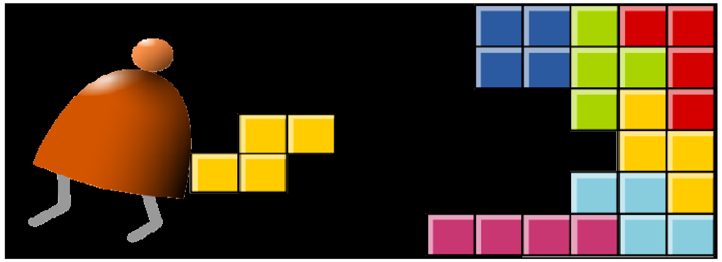
Assembler



Building a Modern Computer From First Principles

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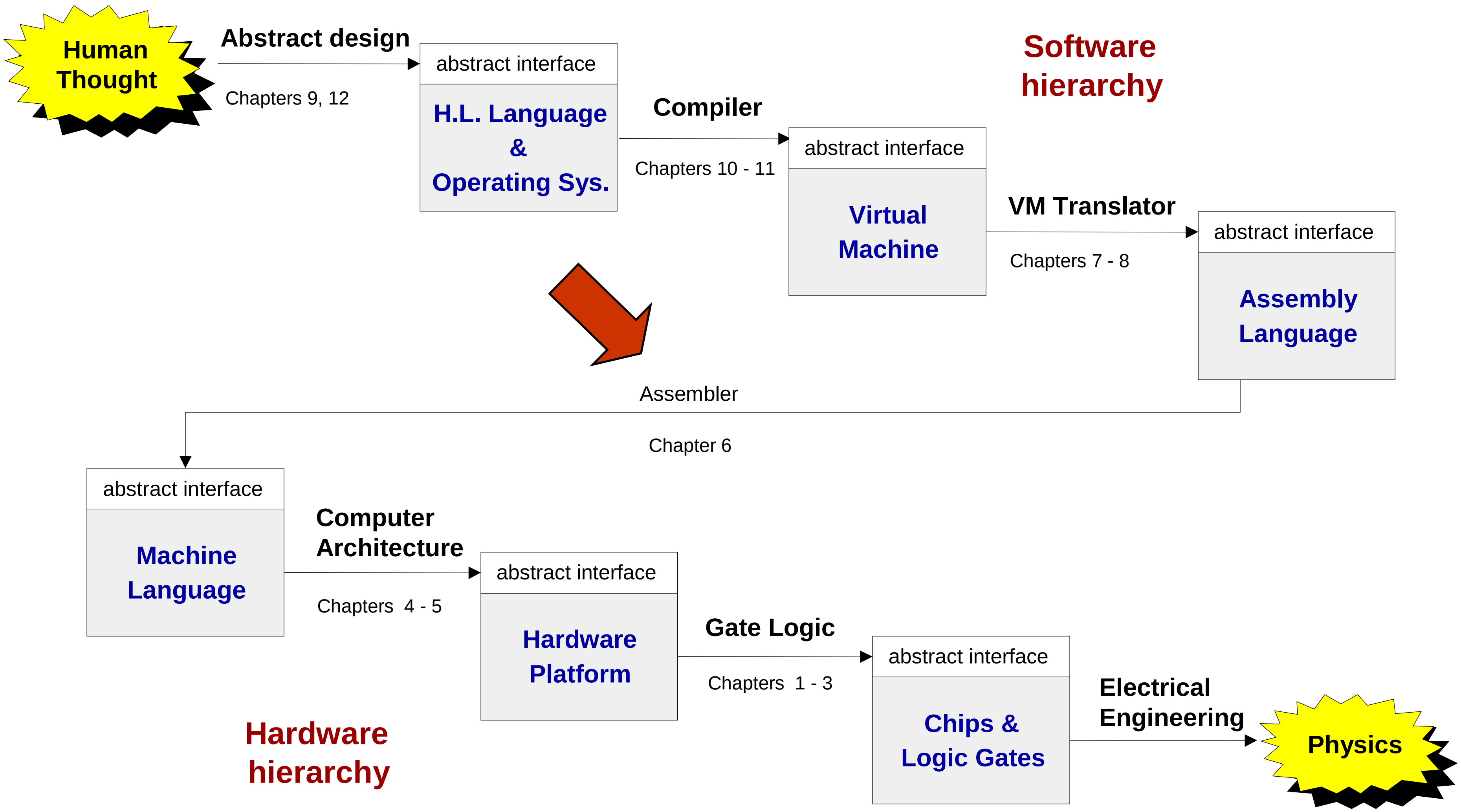
Where we are at:



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.

Assembly example

For now, ignore all details!

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

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

execute

<u>The program translation challenge</u>

- 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

<u>Assembler = simple translator</u>

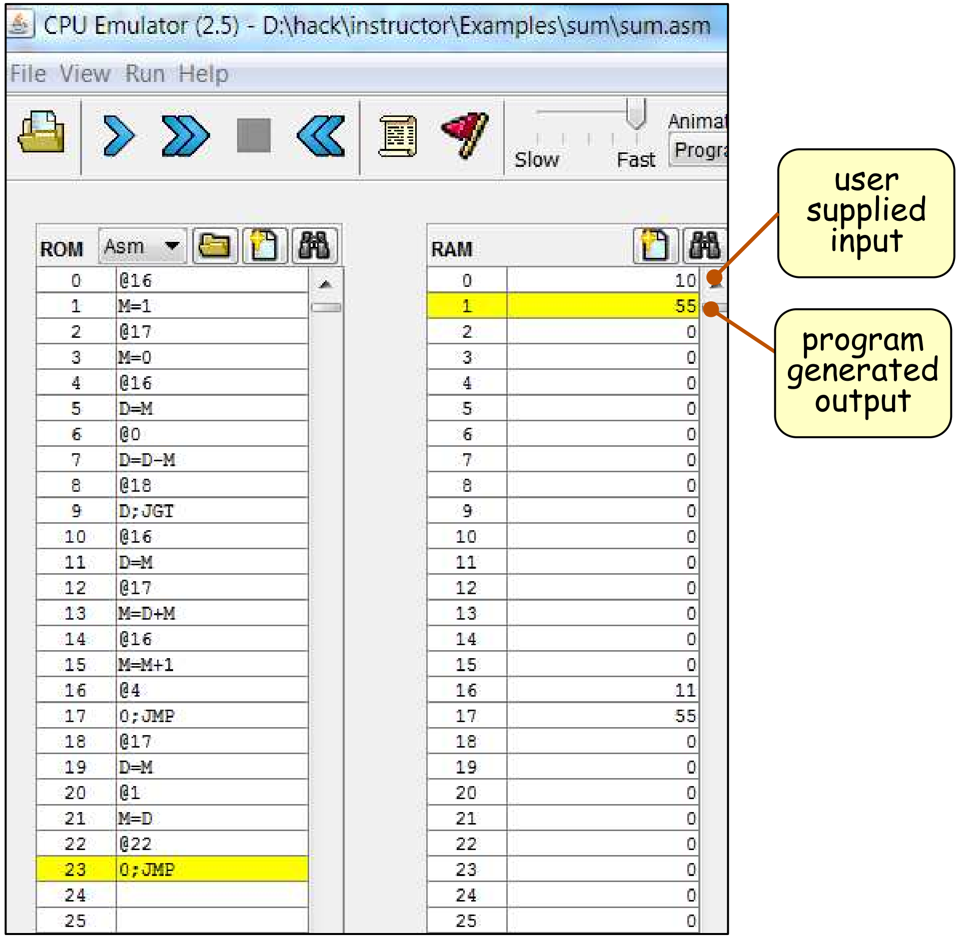
- Translates each assembly command into one or more binary machine instructions
- Handles symbols (e.g. `i`, `sum`, `LOOP`, …).

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
    @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
```

CPU emulator screen shot after running this program



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
    @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
```

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

- A-instruction
- C-instruction
- Symbol declaration: (SYMBOL)
- Comment or white space:
  // comment

The challenge:

Translate the program into a sequence of 16-bit instructions that can be executed by the target hardware platform.

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
- 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			
A	1	1	0	0			
!D	0	0	1	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
				Memory[A] and D register
				A register
				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

Translation to binary: simple!

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

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
```

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

- 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*)

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)
- Pre-defined symbols (used by the Hack platform).

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: 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

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

(why start at 16? Later.)

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

Q: Who does all the "automatic" assignments of symbols to RAM addresses?

A: As part of the program translation process, the assembler resolves all the symbols into RAM addresses.

Handling symbols: pre-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
```

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)

Q: Who does all the "automatic" assignments of symbols to RAM addresses?

A: As part of the program translation process, the assembler resolves all the symbols into RAM addresses.

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
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
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.

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
- Second pass: march again through the source code, 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.

We propose 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.

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 (a software module in the assembler program)

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 (a software module in the assembler program) / continued

`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 (a software module in the assembler program)

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.

SymbolTable (a software module in the assembler program)

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 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.