Chapter 6

Assembler

These slides support chapter 6 of the book

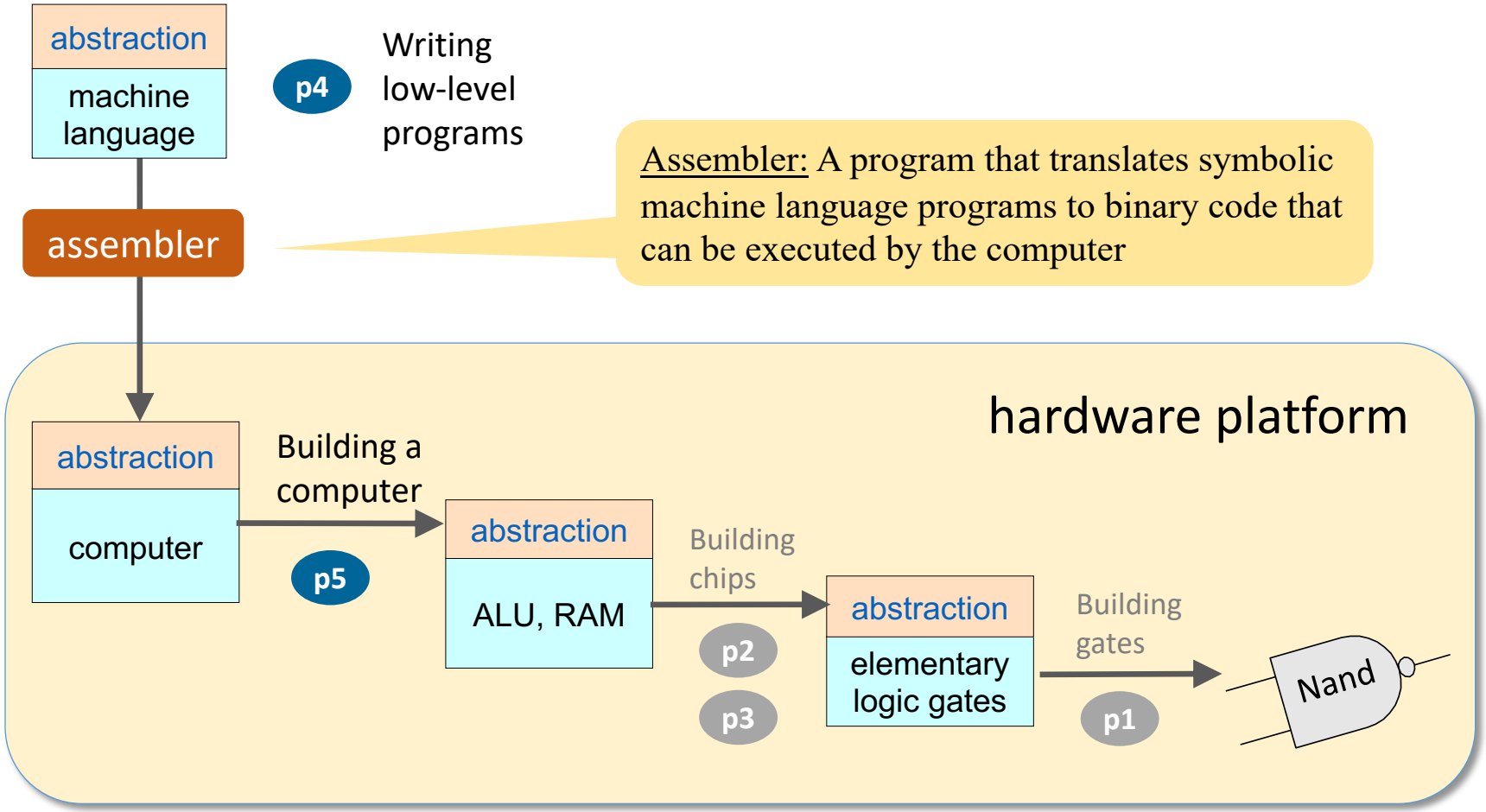
The Elements of Computing Systems

(1st and 2nd editions)

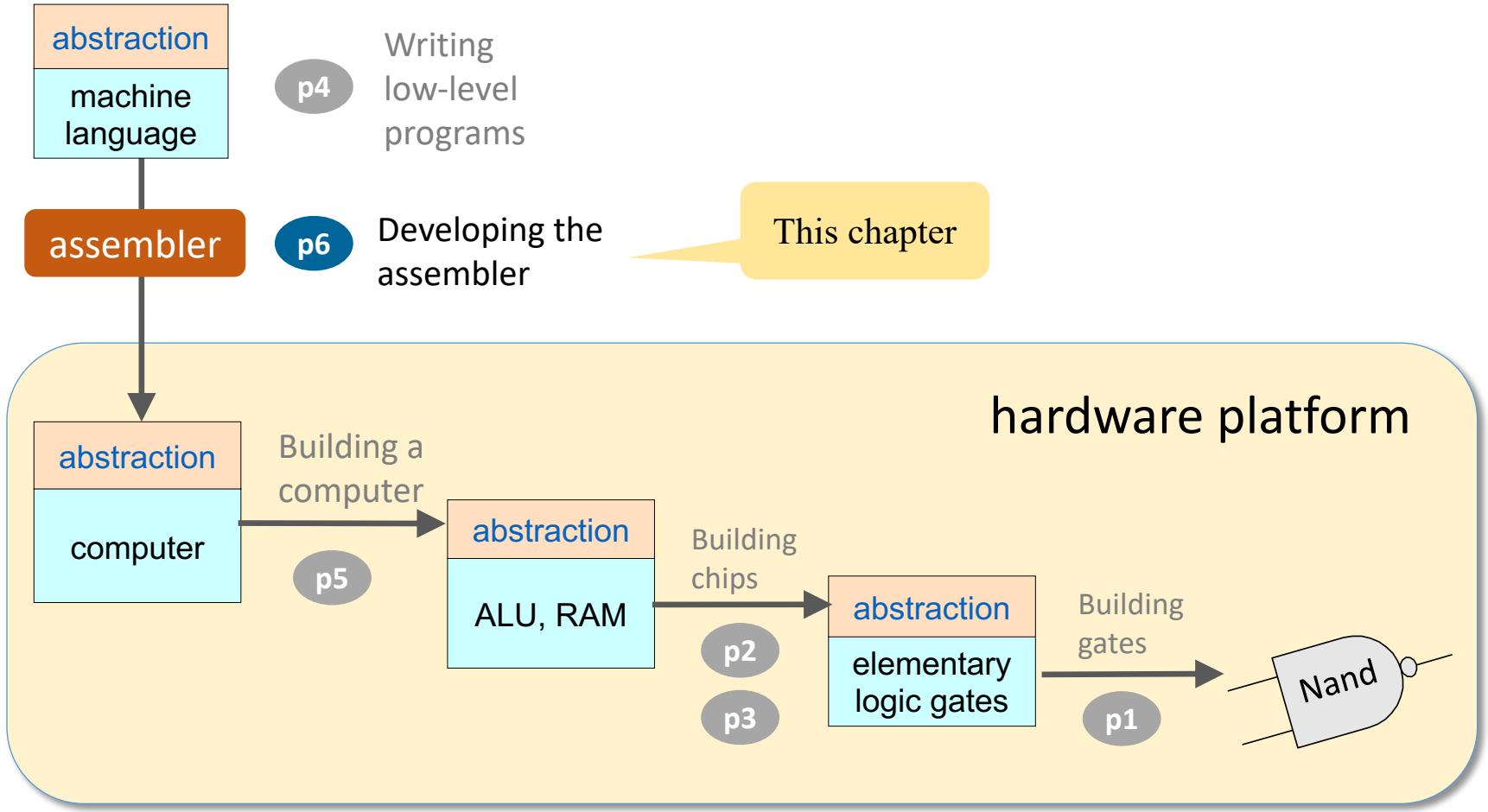
By Noam Nisan and Shimon Schocken

MIT Press

Nand to Tetris Roadmap (Part I: Hardware)



Nand to Tetris Roadmap (Part I: Hardware)



The assembler

Symbolic low-level program

```
// Program: Sum1ToN (R0 represents N)
// Computes R1 = 1 + 2 + 3 + ... + R0
// Usage: put a value >= 1 in R0
   // i = 1
   @i
   M=1
   // sum = 0
   @sum
   M=0
(LOOP)
   // if (i > R0) goto STOP
   @i
   D=M
   @R0
   D=D-M
   @STOP
   D;JGT
   // sum = sum + i
   @sum
   D=M
   @i
   D=D+M
   @sum
   M=D
   // i = i + 1
   @i
   M=M+1
   // goto LOOP
   @LOOP
   0;JMP
   ...
```

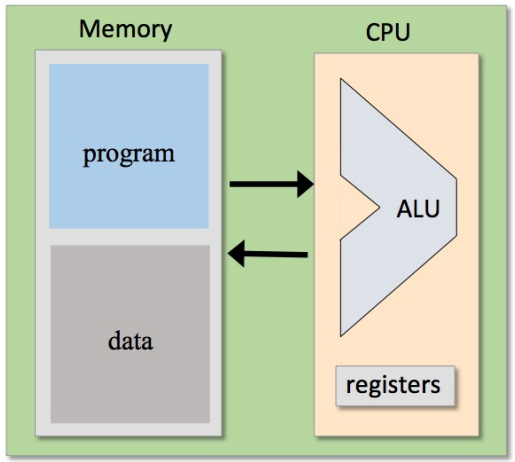
assembler

Binary code

```
0101111100111100
1010101010101010
1100000010101010
1011000010000001
0101111100111100
1010101010101010
1100000010101010
0101111100111100
1010101010101010
1100000010101010
1011000010000001
0101111100111100
1010101010101010
1100000010101010
0101111100111100
1010101010101010
1100000010101010
1011000010000001
0101111100111100
1010101010101010
1100000010101010
...
```

load and execute

Computer



Why write an assembler?

- Because it is the "linchpin" that connects the hardware platform and the software hierarchy that sits on top of it
- Because it provides a simple example of key software engineering techniques (parsing, code generation, symbol tables, …)

Chapter 6: Assembler

- Overview
- Translating instructions
- Translating programs
- Handling symbols
- Assembler architecture
- Assembler API
- Project 6
- Some history

Chapter 6: Assembler

- Overview
- Translating instructions
  - A-instructions
  - C-instructions
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Translating A-instructions

Symbolic syntax:

`@`*xxx*

Binary syntax:

`0`*vvvvvvvvvvvvvvvv*

Where *xxx* is a non-negative decimal value, or a symbol bound to such a value

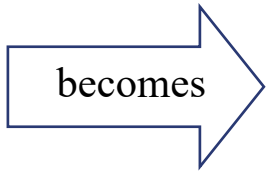
Where:

`0` is the A-instruction op-code, and

v v v ... v is the value in binary

Example:

`@17`



`0000000000010001`

Implementation

Simple: Translate the decimal value into its 16-bit representation.

Translating C-instructions

Symbolic syntax: *dest* `=` *comp* `;` *jump*

Binary syntax: `1 1 1` *a c c c c c c d d d j j j*

comp		*c*	*c*	*c*	*c*	*c*	*c*
`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`	`M`	`1`	`1`	`0`	`0`	`0`	`0`
`!D`		`0`	`0`	`1`	`1`	`0`	`1`
`!A`	`!M`	`1`	`1`	`0`	`0`	`0`	`1`
`-D`		`0`	`0`	`1`	`1`	`1`	`1`
`-A`	`-M`	`1`	`1`	`0`	`0`	`1`	`1`
`D+1`		`0`	`1`	`1`	`1`	`1`	`1`
`A+1`	`M+1`	`1`	`1`	`0`	`1`	`1`	`1`
`D-1`		`0`	`0`	`1`	`1`	`1`	`0`
`A-1`	`M-1`	`1`	`1`	`0`	`0`	`1`	`0`
`D+A`	`D+M`	`0`	`0`	`0`	`0`	`1`	`0`
`D-A`	`D-M`	`0`	`1`	`0`	`0`	`1`	`1`
`A-D`	`M-D`	`0`	`0`	`0`	`1`	`1`	`1`
`D&A`	`D&M`	`0`	`0`	`0`	`0`	`0`	`0`
`D|A`	`D|M`	`0`	`1`	`0`	`1`	`0`	`1`
a `==0`	*a* `==1`						

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]`

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

Implementation: Simple: Translate each field of the symbolic instruction (*dest*, *comp*, *jump*) into its binary code, and assemble the codes into a 16-bit instruction.

Translating C-instructions

Symbolic syntax: *dest* = *comp* ; *jump*

Binary syntax: `1 1 1 a c c c c c c d d d j j j`

comp		*c*	*c*	*c*	*c*	*c*	*c*
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	M	1	1	0	0	0	0
!D		0	0	1	1	0	1
!A	!M	1	1	0	0	0	1
-D		0	0	1	1	1	1
-A	-M	1	1	0	0	1	1
D+1		0	1	1	1	1	1
A+1	M+1	1	1	0	1	1	1
D-1		0	0	1	1	1	0
A-1	M-1	1	1	0	0	1	0
D+A	D+M	0	0	0	0	1	0
D-A	D-M	0	1	0	0	1	1
A-D	M-D	0	0	0	1	1	1
D&A	D&M	0	0	0	0	0	0
D|A	D|M	0	1	0	1	0	1
		a == 0			*a* == 1		

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]

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

Example: `D=D+1;JLE` 

Binary: `1110011111010110`

Translating C-instructions

Symbolic syntax: *dest* `=` *comp* `;` *jump*

Binary syntax: `1 1 1` *a c c c c c c d d d j j j*

comp		*c*	*c*	*c*	*c*	*c*	*c*
`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`	`M`	1	1	0	0	0	0
`!D`		0	0	1	1	0	1
`!A`	`!M`	1	1	0	0	0	1
`-D`		0	0	1	1	1	1
`-A`	`-M`	1	1	0	0	1	1
`D+1`		0	1	1	1	1	1
`A+1`	`M+1`	1	1	0	1	1	1
`D-1`		0	0	1	1	1	0
`A-1`	`M-1`	1	1	0	0	1	0
`D+A`	`D+M`	0	0	0	0	1	0
`D-A`	`D-M`	0	1	0	0	1	1
`A-D`	`M-D`	0	0	0	1	1	1
`D&A`	`D&M`	0	0	0	0	0	0
`D|A`	`D|M`	0	1	0	1	0	1
a `==0`	*a* `==1`						

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]`

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

Example: `A=-1`

Binary:

`1110111010100000`

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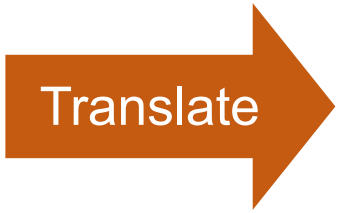
Program translation

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @i
    M=1
    // sum = 0
    @sum
    M=0
(LOOP)
    // if i>R0 goto STOP
    @i
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    // sum += i
    @i
    D=M
    @sum
    M=D+M
    // i++
    @i
    M=M+1
    @LOOP
    0;JMP
(STOP)
    @sum
    D=M
    ...
```



Need to handle:

- White space
- Instructions
- Symbols

We'll start with programs that have no symbols,

and handle symbols later

Binary code

```
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
0000000000010010
1110001100000001
0000000000010000
1111110000010000
0000000000010001
1111000010001000
0000000000010000
1111110111001000
0000000000000100
1110101010000111
0000000000010001
1111110000010000
...
```

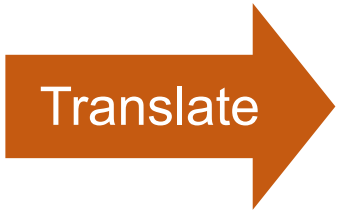
Program translation

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @16
    M=1
    // sum = 0
    @17
    M=0

    // if i>R0 goto STOP
    @16
    D=M
    @0
    D=D-M
    @18
    D;JGT
    // sum += i
    @16
    D=M
    @17
    M=D+M
    // i++
    @16
    M=M+1
    @4
    0;JMP
    @17
    D=M
    ...
```

no symbols



Need to handle:

- White space
- Instructions
- Symbols (later)

Binary code

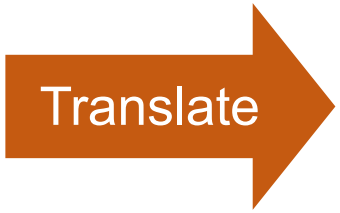
Program translation

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @16
    M=1
    // sum = 0
    @17
    M=0

    // if i>R0 goto STOP
    @16
    D=M
    @0
    D=D-M
    @18
    D;JGT
    // sum += i
    @16
    D=M
    @17
    M=D+M
    // i++
    @16
    M=M+1
    @4
    0;JMP
    @17
    D=M
    ...
```

no symbols



Need to handle:

- White space
- Instructions
- Symbols (later)

Binary code

Program translation

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @16
    M=1
    // sum = 0
    @17
    M=0

    // if i>R0 goto STOP
    @16
    D=M
    @0
    D=D-M
    @18
    D;JGT
    // sum += i
    @16
    D=M
    @17
    M=D+M
    // i++
    @16
    M=M+1
    @4
    0;JMP
    @17
    D=M
    ...
```

no symbols

Translate

Binary code

Need to handle:

- White space — Ignore it
- Instructions
- Symbols (later)

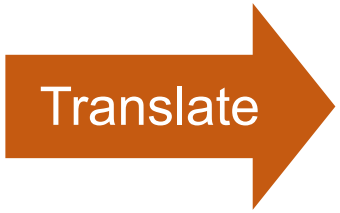
White space:

- Empty lines,
- Comments,
- Indentation

Program translation

Symbolic code

```
@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
...
```



Binary code

Need to handle:

- ✓ White space
- Instructions
- Symbols (later)

Program translation

Symbolic code

```
@16
M=1
@17
M=0
@16
D=M
@0
D=D-M
@18
D;JGT
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D=M
@17
M=D+M
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D=M
...
```
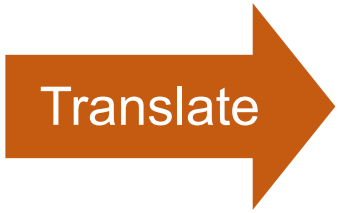



Binary code

Need to handle:

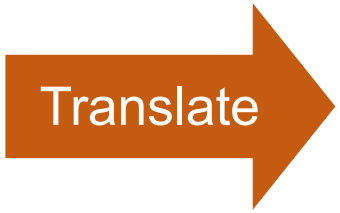
- White space
- Instructions
- Symbols (later)

Translate, one by one

Program translation

Symbolic code

```
@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
...
```



Need to handle:

- White space
- Instructions
- Symbols (later)

Translate, one by one

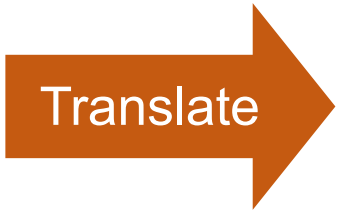
Binary code

```
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
0000000000010010
1110001100000001
0000000000010000
1111110000010000
0000000000010001
1111000010001000
0000000000010000
1111110111001000
0000000000000100
1110101010000111
0000000000010001
1111110000010000
...
```

Program translation

Symbolic code

```
@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
...
```



Need to handle:

- ✓ White space
- ✓ Instructions
- Symbols

Binary code

```
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
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1111010011010000
0000000000010010
1110001100000001
0000000000010000
1111110000010000
0000000000010001
1111000010001000
0000000000010000
1111110111001000
0000000000000100
1110101010000111
0000000000010001
1111110000010000
...
```

Program translation

Symbolic code

```
@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
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@17
D=M
...
```

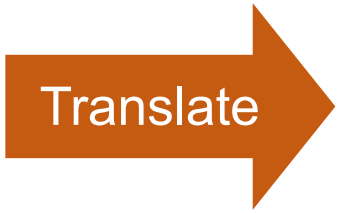

Need to handle:

- White space
- Instructions
- Symbols

Binary code

```
0000000000010000
1110111111001000
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0000000000010000
1111110000010000
0000000000010001
1111000010001000
0000000000010000
1111110111001000
0000000000000100
1110101010000111
0000000000010001
1111110000010000
...
```
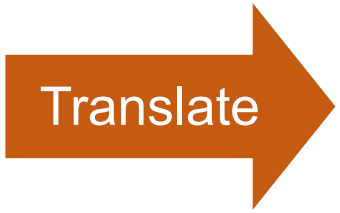

Program translation

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @i
    M=1
    // sum = 0
    @sum
    M=0
(LOOP)
    // if i>R0 goto STOP
    @i
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    // sum += i
    @i
    D=M
    @sum
    M=D+M
    // i++
    @i
    M=M+1
    @LOOP
    0;JMP
(STOP)
    @sum
    D=M
    ...
```

Original program, with symbols



Need to handle:

- White space
- Instructions
- Symbols

Binary code

Handling symbols

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @i
    M=1
    // sum = 0
    @sum
    M=0
(LOOP)
    // if i>R0 goto STOP
    @i
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    // sum += i
    @i
    D=M
    @sum
    M=D+M
    // i++
    @i
    M=M+1
    @LOOP
    0;JMP
(STOP)
    @sum
    D=M
    ...
```

Original program, with symbols

Symbols

- Predefined symbols
- Label symbols
- Variable symbols

Handling symbols

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @i
    M=1
    // sum = 0
    @sum
    M=0
(LOOP)
    // if i>R0 goto STOP
    @i
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    // sum += i
    @i
    D=M
    @sum
    M=D+M
    // i++
    @i
    M=M+1
    @LOOP
    0;JMP
(STOP)
    @sum
    D=M
    ...
```

Original program, with symbols

Symbols

- Predefined symbols
- Label symbols
- Variable symbols

Handling symbols

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @i
    M=1
    // sum = 0
    @sum
    M=0
(LOOP)
    // if i>R0 goto STOP
    @i
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    // sum += i
    @i
    D=M
    @sum
    M=D+M
    // i++
    @i
    M=M+1
    @LOOP
    0;JMP
(STOP)
    @sum
    D=M
    ...
```

Symbols

- Predefined symbols
- Label symbols
- Variable symbols

This particular program uses one predefined symbol: `R0`

Handling symbols

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @i
    M=1
    // sum = 0
    @sum
    M=0
(LOOP)
    // if i>R0 goto STOP
    @i
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    // sum += i
    @i
    D=M
    @sum
    M=D+M
    // i++
    @i
    M=M+1
    @LOOP
    0;JMP
(STOP)
    @sum
    D=M
    ...
```

The Hack language features 23 *predefined symbols*:

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

This particular program uses one predefined symbol: `R0`

Handling symbols

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @i
    M=1
    // sum = 0
    @sum
    M=0
(LOOP)
    // if i>R0 goto STOP
    @i
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    // sum += i
    @i
    D=M
    @sum
    M=D+M
    // i++
    @i
    M=M+1
    @LOOP
    0;JMP
(STOP)
    @sum
    D=M
    ...
```

The Hack language features
23 *predefined symbols*:

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

Translating @*preDefinedSymbol* :

Replace *preDefinedSymbol* with its *value*

Example: `@R15`  `0000000000001111`

Handling symbols

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @i
    M=1
    // sum = 0
    @sum
    M=0
(LOOP)
    // if i>R0 goto STOP
    @i
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    // sum += i
    @i
    D=M
    @sum
    M=D+M
    // i++
    @i
    M=M+1
    @LOOP
    0;JMP
(STOP)
    @sum
    D=M
    ...
```

Symbols

✓ Predefined symbols

- Label symbols
- Variable symbols

Handling symbols

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @i
    M=1
    // sum = 0
    @sum
    M=0
(LOOP)
    // if i>R0 goto STOP
    @i
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    // sum += i
    @i
    D=M
    @sum
    M=D+M
    // i++
    @i
    M=M+1
    @LOOP
    0;JMP
(STOP)
    @sum
    D=M
    ...
```

Symbols

- Predefined symbols
- Label symbols
- Variable symbols

Handling symbols

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @i
    M=1
    // sum = 0
    @sum
    M=0
(LOOP)
    // if i>R0 goto STOP
    @i
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    // sum += i
    @i
    D=M
    @sum
    M=D+M
    // i++
    @i
    M=M+1
    @LOOP
    0;JMP
(STOP)
    @sum
    D=M
    ...
```

Symbols

- Predefined symbols
- Label symbols
- Variable symbols

This particular program uses two label symbols: `LOOP`, `STOP`

Handling symbols

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @i
    M=1
    // sum = 0
    @sum
    M=0
(LOOP)
    // if i>R0 goto STOP
    @i
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    // sum += i
    @i
    D=M
    @sum
    M=D+M
    // i++
    @i
    M=M+1
    @LOOP
    0;JMP
(STOP)
    @sum
    D=M
    ...
```

Label symbols

- Used to label destinations of goto instructions
- Declared by the pseudo-instruction (*label*)
- The (*label*) directive defines the symbol *label* to refer to the memory location holding the next instruction in the program,
- Which corresponds to the instruction's *line number*

This particular program uses two label symbols: `LOOP`, `STOP`

Handling symbols

Symbolic code

```
    // Computes R1=1 + ... + R0
        // i = 1
0       @i
1       M=1
        // sum = 0
2       @sum
3       M=0
    (LOOP)
        // if i>R0 goto STOP
4       @i
5       D=M
6       @R0
7       D=D-M
8       @STOP
9       D;JGT
        // sum += i
10      @i
11      D=M
12      @sum
13      M=D+M
        // i++
14      @i
15      M=M+1
16      @LOOP
17      0;JMP
    (STOP)
18      @sum
19      D=M
...     ...
```

Label symbols

- Used to label destinations of goto instructions
- Declared by the pseudo-instruction (*label*)
- The (*label*) directive defines the symbol *label* to refer to the memory location holding the next instruction in the program,
- Which corresponds to the instruction's *line number*

Example:

symbol	*value*
LOOP	4
STOP	18

This particular program uses two label symbols: LOOP, STOP

Handling symbols

Symbolic code

```
    // Computes R1=1 + ... + R0
        // i = 1
0       @i
1       M=1
        // sum = 0
2       @sum
3       M=0
    (LOOP)
        // if i>R0 goto STOP
4       @i
5       D=M
6       @R0
7       D=D-M
8       @STOP
9       D;JGT
        // sum += i
10      @i
11      D=M
12      @sum
13      M=D+M
        // i++
14      @i
15      M=M+1
16      @LOOP
17      0;JMP
    (STOP)
18      @sum
19      D=M
...     ...
```

Label symbols

- Used to label destinations of goto instructions
- Declared by the pseudo-instruction (*label*)
- The (*label*) directive defines the symbol *label* to refer to the memory location holding the next instruction in the program,
- Which corresponds to the instruction's *line number*

Example:

symbol	*value*
LOOP	4
STOP	18

Translating @*labelSymbol* :

Replace *labelSymbol* with its *value*

Example: @LOOP  `0000000000000100`

Handling symbols

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @i
    M=1
    // sum = 0
    @sum
    M=0
(LOOP)
    // if i>R0 goto STOP
    @i
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    // sum += i
    @i
    D=M
    @sum
    M=D+M
    // i++
    @i
    M=M+1
    @LOOP
    0;JMP
(STOP)
    @sum
    D=M
    ...
```

Symbols

✓ Predefined symbols

✓ Label symbols

- Variable symbols

Handling symbols

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @i
    M=1
    // sum = 0
    @sum
    M=0
(LOOP)
    // if i>R0 goto STOP
    @i
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    // sum += i
    @i
    D=M
    @sum
    M=D+M
    // i++
    @i
    M=M+1
    @LOOP
    0;JMP
(STOP)
    @sum
    D=M
    ...
```

Symbols

- Predefined symbols
- Label symbols
- Variable symbols

Handling symbols

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @i
    M=1
    // sum = 0
    @sum
    M=0
(LOOP)
    // if i>R0 goto STOP
    @i
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    // sum += i
    @i
    D=M
    @sum
    M=D+M
    // i++
    @i
    M=M+1
    @LOOP
    0;JMP
(STOP)
    @sum
    D=M
    ...
```

Symbols

- Predefined symbols
- Label symbols
- Variable symbols

This particular program uses two variable symbols: `i`, `sum`

Handling symbols

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @i
    M=1
    // sum = 0
    @sum
    M=0
(LOOP)
    // if i>R0 goto STOP
    @i
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    // sum += i
    @i
    D=M
    @sum
    M=D+M
    // i++
    @i
    M=M+1
    @LOOP
    0;JMP
(STOP)
    @sum
    D=M
    ...
```

Variable symbols

- Any symbol *xxx* which is neither predefined, nor defined elsewhere using an (*xxx*) label declaration, is treated as a *variable*
- Each variable is bound to a running memory address, starting at 16

Example:

symbol	*value*
i	16
sum	17

This particular program uses two variable symbols: `i`, `sum`

Handling symbols

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @i
    M=1
    // sum = 0
    @sum
    M=0
(LOOP)
    // if i>R0 goto STOP
    @i
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    // sum += i
    @i
    D=M
    @sum
    M=D+M
    // i++
    @i
    M=M+1
    @LOOP
    0;JMP
(STOP)
    @sum
    D=M
    ...
```

Variable symbols

- Any symbol *xxx* which is neither predefined, nor defined elsewhere using an (*xxx*) label declaration, is treated as a *variable*
- Each variable is bound to a running memory address, starting at 16

Example:

symbol	*value*
i	16
sum	17

Translating @*variableSymbol* :

1. If *variableSymbol* is seen for the first time, bind to it a *value*, from 16 onward
   Else, it has a *value*
2. Replace *variableSymbol* with its *value*.

Example: `@sum` → `0000000000010001`

Handling symbols

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @i
    M=1
    // sum = 0
    @sum
    M=0
(LOOP)
    // if i>R0 goto STOP
    @i
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    // sum += i
    @i
    D=M
    @sum
    M=D+M
    // i++
    @i
    M=M+1
    @LOOP
    0;JMP
(STOP)
    @sum
    D=M
    ...
```

Symbol table

symbol	*value*
R0	0
R1	1
R2	2
...	...
R15	15
SCREEN	16384
KBD	24576
SP	0
LCL	1
ARG	2
THIS	3
THAT	4
LOOP	4
STOP	18
i	16
sum	17

A data structure that the assembler creates and uses during the program translation

Contains the
predefined symbols,
label symbols,
variable symbols,
And their bindings.

Handling symbols

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @i
    M=1
    // sum = 0
    @sum
    M=0
(LOOP)
    // if i>R0 goto STOP
    @i
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    // sum += i
    @i
    D=M
    @sum
    M=D+M
    // i++
    @i
    M=M+1
    @LOOP
    0;JMP
(STOP)
    @sum
    D=M
    ...
```

Symbol table

symbol	*value*

A data structure that the assembler creates and uses during the program translation

Handling symbols

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @i
    M=1
    // sum = 0
    @sum
    M=0
(LOOP)
    // if i>R0 goto STOP
    @i
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    // sum += i
    @i
    D=M
    @sum
    M=D+M
    // i++
    @i
    M=M+1
    @LOOP
    0;JMP
(STOP)
    @sum
    D=M
    ...
```

Symbol table

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

A data structure that the assembler creates and uses during the program translation

Initialization:
Creates the table and adds all the predefined symbols

Handling symbols

Symbolic code

```
    // Computes R1=1 + ... + R0
        // i = 1
0       @i
1       M=1
        // sum = 0
2       @sum
3       M=0
    (LOOP)
        // if i>R0 goto STOP
4       @i
5       D=M
6       @R0
7       D=D-M
8       @STOP
9       D;JGT
        // sum += i
10      @i
11      D=M
12      @sum
13      M=D+M
        // i++
14      @i
15      M=M+1
16      @LOOP
17      0;JMP
    (STOP)
18      @sum
19      D=M
...     ...
```

Symbol table

symbol	*value*
R0	0
R1	1
R2	2
...	...
R15	15
SCREEN	16384
KBD	24576
SP	0
LCL	1
ARG	2
THIS	3
THAT	4
LOOP	4
STOP	18

A data structure that the assembler creates and uses during the program translation

Initialization:
Creates the table and adds all the predefined symbols

First pass: Counts lines and adds the label symbols

Handling symbols

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @i
    M=1
    // sum = 0
    @sum
    M=0
(LOOP)
    // if i>R0 goto STOP
    @i
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    // sum += i
    @i
    D=M
    @sum
    M=D+M
    // i++
    @i
    M=M+1
    @LOOP
    0;JMP
(STOP)
    @sum
    D=M
    ...
```

Symbol table

symbol	*value*
R0	0
R1	1
R2	2
...	...
R15	15
SCREEN	16384
KBD	24576
SP	0
LCL	1
ARG	2
THIS	3
THAT	4
LOOP	4
STOP	18
i	16
sum	17

A data structure that the assembler creates and uses during the program translation

Initialization:
Creates the table and adds all the predefined symbols

First pass: Counts lines and adds the label symbols

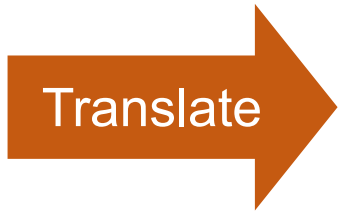
Second pass: Generates binary code; In the process, adds the variable symbols

(details, soon)

Translating programs

Symbolic code

```
// Computes R1=1 + ... + R0
    // i = 1
    @i
    M=1
    // sum = 0
    @sum
    M=0
(LOOP)
    // if i>R0 goto STOP
    @i
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    // sum += i
    @i
    D=M
    @sum
    M=D+M
    // i++
    @i
    M=M+1
    @LOOP
    0;JMP
(STOP)
    @sum
    D=M
    ...
```



Need to handle:

- ✓ White space
- ✓ Instructions
- ✓ Symbols

Binary code

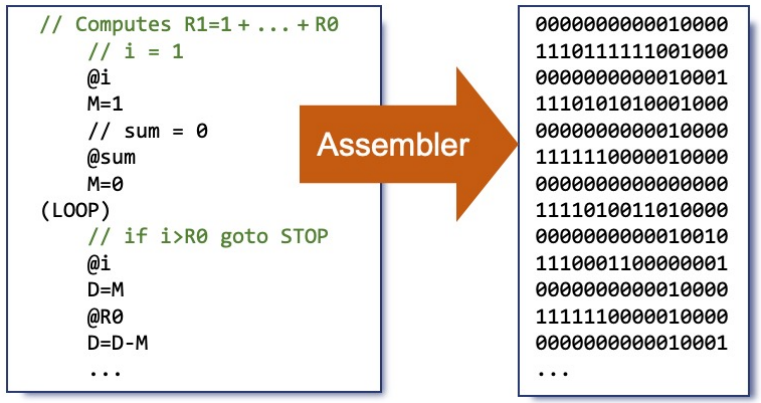
```
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
0000000000010010
1110001100000001
0000000000010000
1111110000010000
0000000000010001
1111000010001000
0000000000010000
1111110111001000
0000000000000100
1110101010000111
0000000000010001
1111110000010000
...
```

Chapter 6: Assembler

- Overview
- Translating instructions
- Translating programs
- Handling symbols

- Assembler architecture
- Assembler API
- Project 6
- Some history

Assembler: Usage



Input (*Prog*.asm): a text file containing a sequence of lines, each being a comment, an A instruction, or a C-instruction

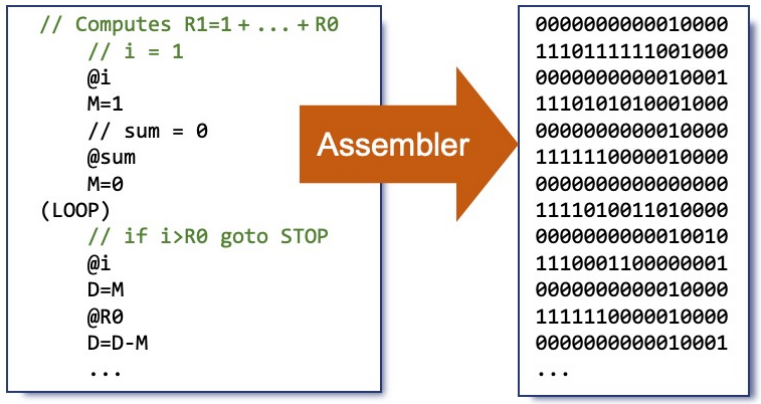
Output (*Prog*.hack): a text file containing a sequence of lines, each being a string of sixteen 0 and 1 characters

Usage: (if the assembler is implemented in Java)

```
$ java HackAssembler Prog.asm
```

Action: Creates a *Prog*.hack file, containing the translated Hack program

Assembler: Algorithm



Initialize:

Opens the input file (*Prog*`.asm`),
and gets ready to process it

Constructs a symbol table,
and adds to it all the predefined symbols

First pass:

Reads the program lines, one by one,
focusing only on (*label*) declarations.
Adds the found labels to the symbol table

Second pass (main loop):

(starts again from the beginning of the file)

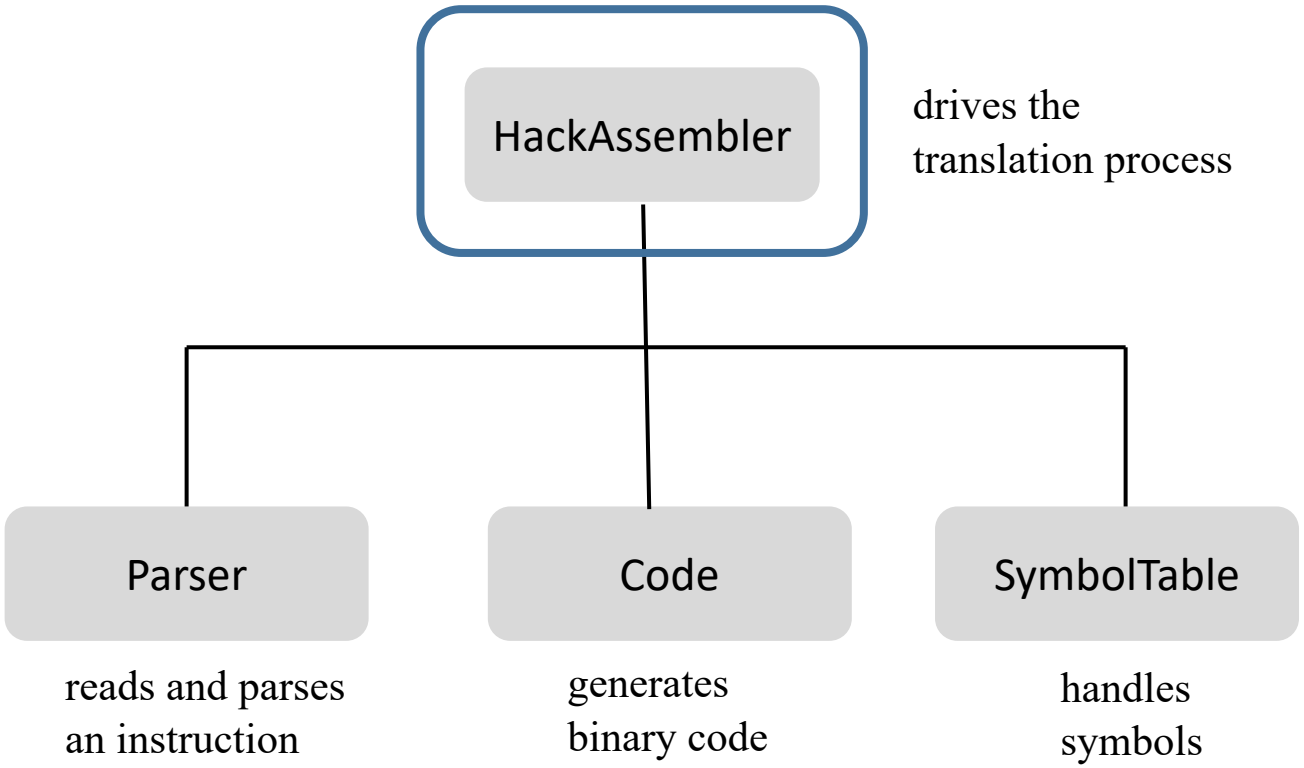
While there are more lines to process:

- Gets the next instruction, and parses it
- If the instruction is `@`*symbol*
  - If *symbol* is not in the symbol table, adds it
  - Translates the *symbol* to its binary value
- If the instruction is *dest*`=`*comp*`;`*jump*
  - Translates each of the three fields into its binary value
- Assembles the binary values into a string of sixteen `0`'s and `1`'s
- Writes the string to the output file.

Assembler implementation options

- Manual
- Program-based

Assembler: Architecture



Proposed architecture

- Four software modules
- Can be realized in any programming language

HackAssembler

Initialize:

Opens the input file (*Prog*`.asm`) and gets ready to process it

Constructs a symbol table, and adds to it all the predefined symbols

First pass:

Reads the program lines, one by one
focusing only on (*label*) declarations.
Adds the found labels to the symbol table

Second pass (main loop):

(starts again from the beginning of the file)

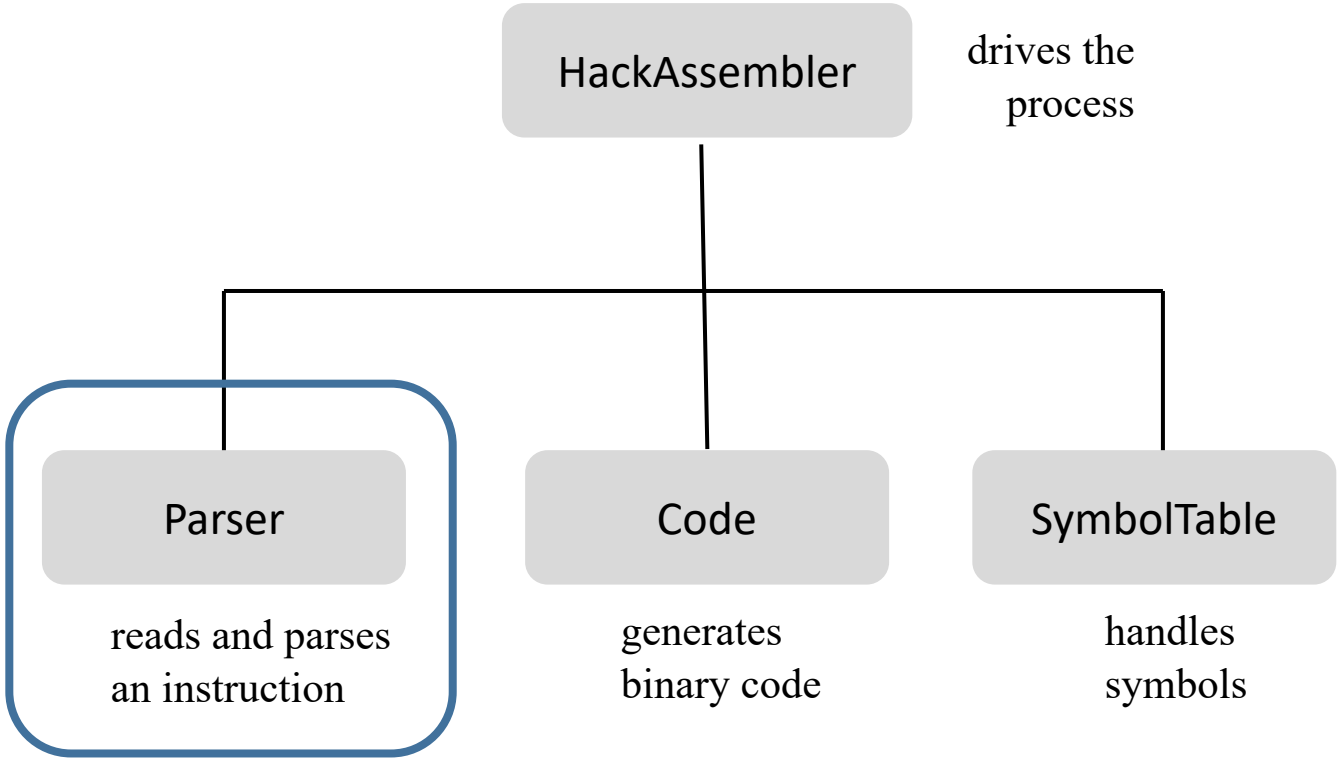
While there are more lines to process:

- Gets the next instruction, and parses it
- If the instruction is `@`*symbol*
  - If *symbol* is not in the symbol table, adds it
  - Translates the *symbol* into its binary value
- If the instruction is *dest*`=`*comp*`;`*jump*
  - Translates each of the three fields into its binary value
- Assembles the binary values into a string of sixteen `0`'s and `1`'s
- Writes the string to the output file.

The `HackAssembler` implements the assembly algorithm, using the services of:

- `Parser`
- `Code`
- `SymbolTable`

Assembler API



`Parser` API

Routines:

- Constructor / initializer: Creates a `Parser` and opens the source text file
- Getting the current instruction:

  `hasMoreLines()`: Checks if there is more work to do (boolean)

  `advance()`: Gets the next instruction and makes it the *current instruction* (string)
- Parsing the *current instruction*:

  `instructionType()`: Returns the current instruction type (constant):

  `A_INSTRUCTION` for `@`*xxx*, where *xxx* is either a decimal number or a symbol

  `C_INSTRUCTION` for *dest* `=` *comp* `;` *jump*

  `L_INSTRUCTION` for `(`*label*`)`

Examples:

current instruction	
`@17`	`instructionType()` returns `A_INSTRUCTION`
`@sum`	`instructionType()` returns `A_INSTRUCTION`
`D=0`	`instructionType()` returns `C_INSTRUCTION`
`(END)`	`instructionType()` returns `L_INSTRUCTION`

`Parser` API

Routines:

- Constructor / initializer: Creates a `Parser` and opens the source text file
- Getting the current instruction:

  `hasMoreLines()`: Checks if there is more work to do

  `advance()`: Gets the next instruction and makes it the *current instruction*
- Parsing the *current instruction*:

  `instructionType()`: Returns the instruction type

  `symbol()`: Returns the instruction's *symbol* (string)

Used if the current instruction is `@`*symbol* or `(`*symbol*`)`

Examples:

current instruction	
`@sum`	`symbol()` returns `"sum"`
`(LOOP)`	`symbol()` returns `"LOOP"`

`Parser` API

Routines:

- Constructor / initializer: Creates a `Parser` and opens the source text file
- Getting the current instruction:

  `hasMoreLines()`: Checks if there is more work to do

  `advance()`: Gets the next instruction and makes it the *current instruction*
- Parsing the *current instruction*:

  `instructionType()`: Returns the instruction type

  `symbol()`: Returns the instruction's *symbol* (string)

  `dest()`: Returns the instruction's *dest* field (string)

  `comp()`: Returns the instruction's *comp* field (string)

  `jump()`: Returns the instruction's *jump* field (string)

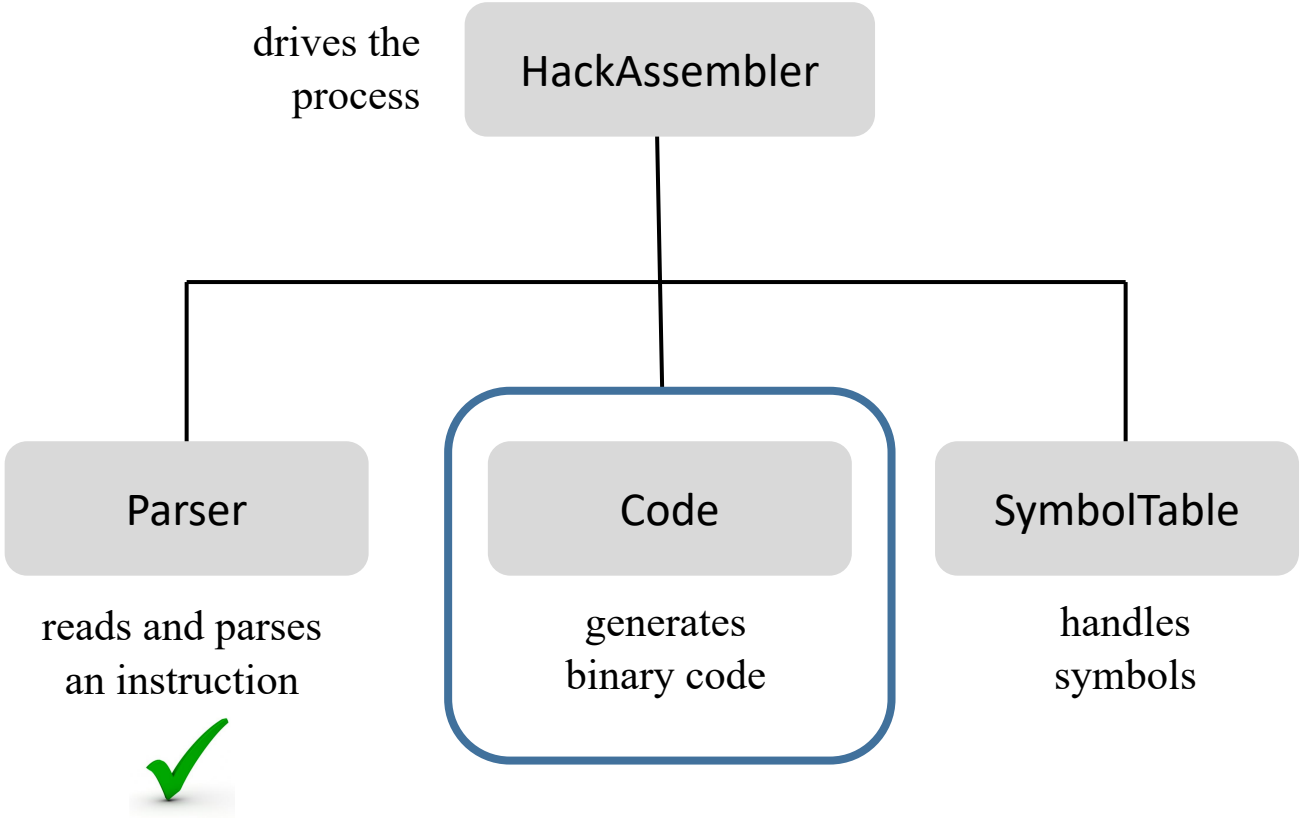
Used if the current instruction is *dest* = *comp* ; *jump*

Examples:

current instruction

`D=D+1;JLE`	`dest()` returns `"D"`	`comp()` returns `"D+1"` `jump()` returns `"JLE"`
`M=-1`	`dest()` returns `"M"`	`comp()` returns `"-1"` `jump()` returns `null`

Implementation



Code API

Deals only with C-instructions: *dest* = *comp* ; *jump*

Routines:

`dest(`string`)`: Returns the binary representation of the parsed *dest* field (string)

`comp(`string`)`: Returns the binary representation of the parsed *comp* field (string)

`jump(`string`)`: Returns the binary representation of the parsed *jump* field (string)

According to the language specification:

comp		c	c	c	c	c	c
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	M	1	1	0	0	0	0
!D		0	0	1	1	0	1
!A	!M	1	1	0	0	0	1
-D		0	0	1	1	1	1
-A	-M	1	1	0	0	1	1
D+1		0	1	1	1	1	1
A+1	M+1	1	1	0	1	1	1
D-1		0	0	1	1	1	0
A-1	M-1	1	1	0	0	1	0
D+A	D+M	0	0	0	0	1	0
D-A	D-M	0	1	0	0	1	1
A-D	M-D	0	0	0	1	1	1
D&A	D&M	0	0	0	0	0	0
D|A	D|M	0	1	0	1	0	1
a == 0	a == 1						

dest	d	d	d
null	0	0	0
M	0	0	1
D	0	1	0
DM	0	1	1
A	1	0	0
AM	1	0	1
AD	1	1	0
ADM	1	1	1

jump	j	j	j
null	0	0	0
JGT	0	0	1
JEQ	0	1	0
JGE	0	1	1
JLT	1	0	0
JNE	1	0	1
JLE	1	1	0
JMP	1	1	1

Examples:

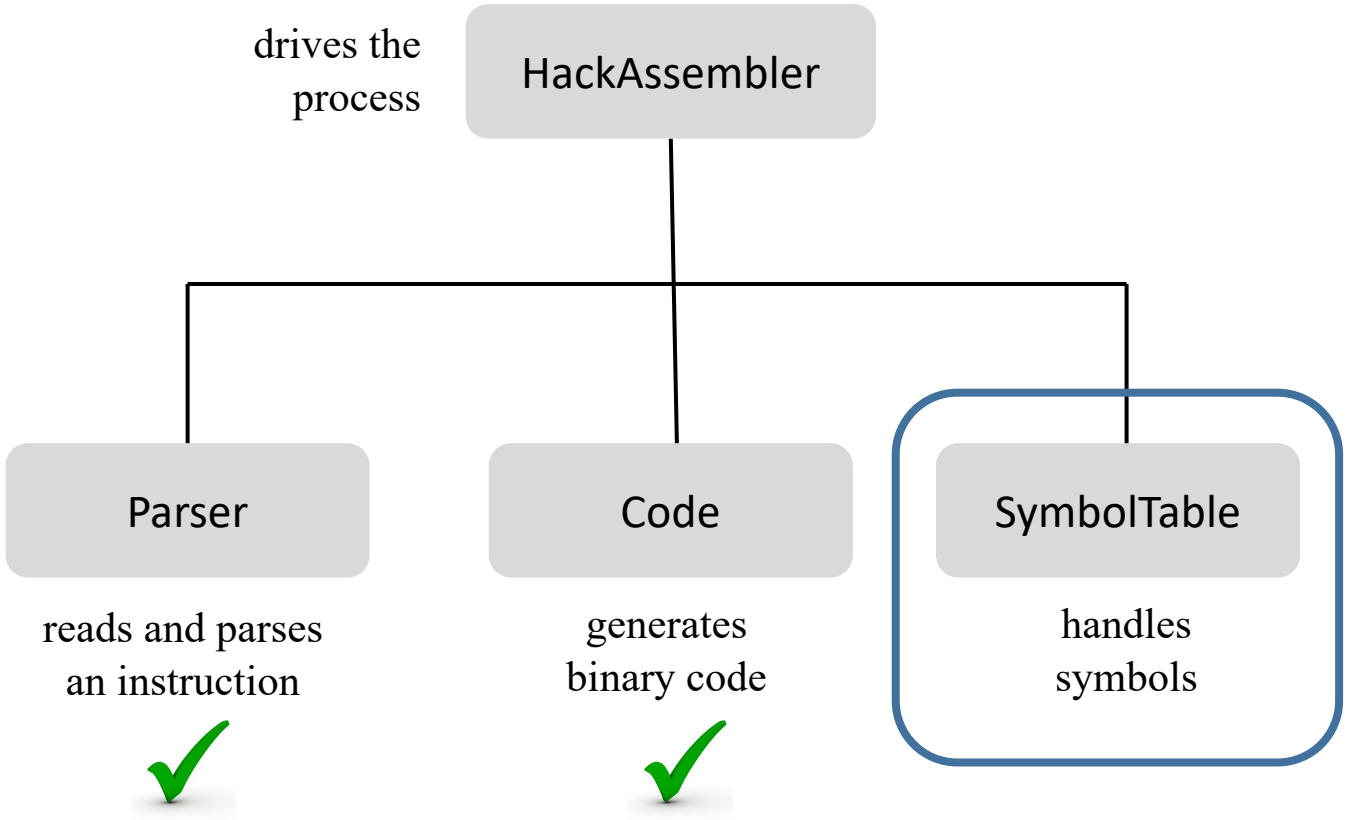
`dest("DM")` returns `"011"`

`comp("A+1")` returns `"0110111"`

`comp("D&M")` returns `"1000000"`

`jump("JNE")` returns `"101"`

Implementation



SymbolTable API

Routines

Constructor / initializer: Creates and initializes a `SymbolTable`

`addEntry(symbol` (string), **`address`** (int)**`):`** Adds `<symbol, address>` to the table (void)

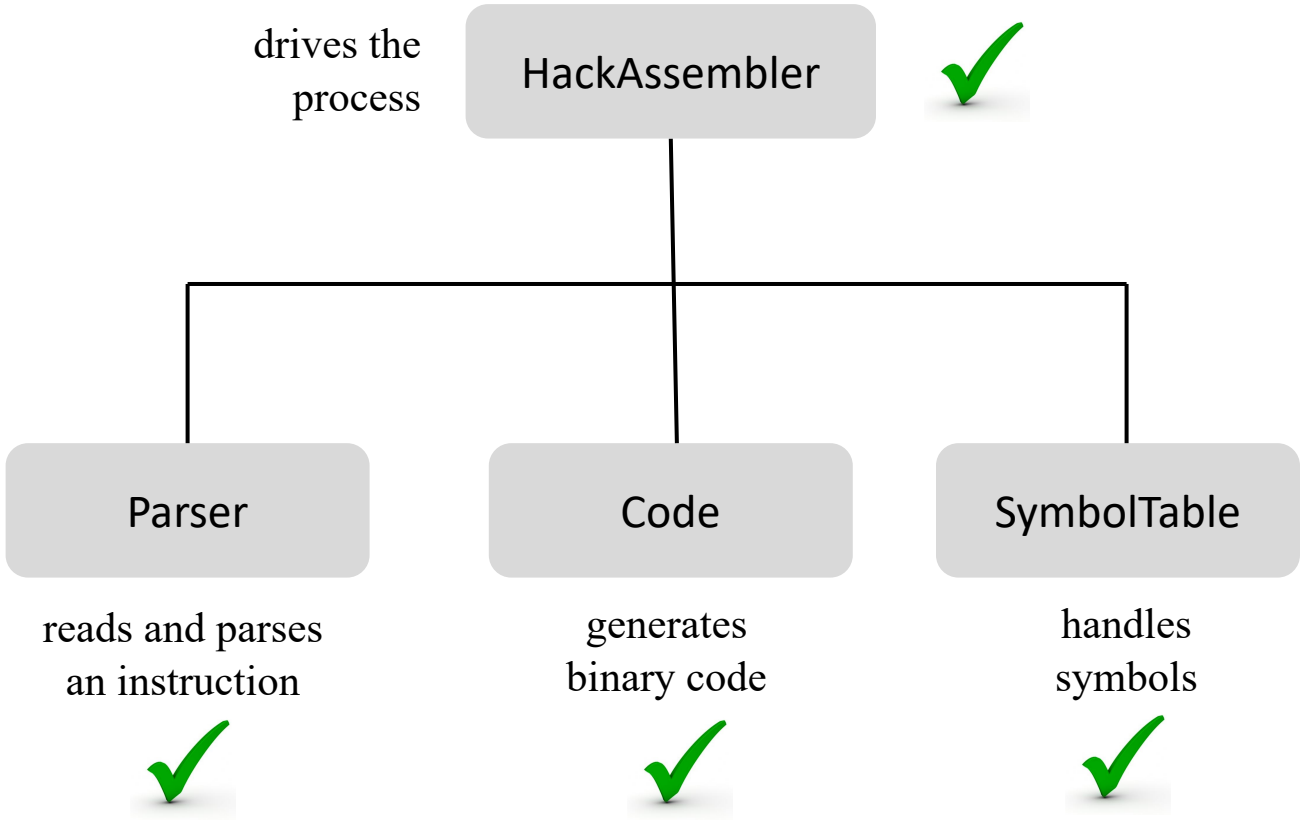
`contains(symbol` (string)**`):`** Checks if `symbol` exists in the table (boolean)

`getAddress(symbol` (string)**`):`** Returns the `address` (int) associated with `symbol`

Symbol table: (example)

symbol	*address*
R0	0
R1	1
R2	2
...	...
R15	15
SCREEN	16384
KBD	24576
SP	0
LCL	1
ARG	2
THIS	3
THAT	4
LOOP	4
STOP	18
i	16
sum	17

`HackAssembler`: Drives the translation process



Assembler API (detailed)

Parser module:

Routine	*Arguments*	*Returns*	*Function*
Constructor / initializer	Input file or stream	—	Opens the input file/stream and gets ready to parse it.
`hasMoreLines`	—	boolean	Are there more lines in the input?
`advance`	—	—	Skips over whitespace and comments, if necessary. Reads the next instruction from the input, and makes it the current instruction. This method should be called only if `hasMoreLines` is true. Initially there is no current instruction.
`instructionType`	—	`A_INSTRUCTION`, `C_INSTRUCTION`, `L_INSTRUCTION` (constants)	Returns the type of the current instruction: `A_INSTRUCTION` for @*xxx*, where *xxx* is either a decimal number or a symbol. `C_INSTRUCTION` for *dest*=*comp*;*jump* `L_INSTRUCTION` for (*xxx*), where *xxx* is a symbol.
`symbol`	—	string	If the current instruction is (*xxx*), returns the symbol *xxx*. If the current instruction is @*xxx*, returns the symbol or decimal *xxx* (as a string). Should be called only if `instructionType` is `A_INSTRUCTION` or `L_INSTRUCTION`.
`dest`	—	string	Returns the symbolic *dest* part of the current *C*-instruction (8 possibilities). Should be called only if `instructionType` is `C_INSTRUCTION`.
`comp`	—	string	Returns the symbolic *comp* part of the current *C*-instruction (28 possibilities). Should be called only if `instructionType` is `C_INSTRUCTION`.
`jump`	—	string	Returns the symbolic *jump* part of the current *C*-instruction (8 possibilities). Should be called only if `instructionType` is `C_INSTRUCTION`.

Assembler API (detailed)

Code module:

Routine	*Arguments*	*Returns*	*Function*
`dest`	string	3 bits, as a string	Returns the binary code of the *dest* mnemonic.
`comp`	string	7 bits, as a string	Returns the binary code of the *comp* mnemonic.
`jump`	string	3 bits, as a string	Returns the binary code of the *jump* mnemonic.

SymbolTable module:

Routine	*Arguments*	*Returns*	*Function*
Constructor	—	—	Creates a new empty symbol table.
`addEntry`	`symbol` (string), `address` (int)	—	Adds `<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`.

HackAssembler module:

We propose no API; Implement as you see fit.

Chapter 6: Assembler

- Overview
- Translating instructions
- Translating programs
- Handling symbols
- Assembler architecture
- Assembler API
- Project 6
- Some history

Developing a Hack Assembler

Contract

- Develop a program that translates symbolic Hack programs into binary Hack instructions
- The source program (input) is supplied as a text file named *Prog*`.asm`
- The generated code (output) is written into a text file named *Prog*`.hack`
- Assumption: *Prog*`.asm` is error-free

Usage (if the assembler is implemented in Java):

```
$ java HackAssembler Prog.asm
```

Staged development plan

1. Develop a basic assembler that translates programs that have no symbols
2. Develop an ability to handle symbols
3. Morph the basic assembler into an assembler that translates any program

Testing

Prog.asm

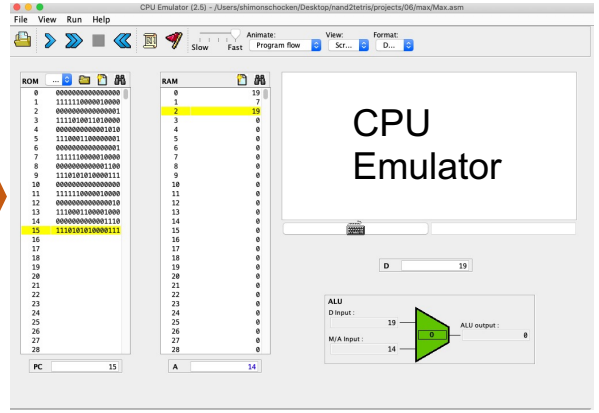
```
// Computes R1 = 1 + ... + R0
      // i = 1
      @i
      M=1
      // sum = 0
      @sum
      M=0
(LOOP)
      // if i > R0 goto STOP
      @i
      D=M
      @R0
      D=D-M
      @STOP
      D;JGT
      ...
```

Your assembler

Prog.hack

```
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
0000000000010010
1110001100000001
0000000000010000
1111110000010000
0000000000010001
1111000010001000
0000000000010000
...
```

Load / Run



Or use a supplied test script that loads `Prog.hack` into the CPU emulator and tests it using pre-defined testing scenarios

Test programs

- `Add.asm`
- `Max.asm`
- `Rect.asm`
- `Pong.asm`

(with symbols)

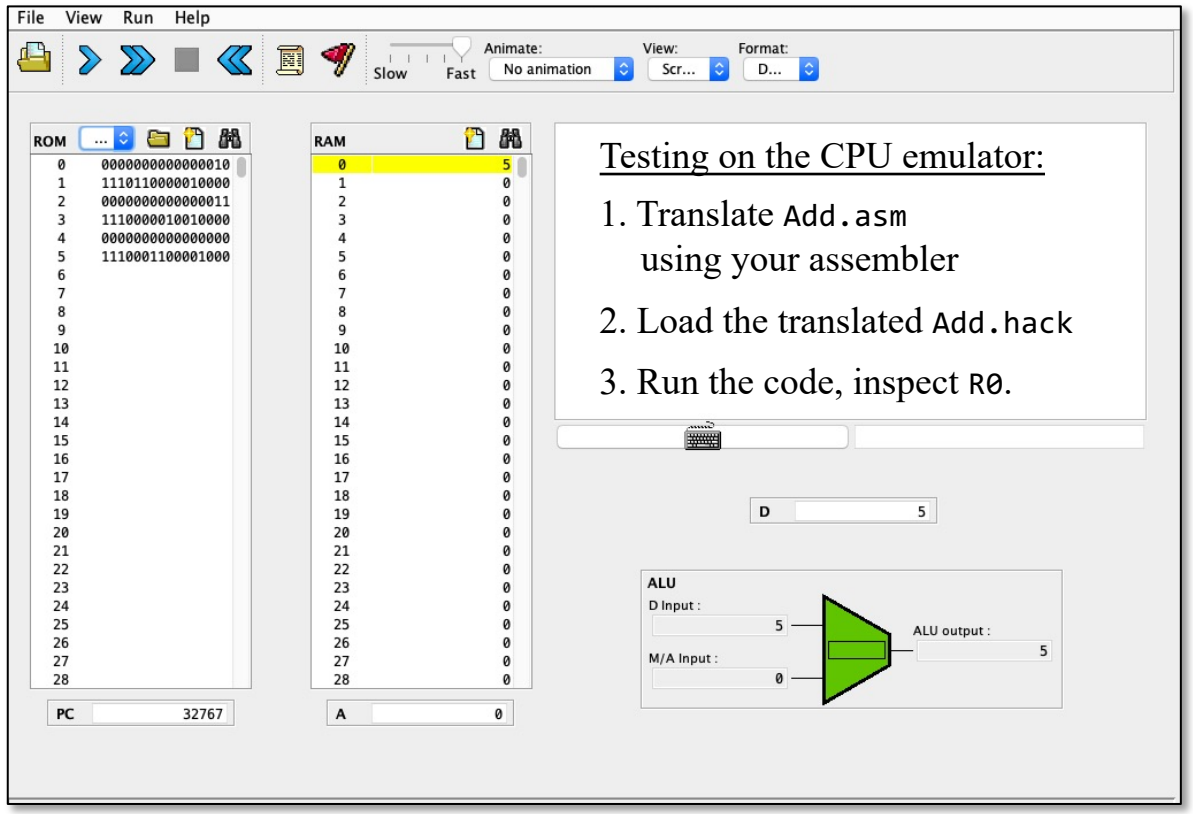
- `MaxL.asm`
- `RectL.asm`
- `PongL.asm`

(same programs, without symbols, for unit-testing the basic assembler)

Testing

Add.asm

```
// Computes RAM[0] =
//           2 + 3
@2
D=A
@3
D=D+A
@0
M=D
```



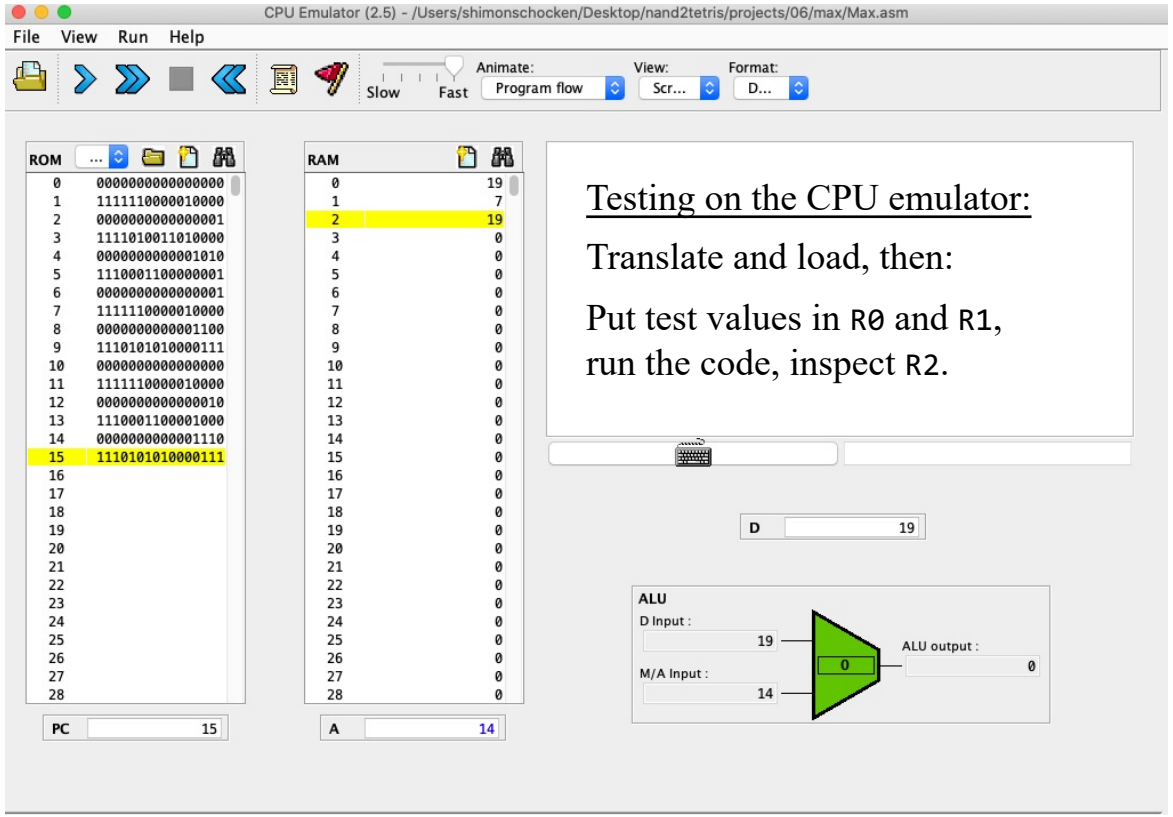
Note: When loading a binary *Prog*.hack file into the CPU emulator, the emulator may translate it back to symbolic code (depending on the emulator's version).

To inspect the binary code, select this option from the ROM menu.

Testing

Max.asm

```
// Computes RAM[2] =
// max(RAM[0],RAM[1])
    @R0
    D=M
    @R1
    D=D-M
    @OUTPUT_RAM0
    D;JGT
    // Output RAM[1]
    @R1
    D=M
    @R2
    M=D
    @END
    0;JMP
(OUTPUT_RAM0)
    @R0
    D=M
    @R2
    M=D
(END)
    @END
    0;JMP
```



Testing

Max.asm

```
// Computes RAM[2] =
// max(RAM[0],RAM[1])
   @R0
   D=M
   @R1
   D=D-M
   @OUTPUT_RAM0
   D;JGT
   // Output RAM[1]
   @R1
   D=M
   @R2
   M=D
   @END
   0;JMP
(OUTPUT_RAM0)
   @R0
   D=M
   @R2
   M=D
(END)
   @END
   0;JMP
```

with symbols

MaxL.asm

```
// Computes RAM[2] =
// max(RAM[0],RAM[1])
   @0
   D=M
   @1
   D=D-M
   @12
   D;JGT
   // Output RAM[1]
   @1
   D=M
   @2
   M=D
   @16
   0;JMP

   @0
   D=M
   @2
   M=D


   @16
   0;JMP
```

without symbols

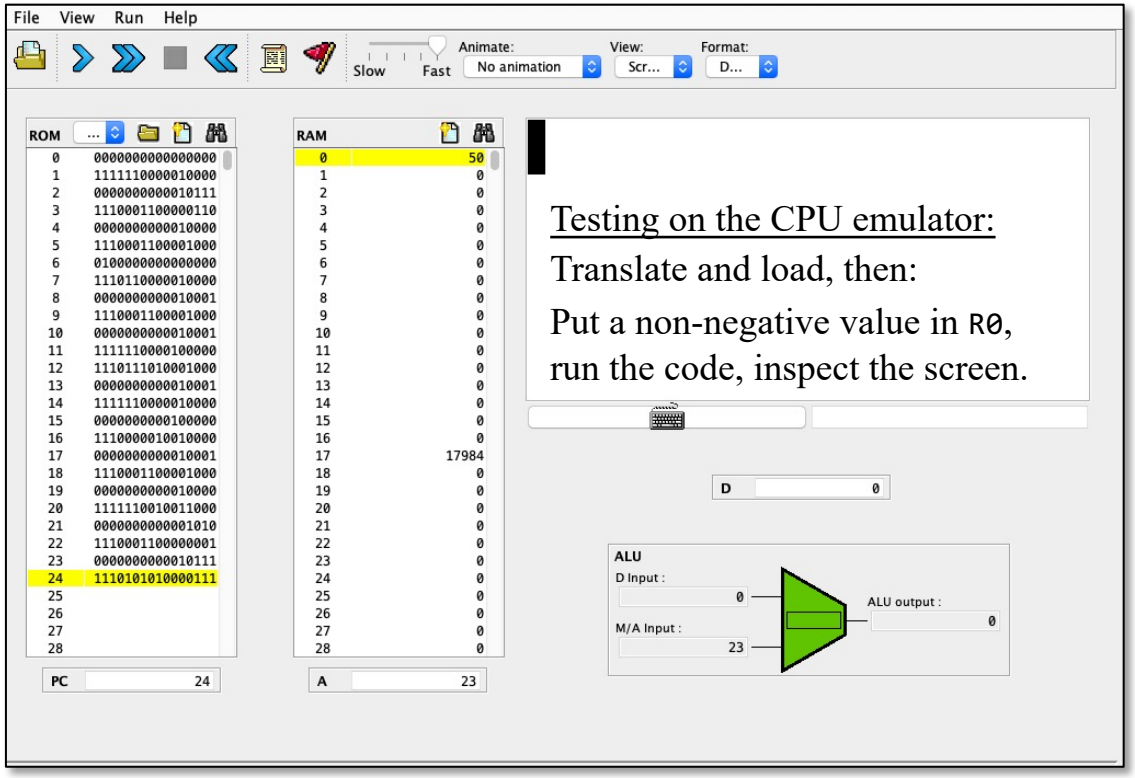
For unit-testing the basic assembler

(Each symbol was replaced with its value)

Testing

Rect.asm

```
// Draws a rectangle.
   @R0
   D=M
   @n
   M=D
   @i
   M=0
   @SCREEN
   D=A
   @address
   M=D
(LOOP)
   @i
   D=M
   @n
   D=D-M
   @END
   D;JGT
   ...
```



Draws a rectangle, 16 pixels wide and R0 lines high

Testing

Rect.asm

```
// Draws a rectangle.
   @R0
   D=M
   @n
   M=D
   @i
   M=0

   @SCREEN
   D=A
   @address
   M=D

(LOOP)
   @i
   D=M
   @n
   D=D-M
   @END
   D;JGT
   ...
```

with symbols

RectL.asm

```
// Draws a rectangle.
   @0
   D=M
   @16
   M=D
   @17
   M=0

   @16384
   D=A
   @18
   M=D

(LOOP)
   @17
   D=M
   @16
   D=D-M
   @27
   D;JGT
   ...
```

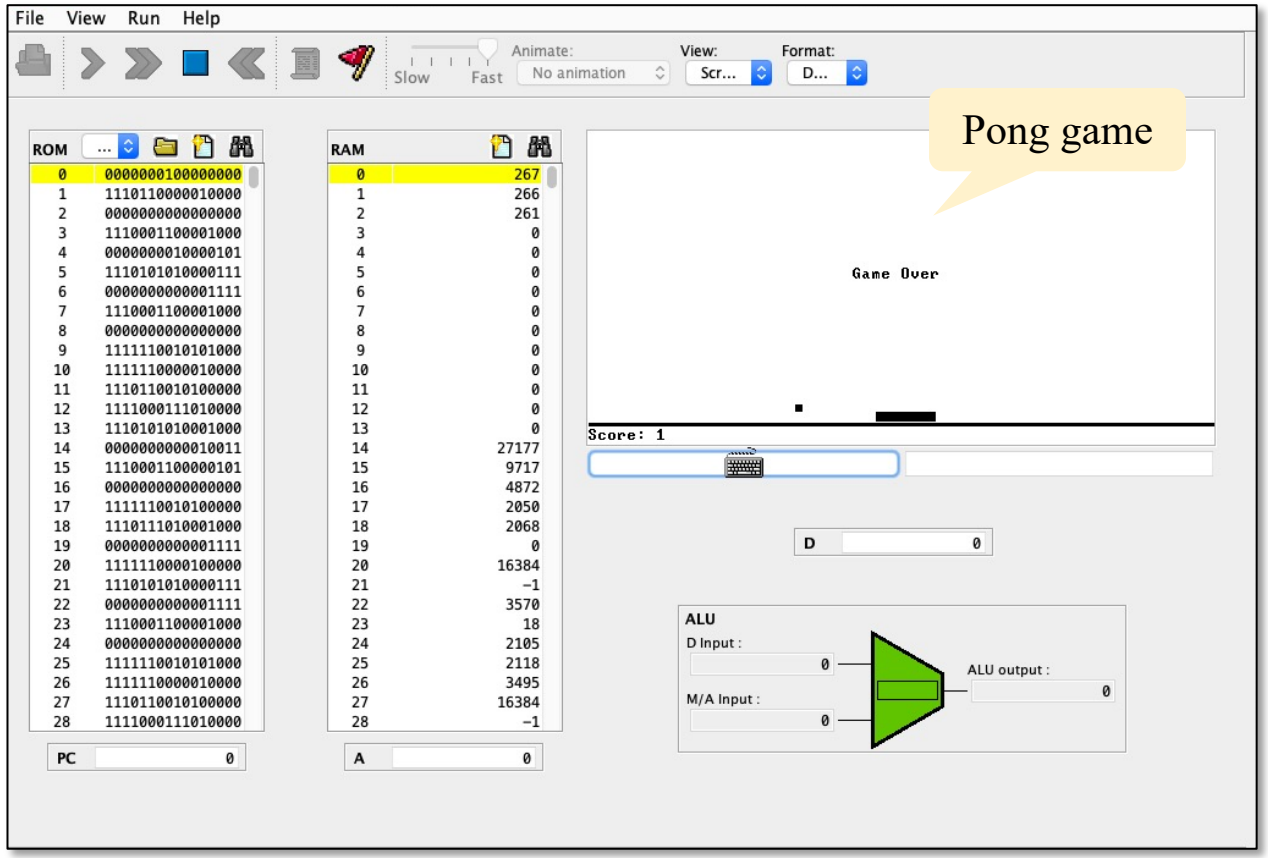
without symbols

For unit-testing the basic assembler

Testing

Pong.asm

```
// Pong.asm
@256
D=A
@SP
M=D
@133
0;JMP
@R15
M=D
@SP
AM=M-1
D=M
A=A-1
D=M-D
M=0
@END_EQ
D;JNE
@SP
A=M-1
M=-1
(END_EQ)
@R15
A=M
...
```



Translate and load, and then play the game:

Select “no animation”, set the speed slider to “fast”, and run the code.
Move the paddle using the left- and right-arrow keys.

Testing

Pong.asm

```
// Pong.asm
@256
D=A
@SP
M=D
@133
0;JMP
@R15
M=D
@SP
AM=M-1
D=M
A=A-1
D=M-D
M=0
@END_EQ
D;JNE
@SP
A=M-1
M=-1
(END_EQ)
@R15
A=M
...
```

28,374 instructions

Background

- The original `Pong` program was written in the high-level Jack language
- The computer's operating system is also written in Jack
- The `Pong` code + the OS code were compiled by the Jack compiler, creating a single `Pong.asm` file

The compiled code (`Pong.asm`) has:

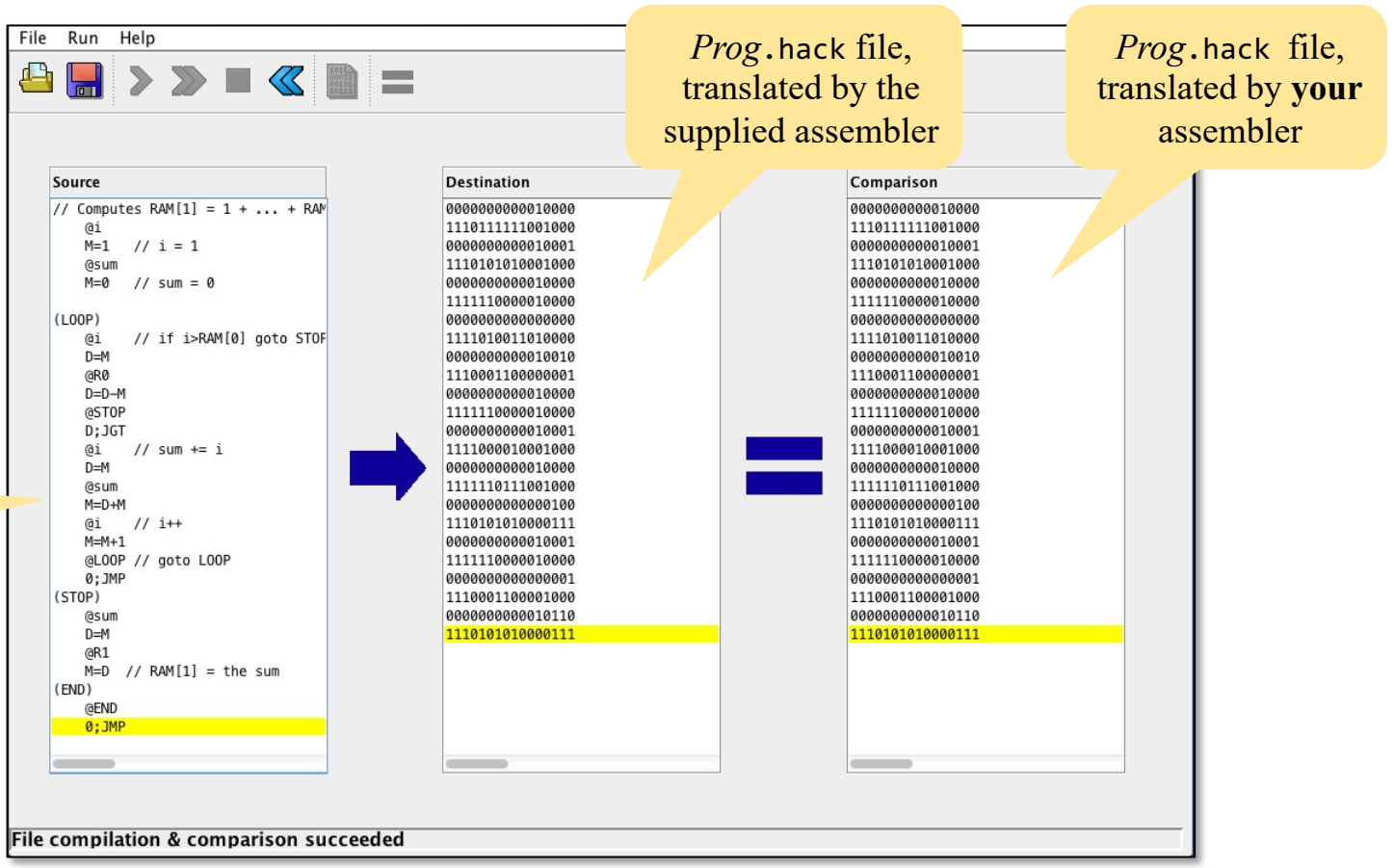
No white space, and

Compiler-generated addresses and symbols (which may look strange)

Testing option II: Using the hardware simulator

1. Use your assembler to translate *Prog*.asm, generating the executable file *Prog*.hack
2. Put the *Prog*.hack file in a folder containing the chips that you developed in project 5: Computer.hdl, CPU.hdl, and Memory.hdl
3. Load Computer.hdl into the Hardware Simulator
4. Load *Prog*.hack into the ROM32K chip-part
5. Run the clock to execute the program.

Testing option III: Using the supplied assembler



1. Use your assembler to translate *Prog*.asm, generating the executable file *Prog*.hack
2. Load *Prog*.asm into the supplied assembler, and load *Prog*.hack as a compare file
3. Translate *Prog*.hack, and inspect the comparison feedback messages.

Project 6

Guidelines: www.nand2tetris.org (projects section)

Files: nand2tetris/projects/06 (on your PC)

Tools

- The programming language in which you develop your assembler
- CPU emulator (for testing the translated programs)
- Assembler (if you plan to use it)

Guides

- CPU emulator tutorial
- Assembler tutorial

Chapter 6: Assembler

- Overview
- Translating instructions
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- Some history

The Industrial Revolution (1760 – 1840) / Case in Point: Textile

Cotton picking

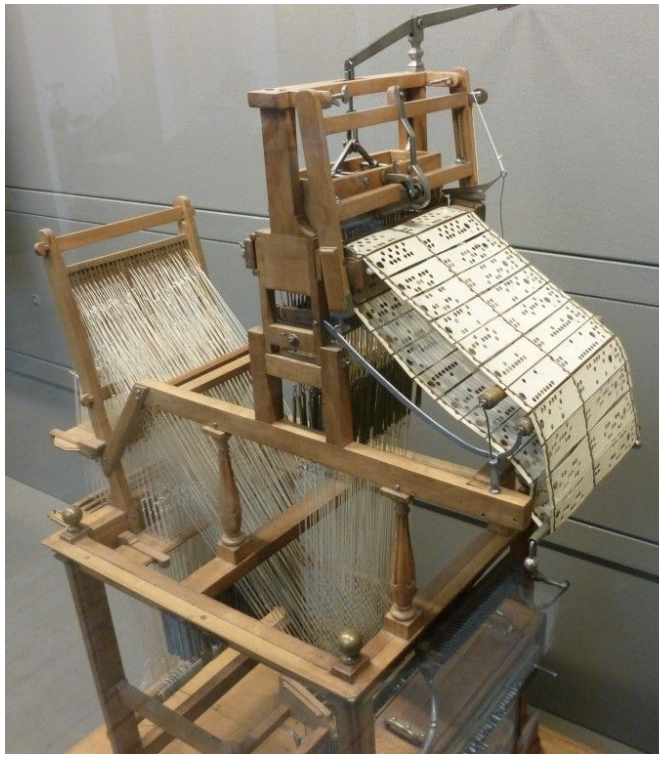
cleaning

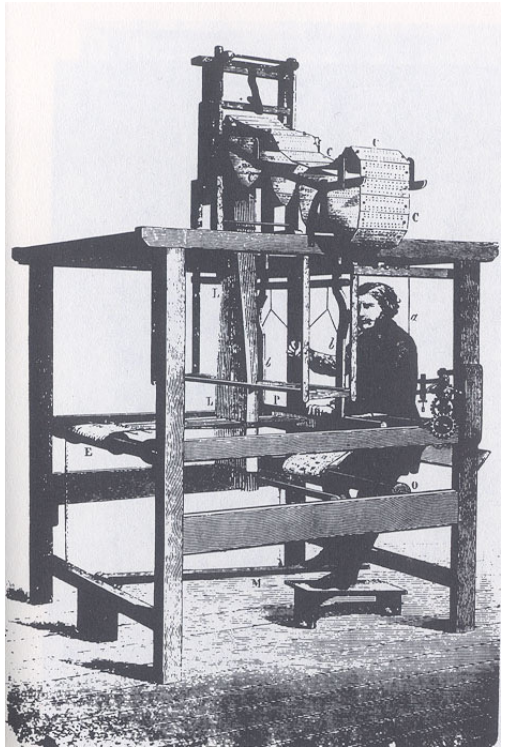
spinning

weaving

- Until 1800: labor intensive / slavery / child labor
- Industrial revolution: all key processes are mechanized.

The Industrial Revolution (1760 – 1840) / Case in Point: Textile





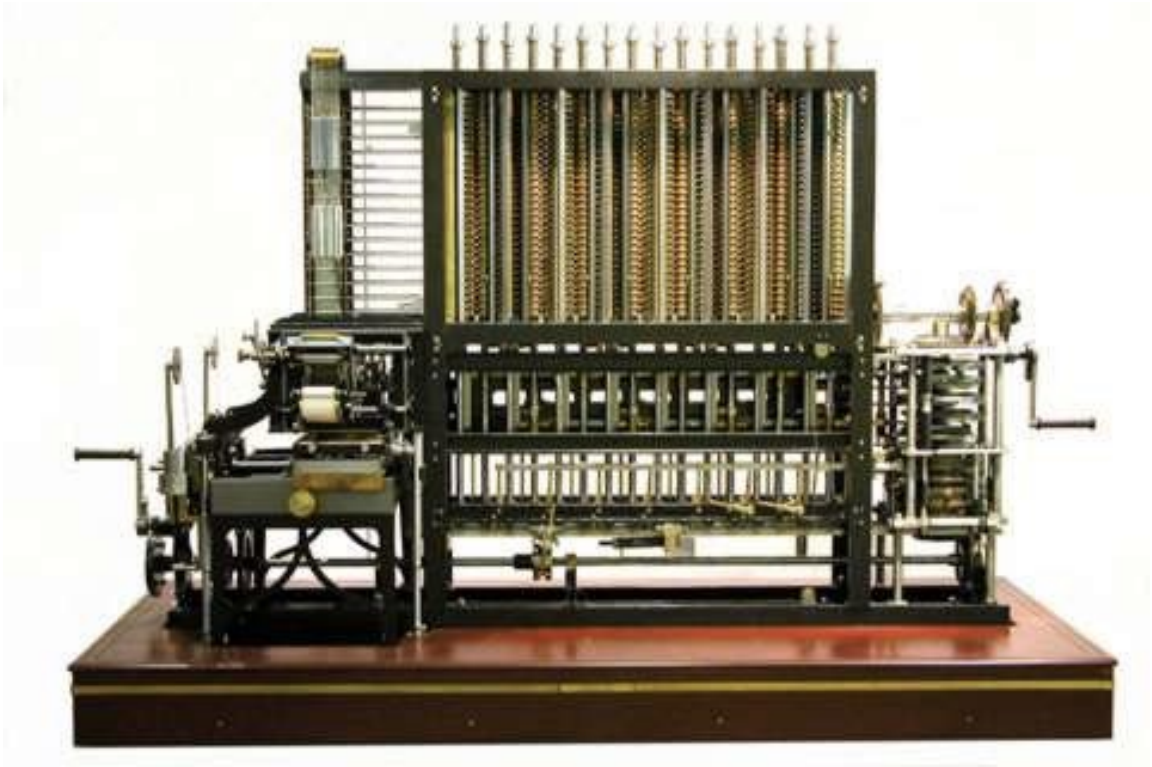
Jacquard loom (1801)

- The weaving instructions were programmed by punched cards
- The cards coded instructions for the loom's hardware.

The Industrial Revolution (1760 – 1840) / Case in Point: Textile

- The weaving instructions were programmed by punched cards
- The cards coded instructions for the loom's hardware.

The Analytic Engine (1837)



- An early mechanical computer, designed by Charles Babbage
- Designed to tabulate data collected in a UK national census

- Featured a simple programming model with conditional branching
- Software = punched cards

Ada Lovelace (1815 – 1852)

Ada's insight:

If you want to give a computer instructions, don't start by punching cards ("binary code")

Instead, write the instructions on paper, using a *symbolic language*

When convinced that the symbolic program is error-free, translate it into punched cards.

- Ada Augusta King-Noel, Countess of Lovelace
- Gifted mathematician and writer
- Worked closely with Babbage on the Analytic Engine.

Ada Lovelace (1815 – 1852)

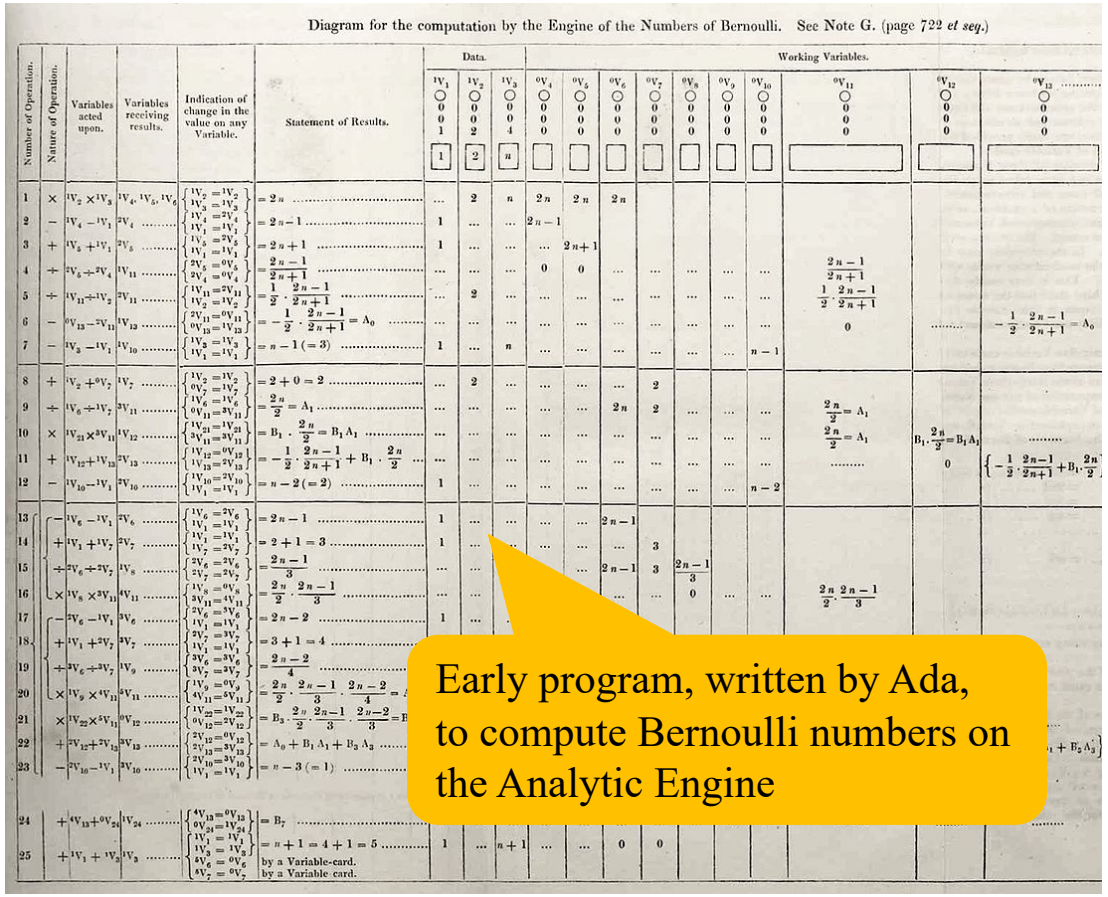


Diagram for the computation by the Engine of the Numbers of Bernoulli. See Note G. (page 722 *et seq.*)

Early program, written by Ada, to compute Bernoulli numbers on the Analytic Engine

- Often described as "the first programmer"
- The programming language Ada is named after her.

Ada Lovelace (1815 – 1852)

"The Analytical Engine might act upon other things besides numbers...

Suppose, for instance, that the fundamental relations of pitched sounds in the science of harmony and of musical composition were susceptible of such expression and adaptations...

If so, the engine might compose elaborate and scientific pieces of music of any degree of complexity."

(1840!)