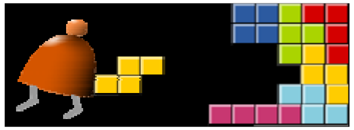
Assembler



Building a Modern Computer From First Principles

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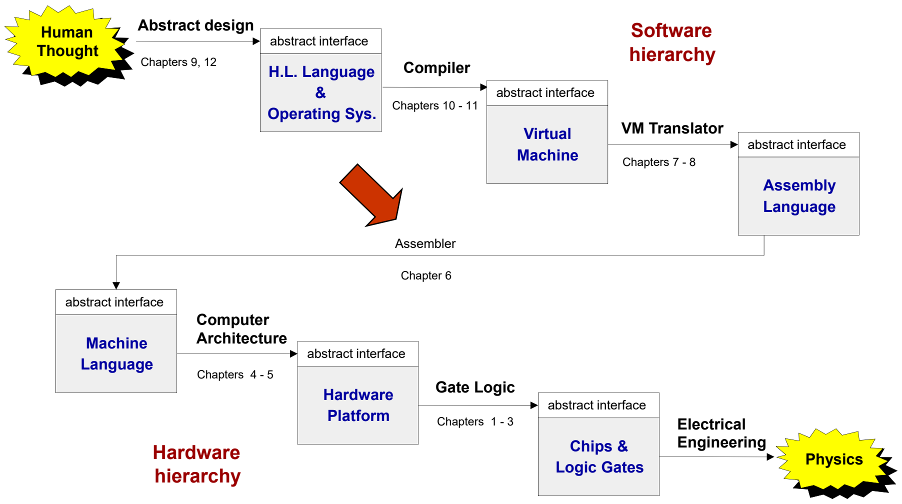
Where we are at:



Human Thought

Abstract design

Chapters 9, 12

abstract interface

H.L. Language & Operating Sys.

Compiler

Chapters 10 - 11

abstract interface

Virtual Machine

Software hierarchy

VM Translator

Chapters 7 - 8

abstract interface

Assembly Language

Assembler

Chapter 6

abstract interface

Machine Language

Computer Architecture

Chapters 4 - 5

abstract interface

Hardware Platform

Gate Logic

Chapters 1 - 3

abstract interface

Chips & Logic Gates

Electrical Engineering

Physics

Hardware hierarchy

Why care about assemblers?

- Assemblers employ nifty programming tricks
- Assemblers are the first rung up the software hierarchy ladder
- An assembler is a translator of a simple language
- Writing an assembler = low-impact practice for writing compilers.

cross-platform compiling

Assembly example

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
    ...    // Etc.
```

assemble

Target code (a text file of binary Hack code)

```
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
0000000000010010
1110001100000001
0000000000010000
1111110000010000
0000000000010001
...
```

execute

The program translation challenge

- Extract the program's semantics from the source program, using the syntax rules of the source language
- Re-express the program's semantics in the target language, using the syntax rules of the target language

Assembler = simple translator

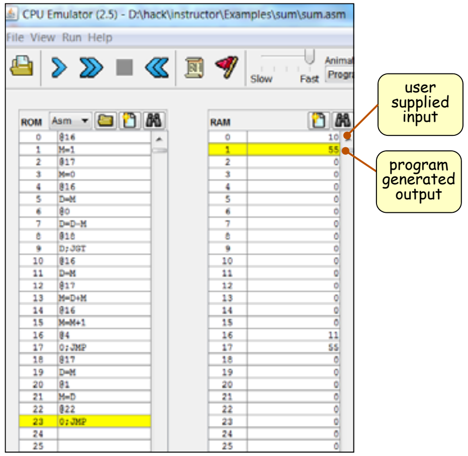
- Translates each assembly command into one or more binary machine instructions
- Handles symbols (e.g. `i`, `sum`, `LOOP`, …).

Revisiting Hack low-level programming: an example

Assembly program (`sum.asm`)

```
// Computes 1+...+RAM[0]
// And stores 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
```

CPU emulator screen shot
after running this program



ROM	
0	@16
1	M=1
2	@17
3	M=0
4	@16
5	D=M
6	@0
7	D=D-M
8	@18
9	D;JGT
10	@16
11	D=M
12	@17
13	M=D+M
14	@16
15	M=M+1
16	@4
17	0;JMP
18	@17
19	D=M
20	@1
21	M=D
22	@22
23	0;JMP
24	
25	

RAM	
0	10
1	55
2	0
3	0
4	0
5	0
6	0
7	0
8	0
9	0
10	0
11	0
12	0
13	0
14	0
15	0
16	11
17	55
18	0
19	0
20	0
21	0
22	0
23	0
24	0
25	0

The CPU emulator allows loading and executing symbolic Hack code. It resolves all the symbolic symbols to memory locations, and executes the code.

The assembler's view of an assembly program

Assembly program

```
// Computes 1+...+RAM[0]
// And stores 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
```

Assembly program =
a stream of text lines, each being one of the following:

The assembler's view of an assembly program

Assembly program

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// Computes 1+...+RAM[0]
// And stores the sum in RAM[1].
    @i
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(LOOP)
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    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
```

Assembly program =
a stream of text lines, each being one of the following:

- White space
    - Empty lines/indentation
    - Line comments
    - In-line comments

The assembler's view of an assembly program

Assembly program

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// And stores the sum in RAM[1].
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(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
```

Assembly program =
a stream of text lines, each being one of the following:

- White space
    - Empty lines/indentation
    - Line comments
    - In-line comments
- Instructions
    - A-instruction
    - C-instruction

The assembler's view of an assembly program

Assembly program

```
// Computes 1+...+RAM[0]
// And stores 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
```

Assembly program =
a stream of text lines, each being
one of the following:

- White space
  - Empty lines/indentation
  - Line comments
  - In-line comments
- Instructions
  - A-instruction
  - C-instruction
- Symbols
  - references
  - Label declaration (XXX)

The assembler's view of an assembly program

Assembly program

```
// Computes 1+...+RAM[0]
// And stores the sum in RAM[1].
    @16
    M=1   // i = 1
    @17
    M=0   // sum = 0

    @16    // if i>RAM[0] goto WRITE
    D=M
    @0
    D=D-M
    @18
    D;JGT
    @16    // sum += i
    D=M
    @17
    M=D+M
    @16    // i++
    M=M+1
    @4 // goto LOOP
    0;JMP

    @17
    D=M
    @1
    M=D  // RAM[1] = the sum

    @22
    0;JMP
```

Assembly program =
a stream of text lines, each being
one of the following:

- White space
  - Empty lines/indentation
  - Line comments
  - In-line comments
- Instructions
  - A-instruction
  - C-instruction
- Symbols
  - references
  - Label declaration (XXX)

Assume that there is
no symbol for now!

White space

Assembly program

```
// Computes 1+...+RAM[0]
// And stores the sum in RAM[1].
    @16
    M=1   // i = 1
    @17
    M=0   // sum = 0

    @16    // if i>RAM[0] goto WRITE
    D=M
    @0
    D=D-M
    @18
    D;JGT
    @16    // sum += i
    D=M
    @17
    M=D+M
    @16    // i++
    M=M+1
    @4 // goto LOOP
    0;JMP

    @17
    D=M
    @1
    M=D  // RAM[1] = the sum

    @22
    0;JMP
```

Assembly program =
a stream of text lines, each being
one of the following:

- White space
  - Empty lines/indentation
  - Line comments
  - In-line comments
- Instructions
  - A-instruction
  - C-instruction
- Symbols
  - references
  - Label declaration (XXX)

White space → ignore/remove them

Assembly program

```
@16
M=1
@17
M=0
@16
D=M
@0
D=D-M
@18
D;JGT
@16
D=M
@17
M=D+M
@16
M=M+1
@4
0;JMP
@17
D=M
@1
M=D
@22
0;JMP
```

Assembly program =
a stream of text lines, each being
one of the following:

- White space
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  - In-line comments
- Instructions
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- Symbols
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  - Label declaration (XXX)

Instructions → binary encoding

Assembly program

```
@16
M=1
@17
M=0
@16
D=M
@0
D=D-M
@18
D;JGT
@16
D=M
@17
M=D+M
@16
M=M+1
@4
0;JMP
@17
D=M
@1
M=D
@22
0;JMP
```

Assembly program =
a stream of text lines, each being one of the following:

- White space
  - Empty lines/indentation
  - Line comments
  - In-line comments
- Instructions
  - A-instruction
  - C-instruction
- Symbols
  - references
  - Label declaration (XXX)

Translating / assembling A-instructions

Symbolic: *@value* // Where *value* is either a non-negative decimal number
// or a symbol referring to such number.

value (v = 0 or 1)

Binary: 0 v v v v v v v v v v v v v v v

Translation to binary:

- If *value* is a non-negative decimal number, simple, e.g. @16
- If *value* is a symbol, later.

Translating / assembling C-instructions

Symbolic: *dest*=*comp*;*jump* // Either the *dest* or *jump* fields may be empty.
// If *dest* is empty, the "=" is ommitted;
// If *jump* is empty, the ";" is omitted.

comp *dest* *jump*

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

(when a=0) ***comp***	c1	c2	c3	c4	c5	c6	(when a=1) ***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

d1	**d2**	**d3**	***Mnemonic***	***Destination (where to store the computed value)***
0	0	0	null	The value is not stored anywhere
0	0	1	M	Memory[A] (memory register addressed by A)
0	1	0	D	D register
0	1	1	MD	Memory[A] and D register
1	0	0	A	A register
1	0	1	AM	A register and Memory[A]
1	1	0	AD	A register and D register
1	1	1	AMD	A register, Memory[A], and D register

j1 (*out* < 0)	**j2** (*out* $= 0$)	**j3** (*out* > 0)	**Mnemonic**	**Effect**
0	0	0	null	No jump
0	0	1	JGT	If *out* > 0 jump
0	1	0	JEQ	If *out* $= 0$ jump
0	1	1	JGE	If *out* ≥ 0 jump
1	0	0	JLT	If *out* < 0 jump
1	0	1	JNE	If *out* $\neq 0$ jump
1	1	0	JLE	If *out* ≤ 0 jump
1	1	1	JMP	Jump

Translating / assembling C-instructions

Symbolic: *dest*=*comp*;*jump* // Either the *dest* or *jump* fields may be empty.
// If *dest* is empty, the "=" is ommitted;
// If *jump* is empty, the ";" is omitted.

Example: MD=D+1

comp *dest* *jump*

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

(when a=0) ***comp***	c1	c2	c3	c4	c5	c6	(when a=1) ***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

d1	**d2**	**d3**	***Mnemonic***	***Destination (where to store the computed value)***
0	0	0	null	The value is not stored anywhere
0	0	1	M	Memory[A] (memory register addressed by A)
0	1	0	D	D register
0	1	1	MD	Memory[A] and D register
1	0	0	A	A register
1	0	1	AM	A register and Memory[A]
1	1	0	AD	A register and D register
1	1	1	AMD	A register, Memory[A], and D register

j1 (*out* < 0)	**j2** (*out* $= 0$)	**j3** (*out* > 0)	**Mnemonic**	**Effect**
0	0	0	null	No jump
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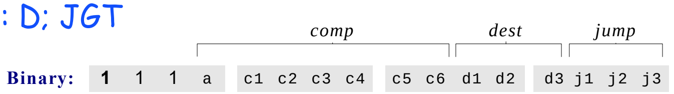
1	1	0	JLE	If *out* ≤ 0 jump
1	1	1	JMP	Jump

Translating / assembling C-instructions

Symbolic: *dest*=*comp*;*jump* // Either the *dest* or *jump* fields may be empty.
// If *dest* is empty, the "=" is ommitted;
// If *jump* is empty, the ";" is omitted.

Example: D; JGT



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

(when a=0) *comp*	c1	c2	c3	c4	c5	c6	(when a=1) *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

d1	d2	d3	*Mnemonic*	*Destination (where to store the computed value)*
0	0	0	null	The value is not stored anywhere
0	0	1	M	Memory[A] (memory register addressed by A)
0	1	0	D	D register
0	1	1	MD	Memory[A] and D register
1	0	0	A	A register
1	0	1	AM	A register and Memory[A]
1	1	0	AD	A register and D register
1	1	1	AMD	A register, Memory[A], and D register

j1 ($out < 0$)	j2 ($out = 0$)	j3 ($out > 0$)	**Mnemonic**	**Effect**
0	0	0	null	No jump
0	0	1	JGT	If $out > 0$ jump
0	1	0	JEQ	If $out = 0$ jump
0	1	1	JGE	If $out \geq 0$ jump
1	0	0	JLT	If $out < 0$ jump
1	0	1	JNE	If $out \neq 0$ jump
1	1	0	JLE	If $out \leq 0$ jump
1	1	1	JMP	Jump

The overall assembly logic

Assembly program

```
// Computes 1+...+RAM[0]
// And stores 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
    @0
    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
    @1
    M=D   // RAM[1] = the sum
(END)
    @END
    0;JMP
```

For each (real) command

- ❑ Parse the command,
  i.e. break it into its underlying fields
- ❑ A-instruction: replace the symbolic reference (if any) with the corresponding memory address, which is a number

  (how to do it, later)
- ❑ C-instruction: for each field in the instruction, generate the corresponding binary code
- ❑ Assemble the translated binary codes into a complete 16-bit machine instruction
- ❑ Write the 16-bit instruction to the output file.

Handling symbols (aka *symbol resolution*)

Typical symbolic Hack assembly code:

```
    @R0
    D=M
    @END
    D;JLE
    @counter
    M=D
    @SCREEN
    D=A
    @x
    M=D
(LOOP)
    @x
    A=M
    M=-1
    @x
    D=M
    @32
    D=D+A
    @x
    M=D
    @counter
    MD=M-1
    @LOOP
    D;JGT
(END)
    @END
    0;JMP
```

Assembly programs typically have many symbols:

- ❑ Labels that mark destinations of goto commands
- ❑ Labels that mark special memory locations
- ❑ Variables

These symbols fall into two categories:

- ❑ User-defined symbols (created by programmers)
  - ❑ Variables
  - ❑ Labels (forward reference could be a problem)
- ❑ Pre-defined symbols (used by the Hack platform).

Handling symbols: user-defined symbols

Typical symbolic Hack assembly code:

```
    @R0
    D=M
    @END
    D;JLE
    @counter
    M=D
    @SCREEN
    D=A
    @x
    M=D
(LOOP)
    @x
    A=M
    M=-1
    @x
    D=M
    @32
    D=D+A
    @x
    M=D
    @counter
    MD=M-1
    @LOOP
    D;JGT
(END)
    @END
    0;JMP
```

Label symbols: Used to label destinations of goto commands. Declared by the pseudo-command (XXX). This directive defines the symbol XXX to refer to the instruction memory location holding the next command in the program. (the assembler needs to maintain instrCtr)

Variable symbols: Any user-defined symbol xxx appearing in an assembly program that is not defined elsewhere using the **(**xxx**)** directive is treated as a variable, and is automatically assigned a unique RAM address, starting at RAM address 16 (the assembler needs to maintain nextAddr)

(why start at 16? Later.)

By convention, Hack programmers use lower-case and upper-case to represent variable and label names, respectively

Handling symbols: pre-defined symbols

Virtual registers:
The symbols R0,…, R15 are automatically predefined to refer to RAM addresses 0,…,15

I/O pointers: The symbols SCREEN and KBD are automatically predefined to refer to RAM addresses 16384 and 24576, respectively (base addresses of the *screen* and *keyboard* memory maps)

VM control pointers: the symbols SP, LCL, ARG, THIS, and THAT (that don't appear in the code example on the right) are automatically predefined to refer to RAM addresses 0 to 4, respectively

(The VM control pointers, which overlap R0,…, R4 will come to play in the virtual machine implementation, covered in the next lecture)

Typical symbolic Hack assembly code:

```
    @R0
    D=M
    @END
    D;JLE
    @counter
    M=D
    @SCREEN
    D=A
    @x
    M=D
(LOOP)
    @x
    A=M
    M=-1
    @x
    D=M
    @32
    D=D+A
    @x
    M=D
    @counter
    MD=M-1
    @LOOP
    D;JGT
(END)
    @END
    0;JMP
```

Handling symbols: symbol table

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
```

Symbol table

R0	0
R1	1
R2	2
...	...
R15	15
SCREEN	16384
KBD	24576
SP	0
LCL	1
ARG	2
THIS	3
THAT	4
LOOP	4
WRITE	18
END	22
i	16
sum	17

This symbol table is generated by the assembler, and used to translate the symbolic code into binary code.

Handling symbols: constructing the symbol table

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
```

Symbol table

R0	0
R1	1
R2	2
...	
R15	15
SCREEN	16384
KBD	24576
SP	0
LCL	1
ARG	2
THIS	3
THAT	4

Initialization: create an empty symbol table and populate it with all the pre-defined symbols

---

Handling symbols: constructing the symbol table

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// And stored the sum in RAM[1]
    @i
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    D;JGT
    @i    // sum += i
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    @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
```

Symbol table

R0	0
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Initialization: create an empty symbol table and populate it with all the pre-defined symbols

First pass: go through the entire source code, and add all the user-defined label symbols to the symbol table (without generating any code)

Handling symbols: constructing the symbol table

Source code (example)

```
// Computes 1+...+RAM[0]
// And stored the sum in RAM[1]
    @i
    M=1   // i = 1
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    @i    // if i>RAM[0] goto WRITE
    D=M
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    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
```

Symbol table

R0	0
R1	1
R2	2
...	
R15	15
SCREEN	16384
KBD	24576
SP	0
LCL	1
ARG	2
THIS	3
THAT	4
LOOP	4
WRITE	18
END	22
i	16
sum	17

Initialization: create an empty symbol table and populate it with all the pre-defined symbols

First pass: go through the entire source code, and add all the user-defined label symbols to the symbol table (without generating any code)

Second pass: go again through the source code, and use the symbol table to translate all the commands. In the process, handle all the user-defined variable symbols.

Handling symbols: constructing the symbol table (one-pass solution?)

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
```

Symbol table

R0	0
R1	1
R2	2
...	
R15	15
SCREEN	16384
KBD	24576
SP	0
LCL	1
ARG	2
THIS	3
THAT	4

The assembly process (detailed)

- Initialization: create the symbol table and initialize it with the pre-defined symbols
- First pass: march through the source code without generating any code.
  For each label declaration `(LABEL)` that appears in the source code, add the pair <`LABEL` , *n* > to the symbol table

---

The assembly process (detailed)

- Second pass: march again through the source, and process each line:
  - If the line is a `C`-instruction, simple
  - If the line is @xxx where xxx is a number, simple
  - If the line is @xxx and xxx is a symbol, look it up in the symbol table and proceed as follows:
    - ☐ If the symbol is found, replace it with its numeric value and complete the command's translation
    - ☐ If the symbol is not found, then it must represent a new variable:
      add the pair <xxx , *n* > to the symbol table, where *n* is the next available RAM address, and complete the command's translation.

      (Platform design decision: the allocated RAM addresses are running, starting at address 16).

The result ...

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

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
```

Note that comment lines and pseudo-commands (label declarations) generate no code.

Proposed assembler implementation

An assembler program can be written in any high-level language. (and could be run in the other platforms, cross-platform compiling)

The book proposes a language-independent design, as follows.

Software modules:

- **`Parser:`** Unpacks each command into its underlying fields
- **`Code:`** Translates each field into its corresponding binary value, and assembles the resulting values
- **`SymbolTable:`** Manages the symbol table
- **`Main:`** Initializes I/O files and drives the show.

Perspective

- Simple machine language, simple assembler
- Most assemblers are not stand-alone, but rather encapsulated in a translator of a higher order
- C programmers that understand the code generated by a C compiler can improve their code considerably
- C programming (e.g. for real-time systems) may involve re-writing critical segments in assembly, for optimization
- Writing an assembler is an excellent practice for writing more challenging translators, e.g. a VM Translator and a compiler, as we will do in the next lectures.