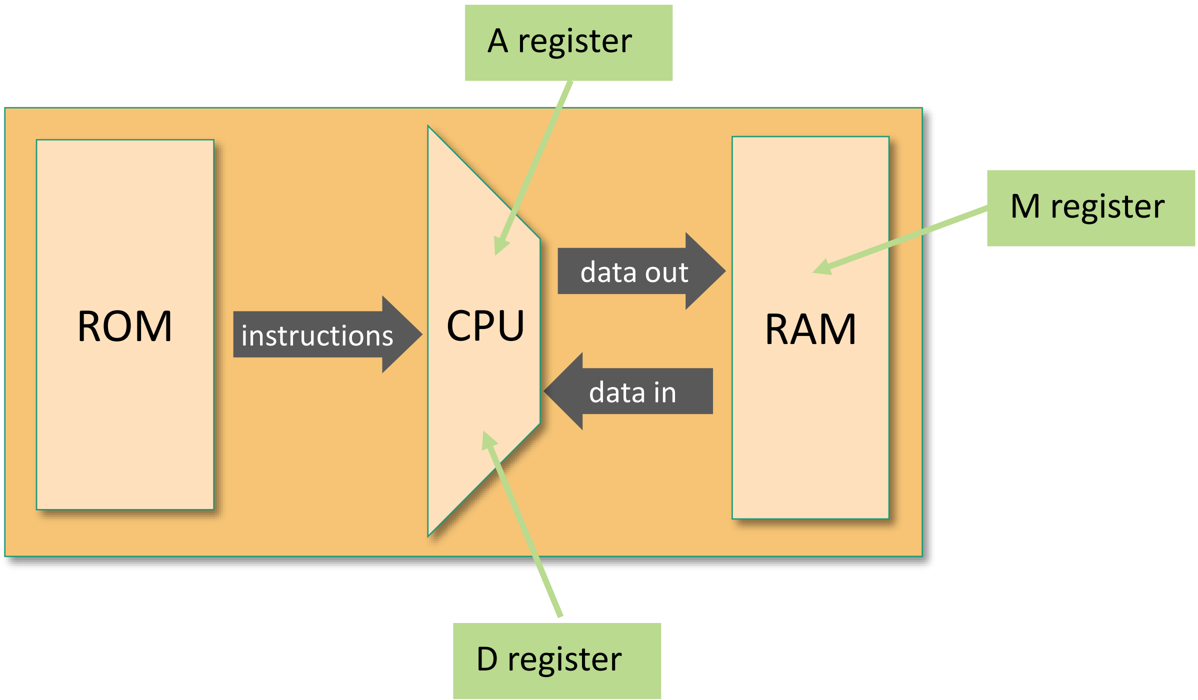
CPU Emulator



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

Registers and memory

- D: Store data.
- A: Store data / address of the memory.
- M: Currently addressed memory register: M = RAM[A].



Registers and memory

- D: Store data.
- A: Store data / address of the memory.
- M: Currently addressed memory register: M = RAM[A].

Typical operations:

```
// D++
D=D+1

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

```
// 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	
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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

(white space ignored)

Memory (ROM)

0	0000000000000000
1	1111110000010000
2	0000000000000001
3	1111000010010000
4	0000000000000010
5	1110001100001000
6	
7	
8	
9	
10	
11	
12	
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binary view

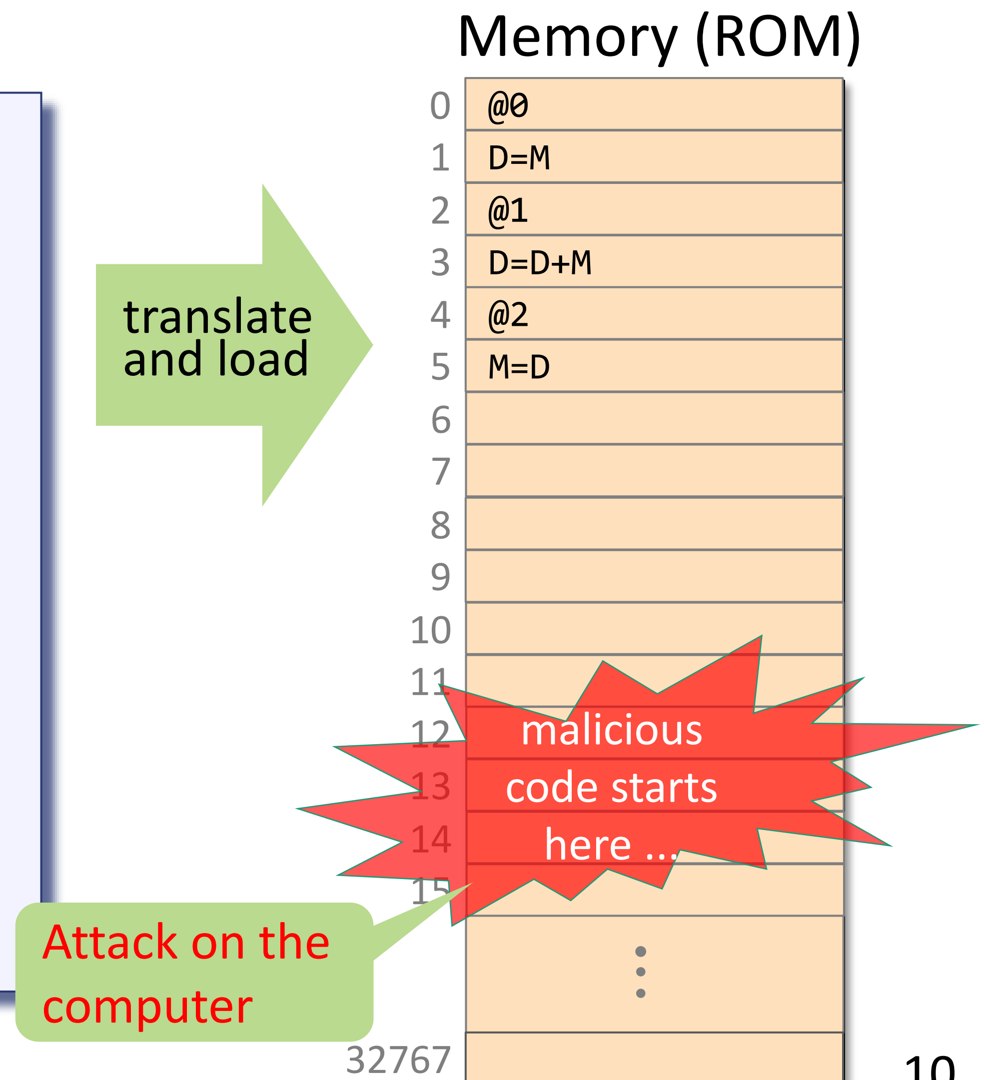
Terminate a program

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
```



Terminate 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 instruction.

translate and load

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	
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<u>Best practice:</u>

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

Built-in symbols

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

symbol	value
R0	0
R1	1
...	...
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 use RAM[5] to represent some variable, and we wish to let RAM[5]=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
...	...
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.

Outlines

- Hack assembly programming
  - Registers and memory
  - Branching, variables, iteration
  - Pointers

Branching

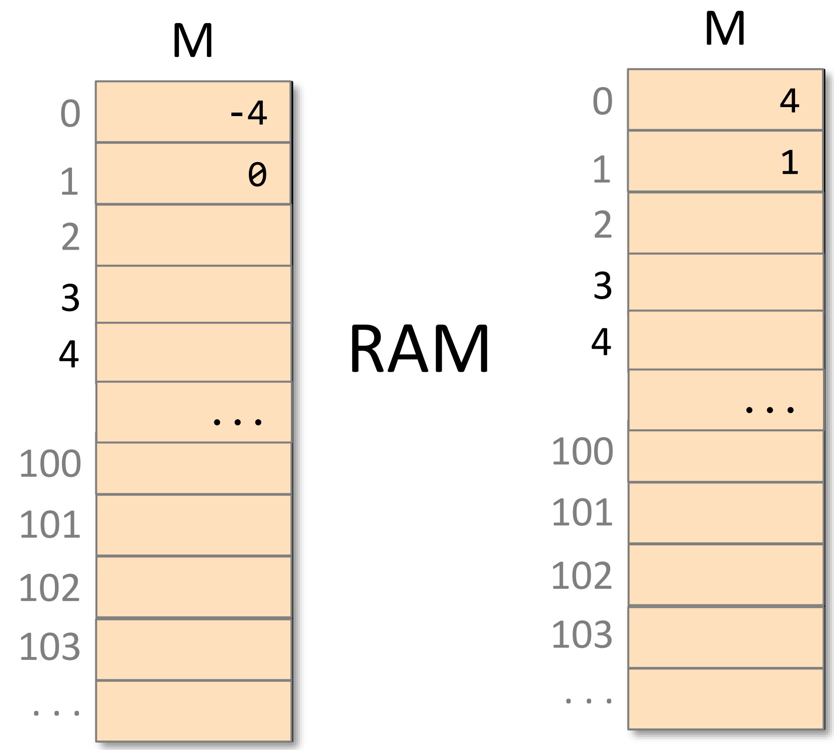
```
      // Program: Signum.asm
      // Computes:
      //       if R0>0
      //          R1=1
      //       else
      //          R1=0
      // Usage: put a value in RAM[0],
      //      run and inspect RAM[0].
 0      @R0
 1      D=M    // D = RAM[0]

 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    // RAM[1]=1

10      @10    // end
11      0;JMP
```



For condition jump, D register will be used in checking the condition.

Labels

```
     // 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 POSITIVE

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

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

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

referring to a label

declaring a label

resolving labels

ROM

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	
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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.

Labels

```
// 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     @END
7     0;JMP  // goto end

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

    (END)
10    @END // 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	
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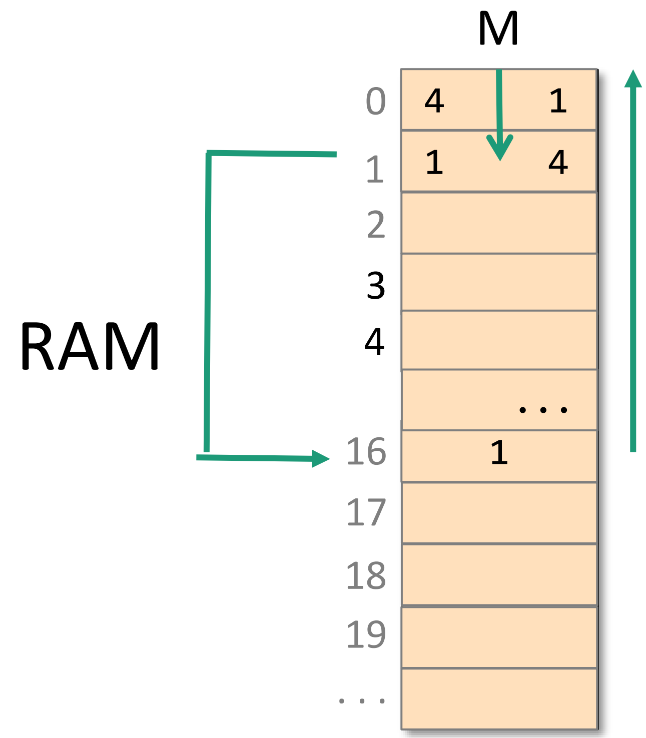
<u>Implications:</u>

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

Variables

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

// RAM[16] = R1
// R1 = R0
// R0 = RAM[16]

   @R1
   D=M
   @16
   M=D     // RAM[16] = R1

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

   @16
   D=M
   @R0
   M=D     // R0 = RAM[16]

(END)
   @END
   0;JMP
```



Variables

```
// 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

<u>Symbol resolution rules:</u>

- A reference to a symbol without 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.*

Note: 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	
	⋮
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Variables

```
// Program: Flip. sm
// 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	
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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 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
   ...
```

M

	0	10
	1	55
	2	
	3	
	4	
		...
n	16	10
i	17	1
sum	18	0
	19	

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	
	⋮
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Variables are allocated to consecutive RAM locations from address 16 onward

Iterative processing

pseudo code

```
// Compute 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
```

$$i > n \Leftrightarrow i - n > 0$$

assembly code

```
// Compute 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 // D = i
   @n
   D=D-M // D = i - n
   @STOP
   D;JGT  // if i > n goto STOP
   @i
   D=M // D = i
   @sum
   M=D+M // sum = sum + i
   @i
   M=M+1  // i = i + 1
   @LOOP
   0;JMP // goto LOOP
(STOP)
   @sum
   D=M // D = sum
   @R1
   M=D    // RAM[1] = sum
(END)
   @END
   0;JMP // end
```

Program execution

assembly program

```
// Compute 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 // D = i
   @n
   D=D-M // D = i - n
   @STOP
   D;JGT  // if i > n goto STOP
   @i
   D=M // D = i
   @sum
   M=D+M // sum = sum + i
   @i
   M=M+1  // i = i + 1
   @LOOP
   0;JMP // goto to LOOP
(STOP)
   @sum
   D=M // D = sum
   @R1
   M=D    // RAM[1] = sum
(END)
   @END
   0;JMP // end
```

Variable-Value Trace Table

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

```
// Compute 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 // D = i
   @n
   D=D-M // D = i - n
   @STOP
   D;JGT  // if i > n goto STOP
   @i
   D=M // D = i
   @sum
   M=D+M // sum = sum + i
   @i
   M=M+1  // i = i + 1
   @LOOP
   0;JMP // goto to LOOP
(STOP)
   @sum
   D=M // D = sum
   @R1
   M=D    // RAM[1] = sum
(END)
   @END
   0;JMP // end
```

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.

Outlines

- Hack assembly programming
  - Registers and memory
  - Branching, variables, iteration
  - Pointers

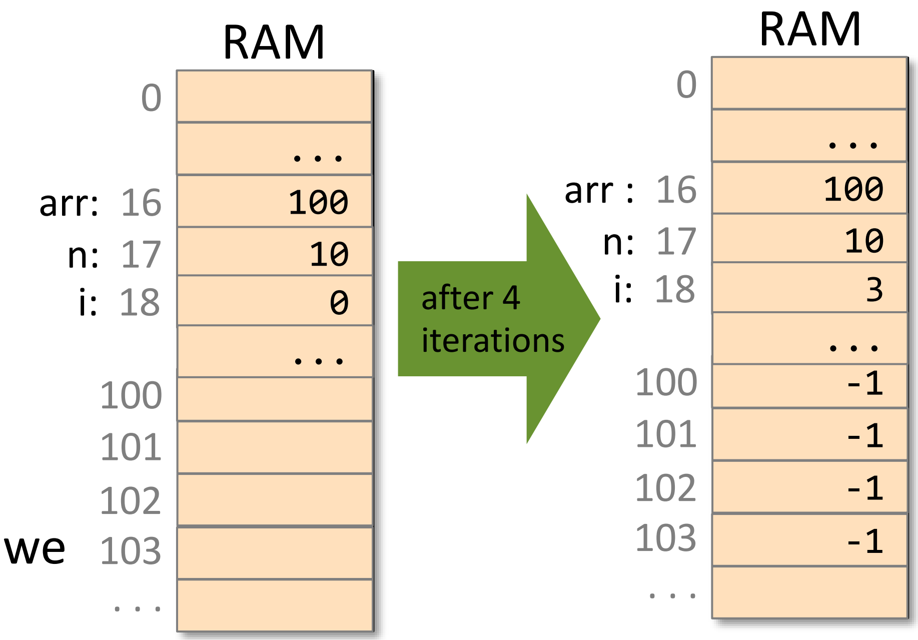
Pointers

Example:

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

<u>Observations:</u>

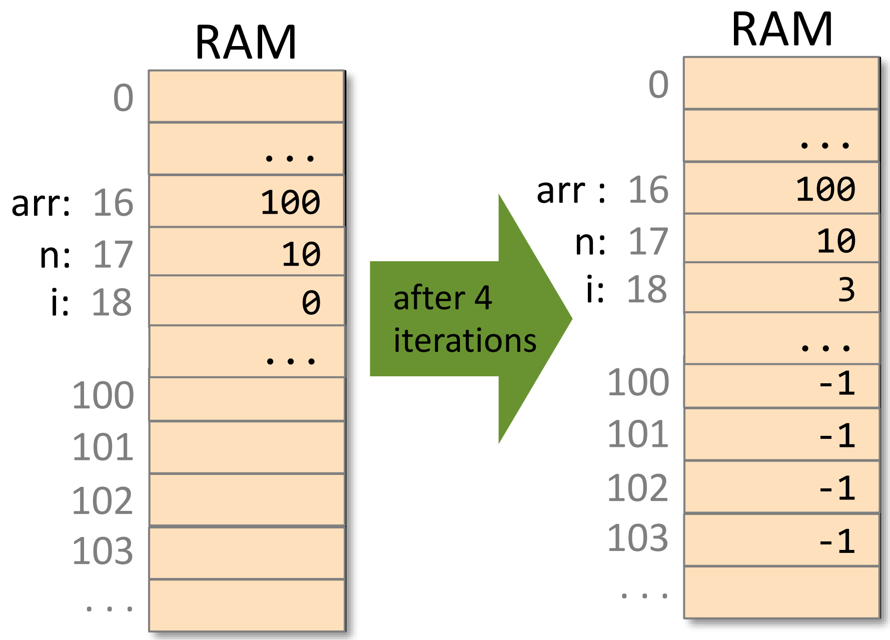
- The array is implemented as a **block of memories**.
- To access these memories one by one, we need a variable to hold the current address.
- *Variables that represent addresses* are called <u>**pointers**</u>.
- There is nothing special about pointer variables, except that their values are interpreted 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 //D = 100
  @arr
  M=D // arr = 100
  // Let n = 10
  @10
  D=A // D = 10
  @n
  M=D // n = 10
  // Let i = 0
  @i
  M=0 // i = 0
  // Loop code continues
  // in next slide...
```

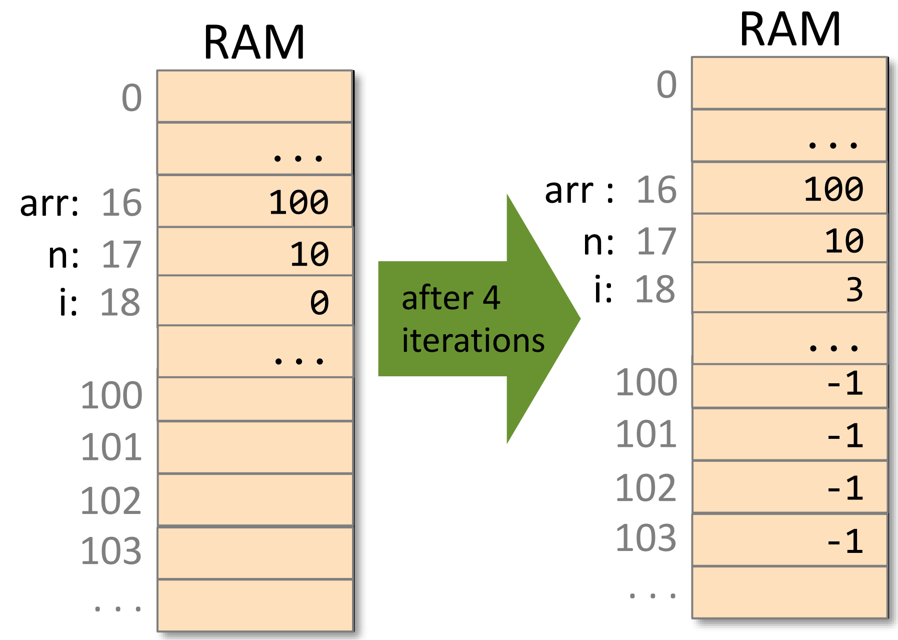


Pointers

Example:

```
(LOOP)
  // if (i==n) goto END
  @i
  D=M // D = i
  @n
  D=D-M // D = i-n
  @END
  D;JEQ // if (i==n) goto END
  // RAM[arr+i] = -1
  @arr
  D=M // D = arr
  @i
  A=D+M // A = arr + i
  M=-1 // M[arr+i] = -1
   // i++
  @i
  M=M+1 // i = i + 1
  // goto LOOP
  @LOOP
  0;JMP
(END)
  @END
  0;JMP // END
```

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".

Acknowlegement

- This set of lecture notes are based on the lecture notes provided by Noam Nisam / Shimon Schocken.
- You may find more information on: www.nand2tetris.org.