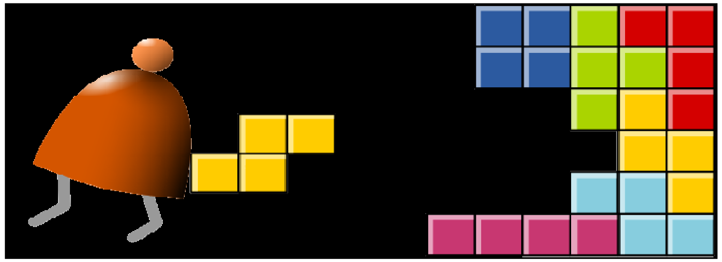
Assembler



Building a Modern Computer From First Principles

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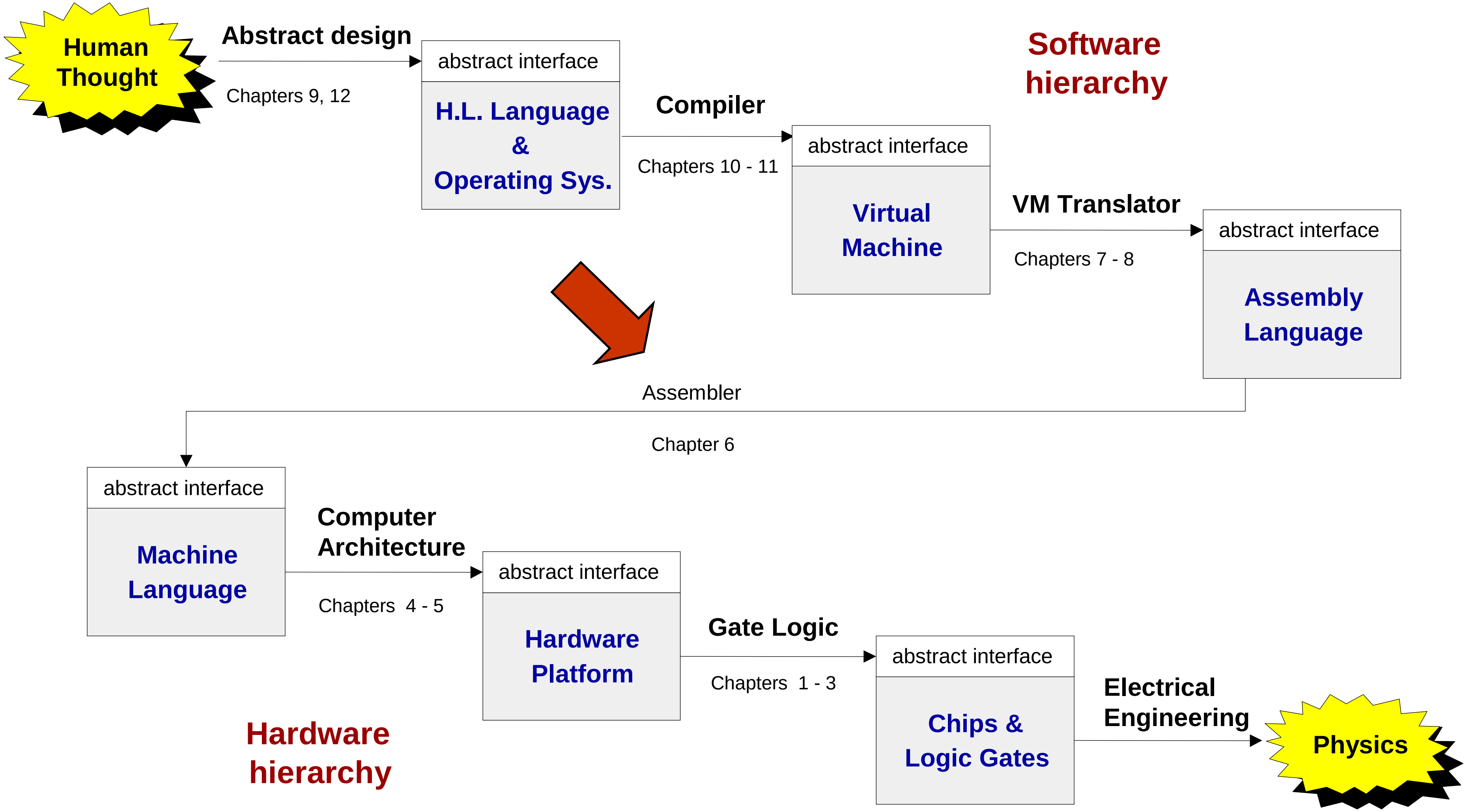
Where we are at:



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

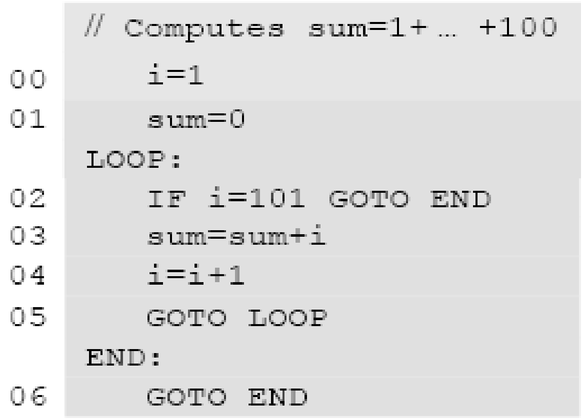
Why care about assemblers?

Because …

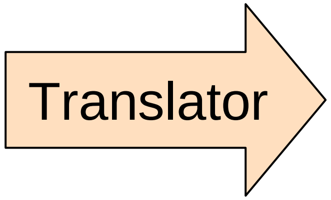
- Assemblers employ nifty programming tricks
- Assemblers are the first rung up the software hierarchy ladder
- An assembler is a translator of a simple language
- Writing an assembler = low-impact practice for writing compilers.

Program translation (for illustration purposes, this is not the Hack language)

Source code

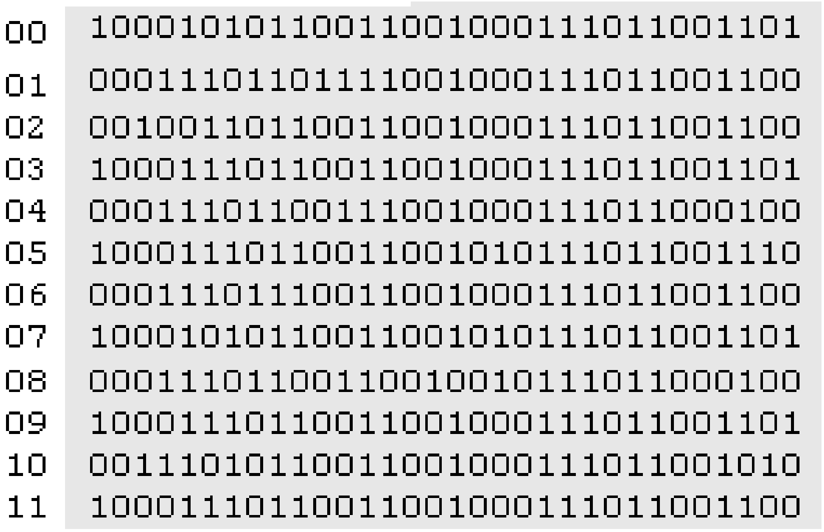


```
   // Computes sum=1+ … +100
00    i=1
01    sum=0
   LOOP:
02    IF i=101 GOTO END
03    sum=sum+i
04    i=i+1
05    GOTO LOOP
   END:
06    GOTO END
```



Translator

Target code



```
00  10001010110011001000111011001101
01  00011101101111001000111011001100
02  00100110110011001000111011001100
03  10001110110011001000111011001101
04  00011101100111001000111011000100
05  10001110110011001010111011001110
06  00011101110011001000111011001100
07  10001010110011001010111011001101
08  00011101100110010010111011000100
09  10001110110011001000111011001101
10  00111010110011001000111011001010
11  10001110110011001000111011001100
```

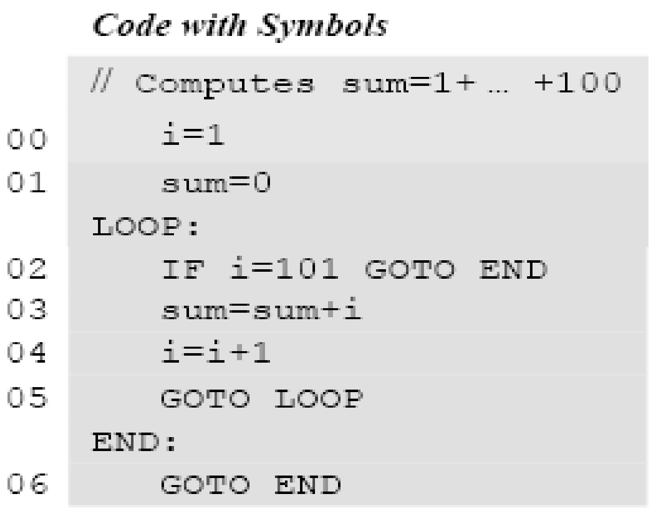
The program translation challenge

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

Assembler = simple translator

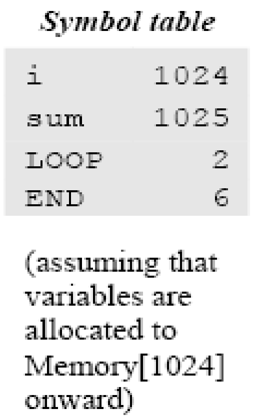
- Translates each assembly command into one or more machine instructions
- Handles symbols (**`i`**, **`sum`**, **`LOOP`**, **`END`**, …).

Symbol resolution (for illustration purposes, this is not the Hack language)



Code with Symbols

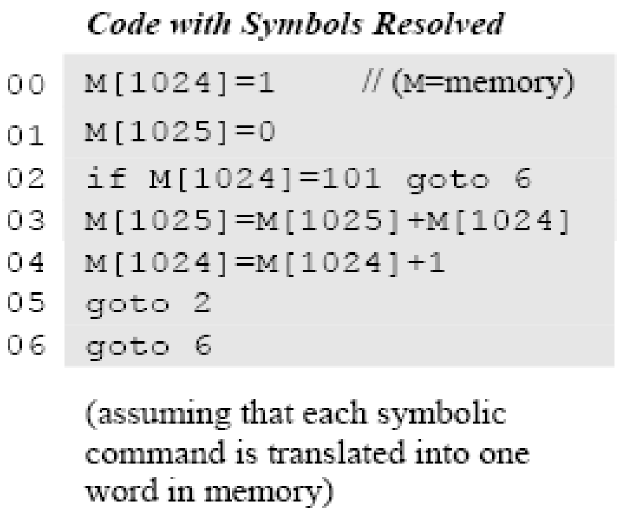
```
      // Computes sum=1+ ... +100
00        i=1
01        sum=0
      LOOP:
02        IF i=101 GOTO END
03        sum=sum+i
04        i=i+1
05        GOTO LOOP
      END:
06        GOTO END
```



Symbol table

i	1024
sum	1025
LOOP	2
END	6

(assuming that variables are allocated to Memory[1024] onward)



Code with Symbols Resolved

```
00  M[1024]=1       // (M=memory)
01  M[1025]=0
02  if M[1024]=101 goto 6
03  M[1025]=M[1025]+M[1024]
04  M[1024]=M[1024]+1
05  goto 2
06  goto 6
```

(assuming that each symbolic command is translated into one word in memory)

In low level languages, symbols are used to code:

- Variable names
- Destinations of goto commands (labels)
- Special memory locations

The assembly process:

- First pass: construct a symbol table
- Second pass: translate the program, using the symbol table for symbols resolution.

This example is based on some simplifying assumptions:

- Each command fits into one memory location
- Each variable fits into one memory location

These assumptions can be relaxed easily.

The Hack assembly language

Assembly program (`Prog.asm`)

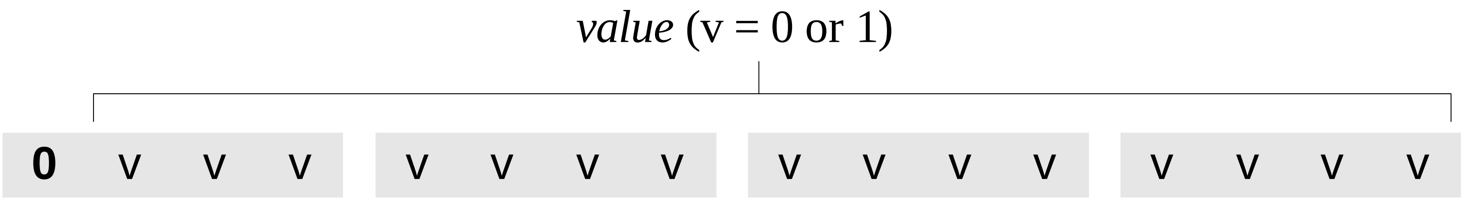
```
// Adds 1 + ... + 100
      @i
      M=1    // i=1
      @sum
      M=0    // sum=0
(LOOP)
      @i
      D=M    // D=i
      @100
      D=D-A  // D=i-100
      @END
      D;JGT  // if (i-100)>0 goto END
      @i
      D=M    // D=i
      @sum
      M=D+M  // sum=sum+i
      @i
      M=M+1  // i=i+1
      @LOOP
      0;JMP  // goto LOOP
 (END)
      @END
      0;JMP  // infinite loop
```

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

- Instruction:
  `A-instruction` or
  `C-instruction`
- Symbol declaration:
  `(symbol)`
- Comment or white space:
  `// comment.`

Handling 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 number: simple
- If *value* is a symbol: later.

Handling C-instruction

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		
A	1	1	0	0	0		
!D	0	0	1	1	0		
!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
				[A] and D register
				er
				er 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* ≠ 0 jump
1	1	0	JLE	If *out* ≤ 0 jump
1	1	1	JMP	Jump

Translation to binary:
simple!

The overall assembly logic

Assembly program (`Prog.asm`)

```
// Adds 1 + ... + 100
      @i
      M=1    // i=1
      @sum
      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=sum+i
      @i
      M=M+1  // i=i+1
      @LOOP
      0;JMP  // goto LOOP
 (END)
      @END
      0;JMP  // infinite loop
```

<u>For each (real) command</u>

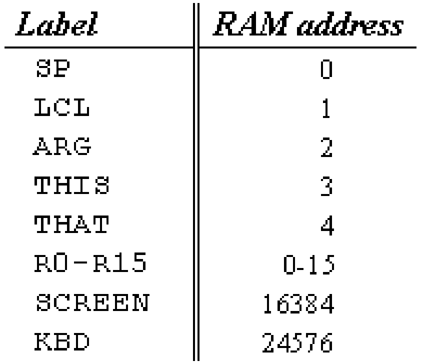
- Parse the command, i.e. break it into its constituent fields
- Replace each symbolic reference (if any) with the corresponding memory address (a binary number)
- For each field, generate the corresponding binary code
- Assemble the binary codes into a complete machine instruction (16-bit code).

Symbols handling (in the Hack language)

Program example

```
// Adds 1 + ... + 100
      @i
      M=1    // i=1
      @sum
      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=sum+i
      @i
      M=M+1  // i=i+1
      @LOOP
      0;JMP  // goto LOOP
 (END)
      @END
      0;JMP  // infinite loop
```

- **Predefined symbols:** (don't appear in this example)



Label	*RAM address*
SP	0
LCL	1
ARG	2
THIS	3
THAT	4
R0-R15	0-15
SCREEN	16384
KBD	24576

- **Label symbols:** The pseudo-command **(label)** declares that the user-defined symbol **label** should refer to the memory location holding the next command in the program
- **Variable symbols:** In a **@label** command, if **label** is neither a predefined symbol, nor a symbol defined elsewhere in the program using the **(label)** pseudo command, then **label** is treated as a variable

Design decision: variables are mapped to consecutive memory locations starting at RAM address 16.

Example

Assembly code (`Prog.asm`)

```
// Adds 1 + ... + 100
      @i
      M=1    // i=1
      @sum
      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=sum+i
      @i
      M=M+1  // i=i+1
      @LOOP
      0;JMP  // goto LOOP
 (END)
      @END
      0;JMP  // infinite loop
```

Assembler

Binary code (`Prog.hack`)

```
(this line should be erased)
0000 0000 0001 0000
1110 1111 1100 1000
0000 0000 0001 0001
1110 1010 1000 1000
(this line should be erased)
0000 0000 0001 0000
1111 1100 0001 0000
0000 0000 0110 0100
1110 0100 1101 0000
0000 0000 0001 0010
1110 0011 0000 0001
0000 0000 0001 0000
1111 1100 0001 0000
0000 0000 0001 0001
1111 0000 1000 1000
0000 0000 0001 0000
1111 1101 1100 1000
0000 0000 0000 0100
1110 1010 1000 0111
(this line should be erased)
0000 0000 0001 0010
1110 1010 1000 0111
```

Proposed implementation

An assembler program can be designed as follows.

Software modules:

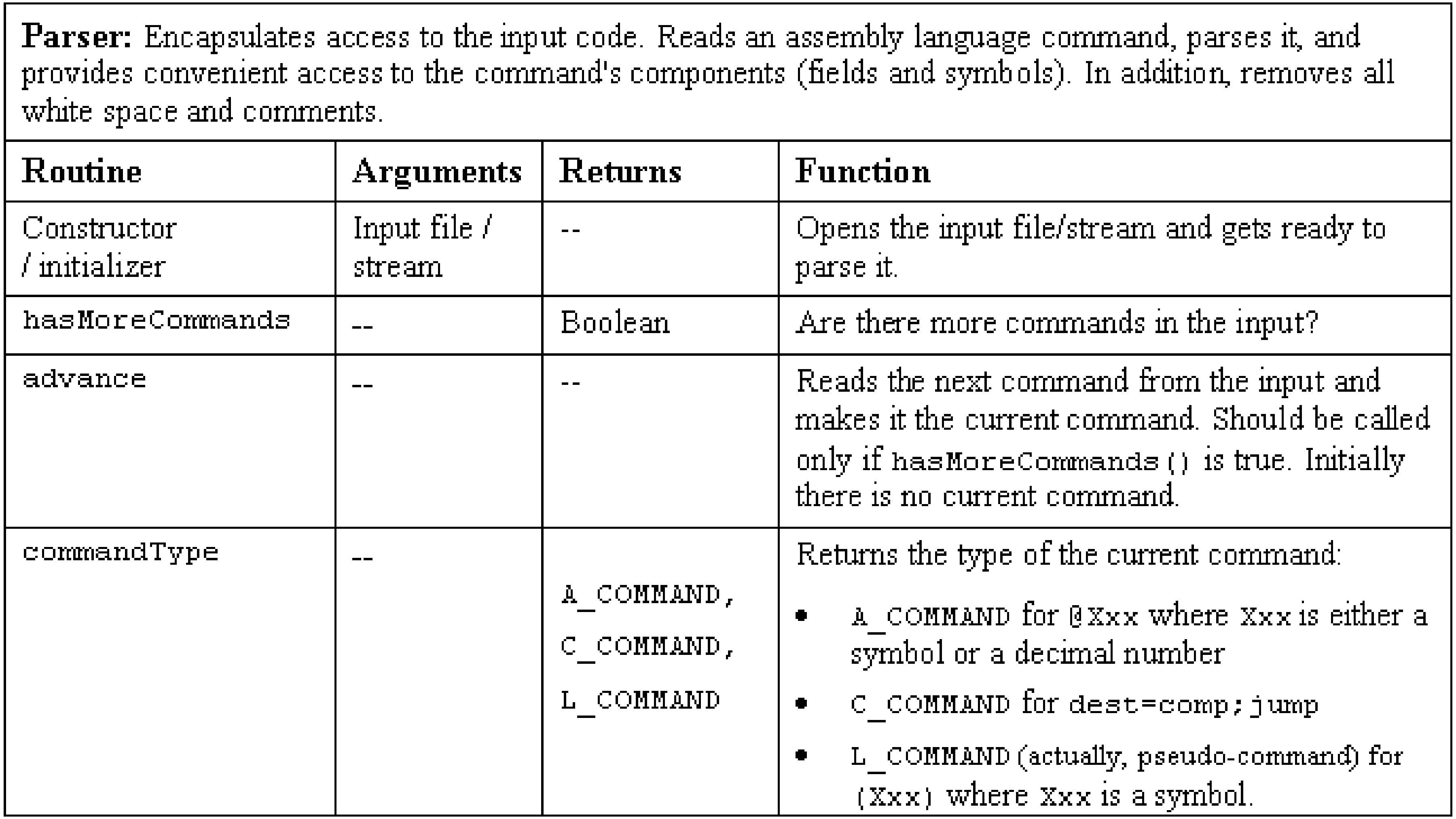
- **`Parser:`** Unpacks each command into its underlying fields
- **`Code:`** Translates each field into its corresponding binary value, and assembles the result
- **`SymbolTable:`** Manages the symbol table
- **`Main:`** Initializes I/O files and drives the show.

Proposed implementation stages

Stage I: Build a basic assembler for programs with no symbols

Stage II: Extend the basic assembler with symbol handling capabilities.

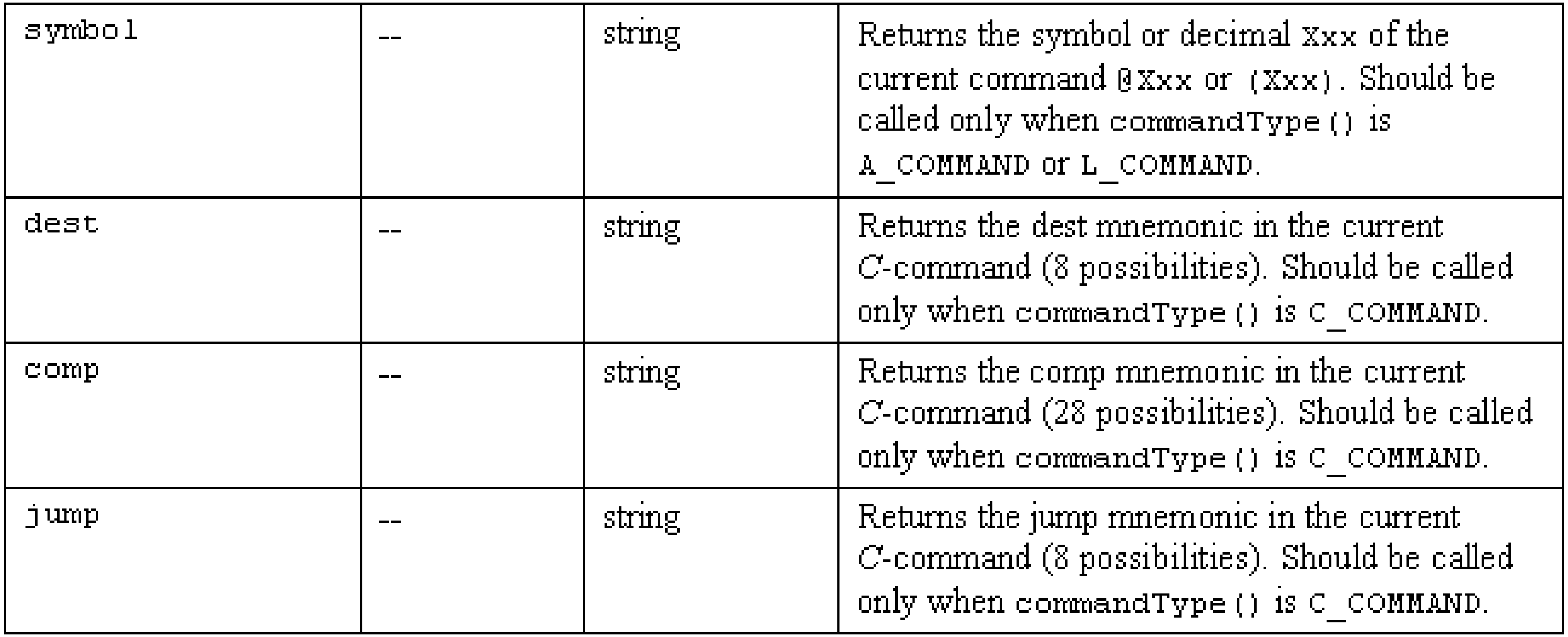
Parser module



Parser: Encapsulates access to the input code. Reads an assembly language command, parses it, and provides convenient access to the command's components (fields and symbols). In addition, removes all white space and comments.

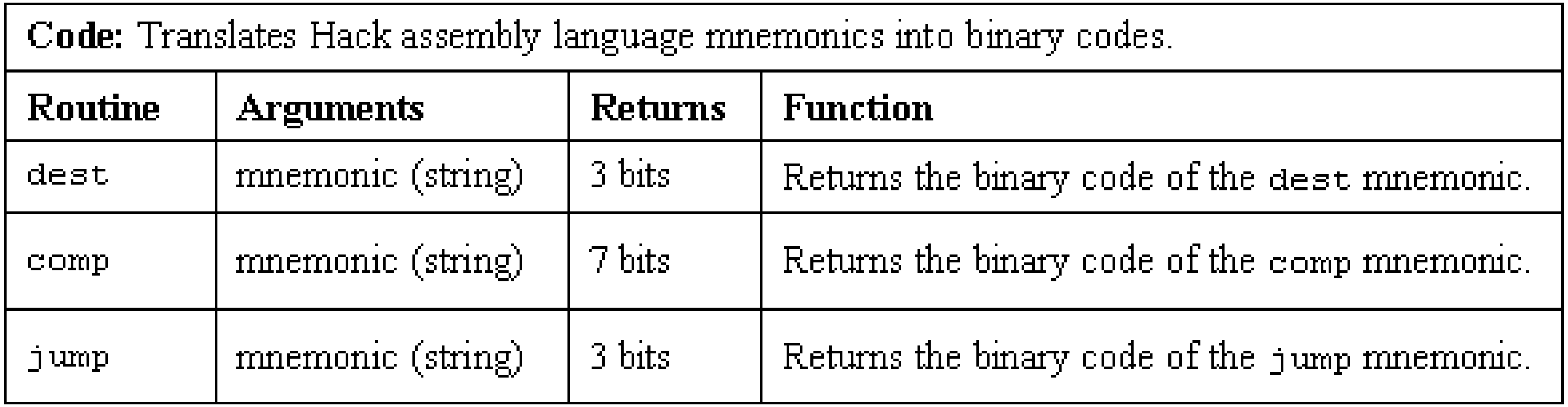
Routine	**Arguments**	**Returns**	**Function**
Constructor / initializer	Input file / stream	--	Opens the input file/stream and gets ready to parse it.
`hasMoreCommands`	--	Boolean	Are there more commands in the input?
`advance`	--	--	Reads the next command from the input and makes it the current command. Should be called only if `hasMoreCommands()` is true. Initially there is no current command.
`commandType`	--	`A_COMMAND`, `C_COMMAND`, `L_COMMAND`	Returns the type of the current command: • `A_COMMAND` for `@Xxx` where `Xxx` is either a symbol or a decimal number • `C_COMMAND` for `dest=comp;jump` • `L_COMMAND` (actually, pseudo-command) for `(Xxx)` where `Xxx` is a symbol.

Parser module (cont.)



`symbol`	--	string	Returns the symbol or decimal `Xxx` of the current command `@Xxx` or `(Xxx)`. Should be called only when `commandType()` is `A_COMMAND` or `L_COMMAND`.
`dest`	--	string	Returns the dest mnemonic in the current *C*-command (8 possibilities). Should be called only when `commandType()` is `C_COMMAND`.
`comp`	--	string	Returns the comp mnemonic in the current *C*-command (28 possibilities). Should be called only when `commandType()` is `C_COMMAND`.
`jump`	--	string	Returns the jump mnemonic in the current *C*-command (8 possibilities). Should be called only when `commandType()` is `C_COMMAND`.

Code module



Code: Translates Hack assembly language mnemonics into binary codes.

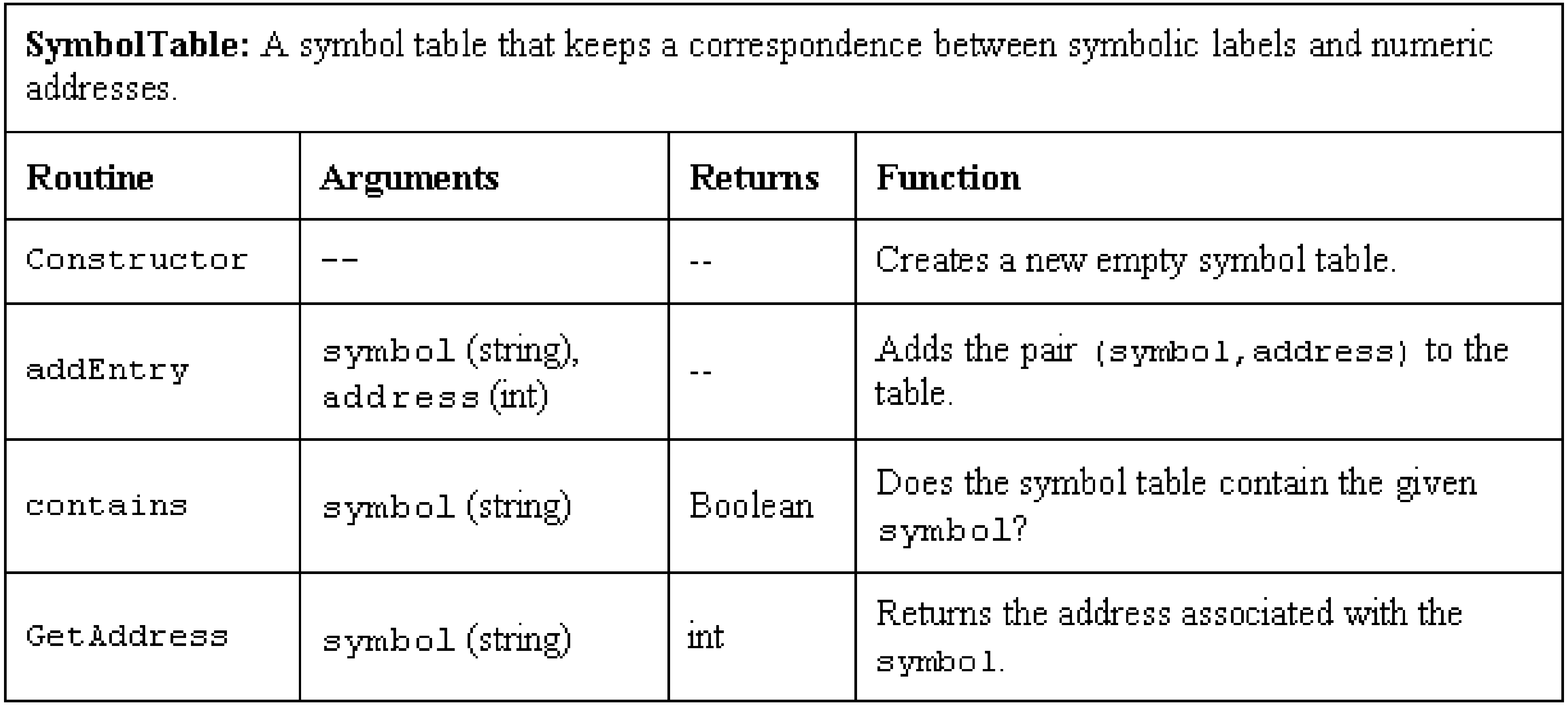
Routine	**Arguments**	**Returns**	**Function**
`dest`	mnemonic (string)	3 bits	Returns the binary code of the `dest` mnemonic.
`comp`	mnemonic (string)	7 bits	Returns the binary code of the `comp` mnemonic.
`jump`	mnemonic (string)	3 bits	Returns the binary code of the `jump` mnemonic.

Building the final Hack assembler

- Initialization: create the symbol table and initialize it with the pre-defined symbols
- First pass: march through the source program without generating any code. For each label declaration "**`(label)`**", add the pair <**`label`**,*n*> to the symbol table
- Second pass: march again through the program, and translate each line:
  - If the line is a *C*-instruction, simple
  - If the line is "**`@label`**" where **`label`** is a number, simple
  - If the line is "**`@label`**" and **`label`** is a symbol, look it up in the symbol table and proceed as follows:
    - ☐ If the symbol is found, replace it with its numeric meaning and complete the command's translation
    - ☐ If the symbol is not found, then it must represent a new variable: add the pair <**`label`**,*n*> to the symbol table, where *n* is the next available RAM address, and complete the command's translation.

      (The allocated RAM addresses are running, starting at address 16).

Symbol table

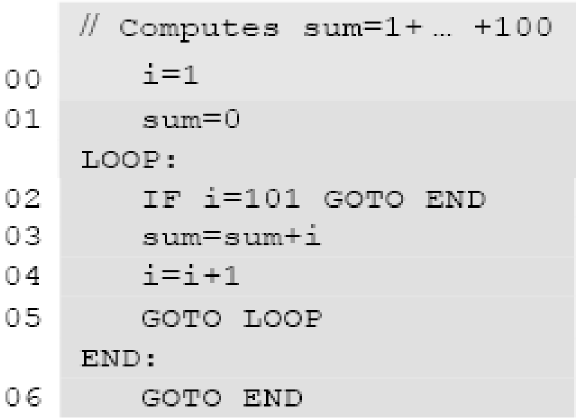


SymbolTable: A symbol table that keeps a correspondence between symbolic labels and numeric addresses.

Routine	**Arguments**	**Returns**	**Function**
`Constructor`	--	--	Creates a new empty symbol table.
`addEntry`	`symbol` (string), `address` (int)	--	Adds the pair `(symbol,address)` to the table.
`contains`	`symbol` (string)	Boolean	Does the symbol table contain the given `symbol`?
`GetAddress`	`symbol` (string)	int	Returns the address associated with the `symbol`.

Perspective

- Simple machine language, simple assembler
- Most assemblers are not stand-alone, but rather encapsulated in a translator of a higher order
- C programming (e.g. for real-time systems) may involve re-writing critical segments in assembly, for optimization
- C programmers that understand the code generated by a C compiler can improve their code considerably
- Macro assemblers:



```
   // Computes sum=1+ … +100
00      i=1
01      sum=0
   LOOP:
02      IF i=101 GOTO END
03      sum=sum+i
04      i=i+1
05      GOTO LOOP
   END:
06      GOTO END
```