Chapter 6

Assembler

These slides support chapter 6 of the book

The Elements of Computing Systems

By Noam Nisan and Shimon Schocken

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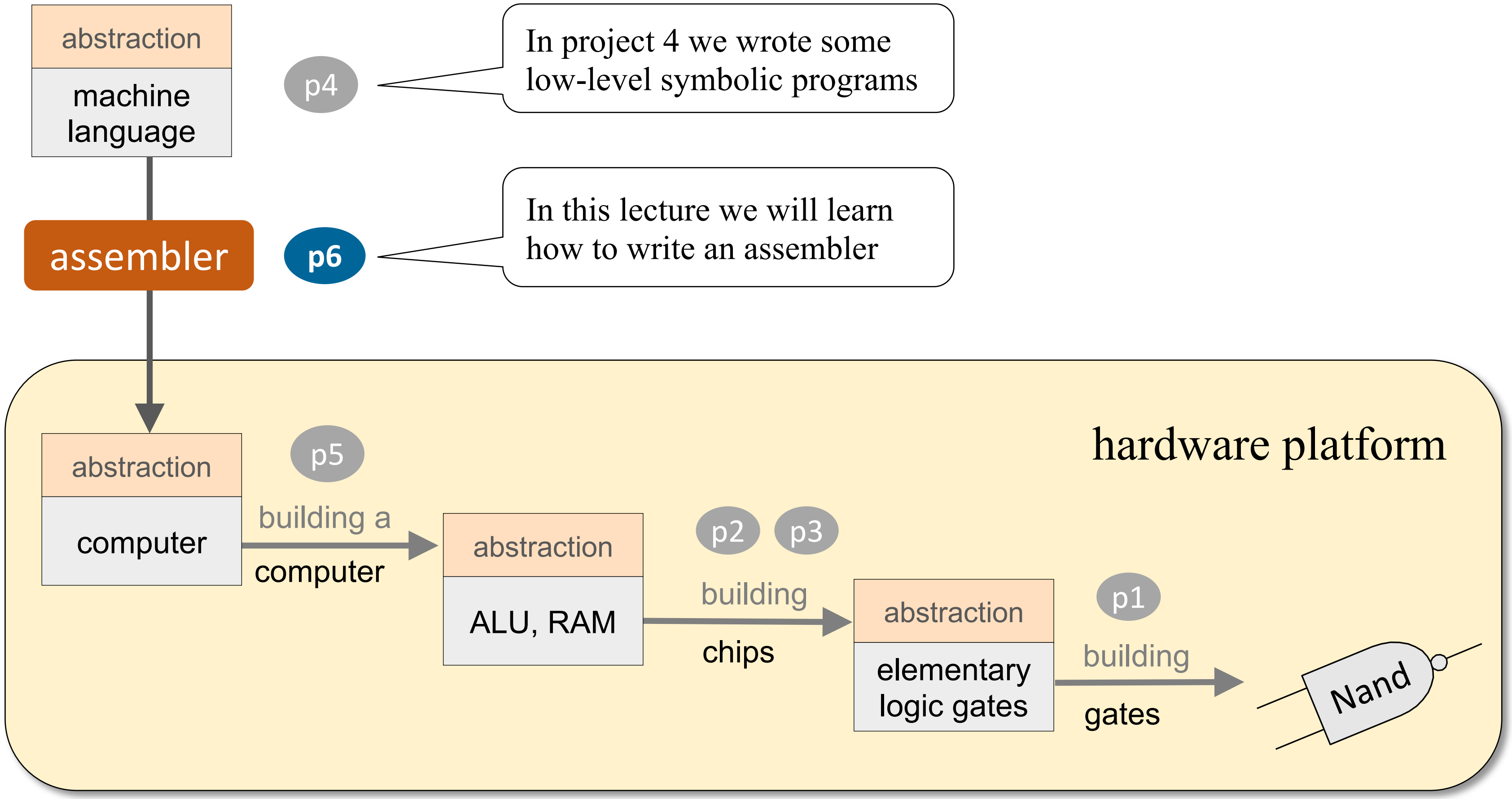
Nand to Tetris Roadmap: Hardware



Program translation

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
   ...
```

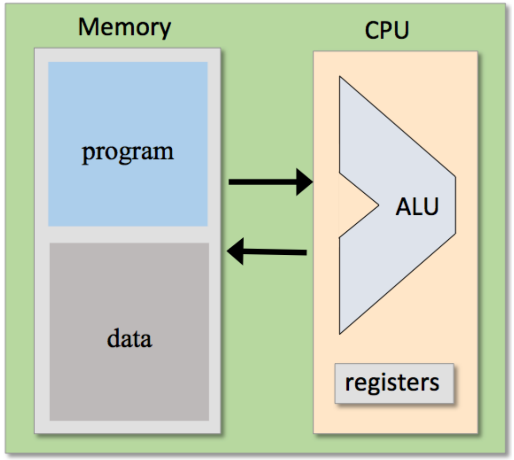
assembler

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



The assembler is…

- The “linchpin” that connects the hardware platform and the software hierarchy
- The lowest rung in the set of translators developed in Part II of the course
- A simple example of key software engineering techniques (parsing, code generation, symbol tables, …)

Lecture plan

- Overview
- Translating Hack code:
  - A-instructions
  - C-instructions
- Translating programs
- Handling symbols
- Assembler architecture
- Assembler API
- Project 6

Translating A-instructions

Symbolic syntax:

`@`*xxx*

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

Binary syntax:

`0`*vvvvvvvvvvvvvvv*

Where:

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

v v v … v is the value in binary

Example:

```
@17
```

translate

```
0000000000010001
```

Implementation

Translate the decimal value into its 16-bit representation;

What about @ *symbol* instructions? Later.

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 (a==0)	*comp* (a==1)	*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

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 (*a*==0)	*comp* (*a*==1)	*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:

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 (a==0)	*comp* (a==1)	*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:

`111`

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 (a==0)	*comp* (a==1)	*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* $\neq 0$ jump
`JLE`	1	1	0	if *comp* ≤ 0 jump
`JMP`	1	1	1	Unconditional jump

Example: `D=D+1;JLE` →

Binary:

`1110011111`

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 (*a*==0)	*comp* (*a*==1)	*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
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AD	1	1	0	A register and D register
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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* $\geq$ 0 jump
JLT	1	0	0	if *comp* $<$ 0 jump
JNE	1	0	1	if *comp* $\neq$ 0 jump
JLE	1	1	0	if *comp* $\leq$ 0 jump
JMP	1	1	1	Unconditional jump

Example: D=D+1;JLE

Binary: 1110011111010

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:
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M	0	0	1	RAM[A]
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null	0	0	0	no jump
JGT	0	0	1	if *comp* > 0 jump
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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 (*a*==0)	*comp* (*a*==1)	*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]
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A	1	0	0	A register
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null	0	0	0	no jump
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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 (*a*==0)	*comp* (*a*==1)	*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:
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jump	*j*	*j*	*j*	effect:
null	0	0	0	no jump
JGT	0	0	1	if *comp* > 0 jump
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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

Translating C-instructions

<u>Symbolic syntax:</u> *dest* = *comp* ; *jump*

<u>Binary syntax:</u> `1 1 1` *a c c c c c c d d d j j j*

comp (*a*==0)	*comp* (*a*==1)	*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]
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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

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

Chapter 6: Assembler

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

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
    ...
```

Translate

Binary code

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

<u>Need to handle</u>:

- White space
- Instructions
- Symbols

We'll start with programs that have no symbols, and handle symbols later

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
- Instructions
- Symbols (later)

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
- Instructions
- Symbols (later)

Ignore it

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
...
```

Translate

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
@16
D=M
@17
M=D+M
@16
M=M+1
@4
0;JMP
@17
D=M
...
```

Translate

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
...
```

Translate

Binary code

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

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
...
```

Translate

Binary code

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

Need to handle:

- ✓ White space
- ✓ Instructions
- Symbols

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
...
```

Translate

Binary code

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

<u>Need to handle:</u>

- White space
- Instructions
- Symbols

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
    ...
```

Translate

Binary code

Need to handle:

- White space
- Instructions
- Symbols

Original program, with 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*

Examples: `@R15` → `0000000000001111`

`@SCREEN` → `0100000000000000`

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

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

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
    ...
```

<u>Variable symbols</u>

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

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*
- Hack convention: 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 to 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 the predefined symbols to the table

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 the predefined symbols to the table

First pass: Counts lines and adds the label symbols to the table

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 the predefined symbols to the table

First pass: Counts lines and adds the label symbols to the table

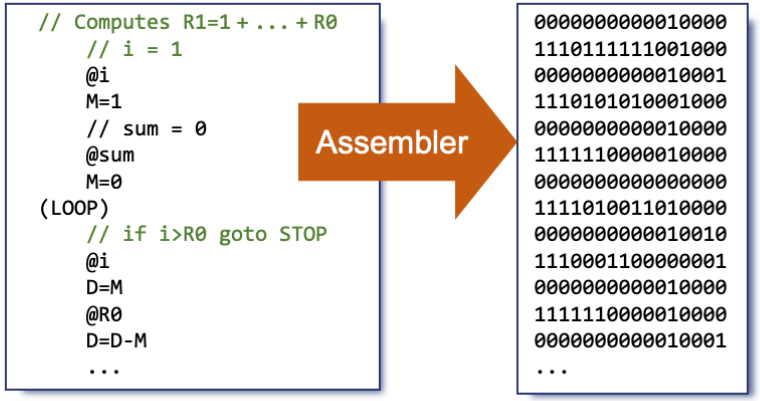
Second pass: Generates binary code; In the process, adds the variable symbols to the table

(details, soon)

Lecture plan

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

Assembler: Usage



<u>Input</u> (*Prog*`.asm`): a text file containing a sequence of lines, each being a string representing a comment, an A-instruction, a C-instruction, or a label declaration

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

<u>Usage</u>: (if the assembler is implemented in Java)

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

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

Assembler: Algorithm

```
// 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
    ...
```

Assembler

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

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 to the table

    Translates the *symbol* to its binary value

  If the instruction is *dest*`=`*comp*`;`*jump*

    Translates each of the three fields into its binary value

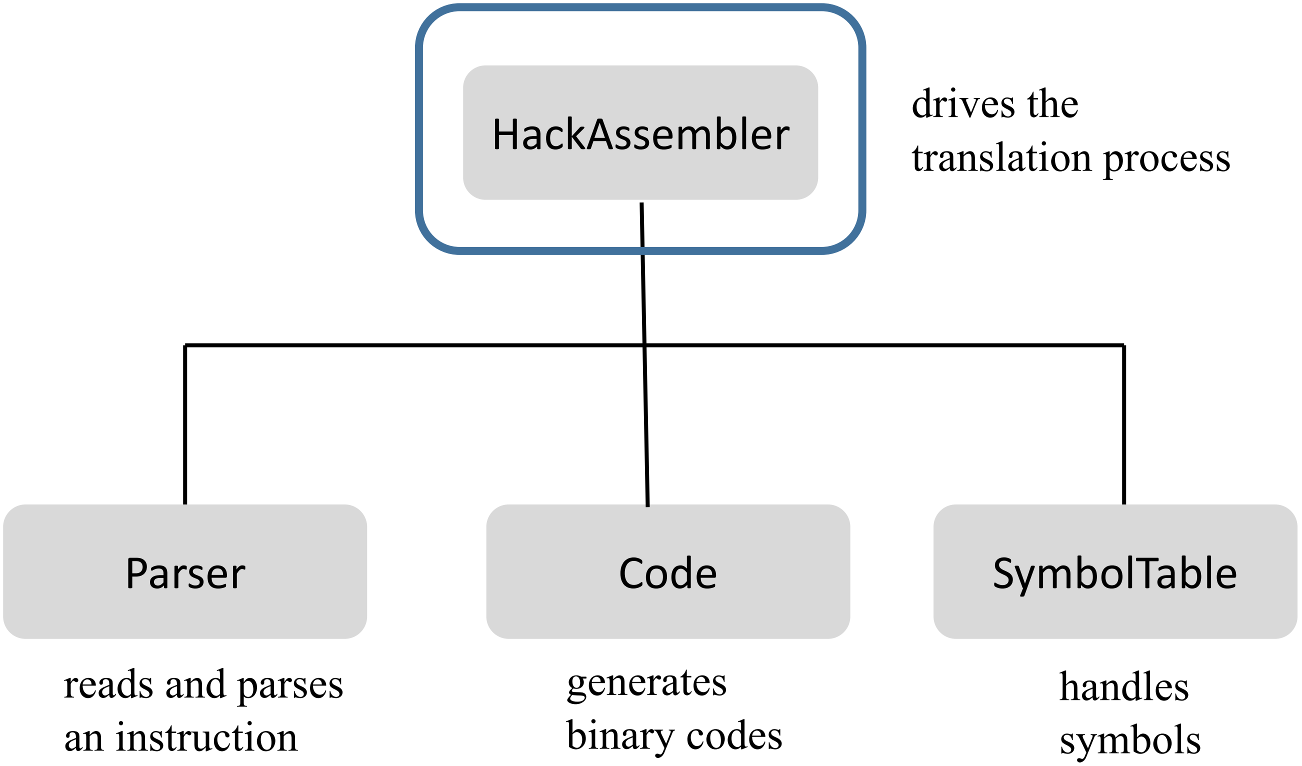
  Assembles the binary values described above into a string of sixteen `0`'s and `1`'s

  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 to the table

Translates the *symbol* into its binary value

If the instruction is *dest*`=`*comp*`;`*jump*

Translates each of the three fields into its binary value

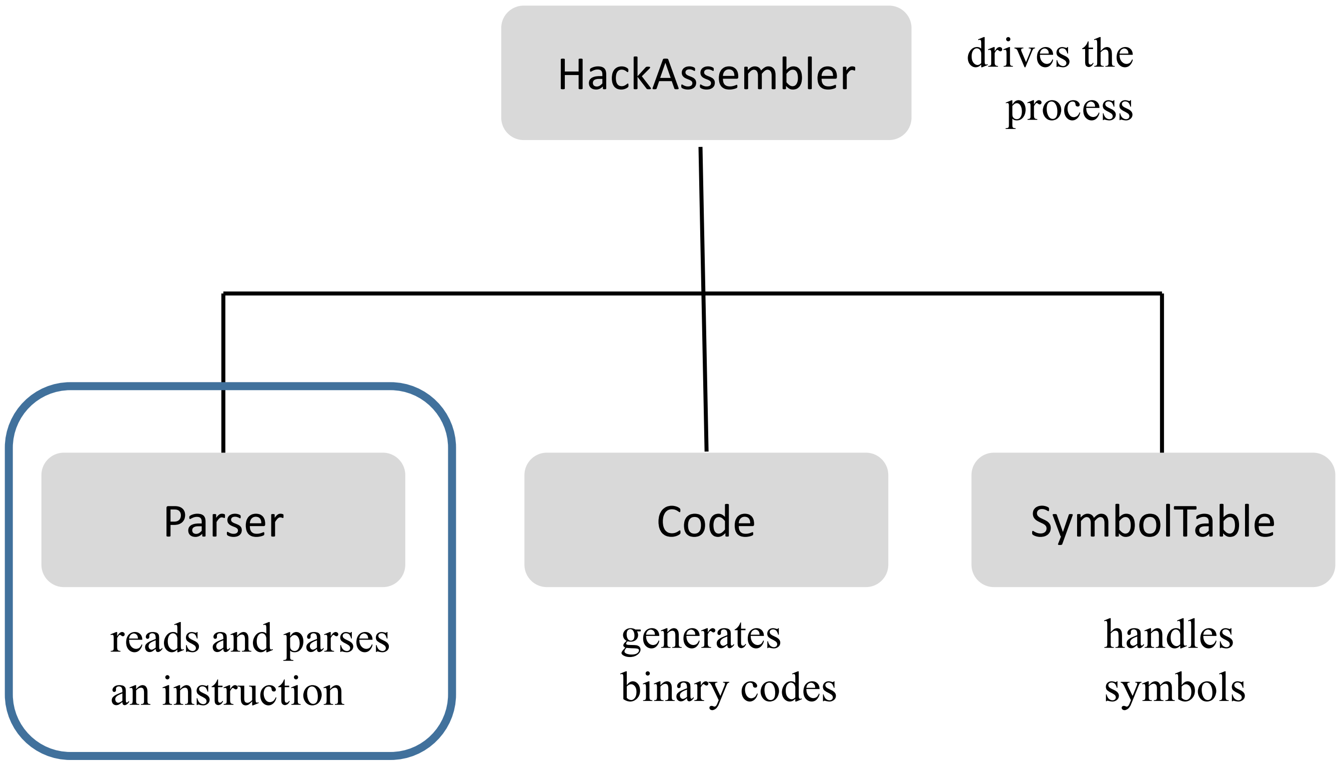
Assembles the binary values into a string of sixteen `0`'s and `1`'s

Writes the string to the output file.

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

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

Assembler API



`Parser` API

<u>Routines</u>

- 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, as a 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

<u>Routines</u>

- 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

`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*`)`

current instruction

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

`Parser` API

<u>Routines</u>

- 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)

`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)

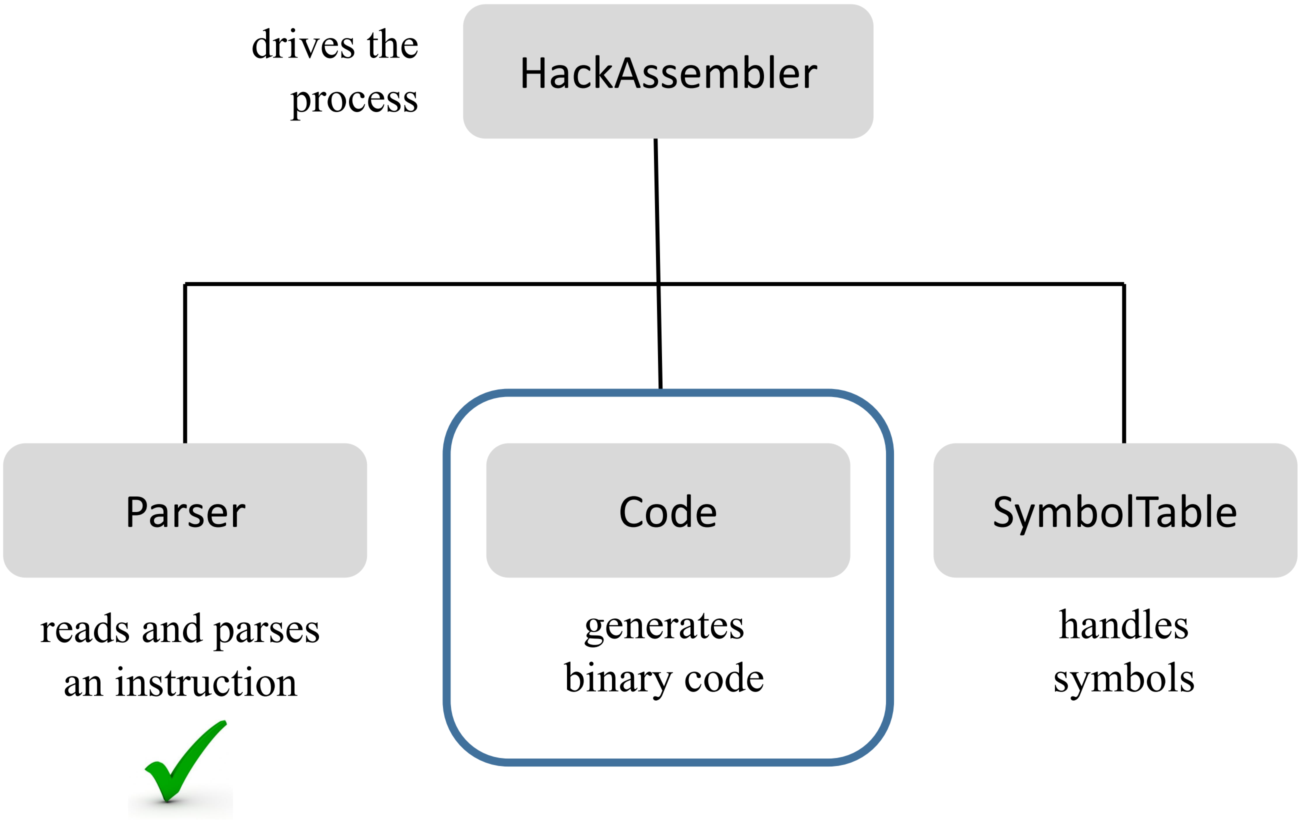
  `comp()`: Returns the instruction's *comp* field (string)

  `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 (a==0)	*comp* (a==1)	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:

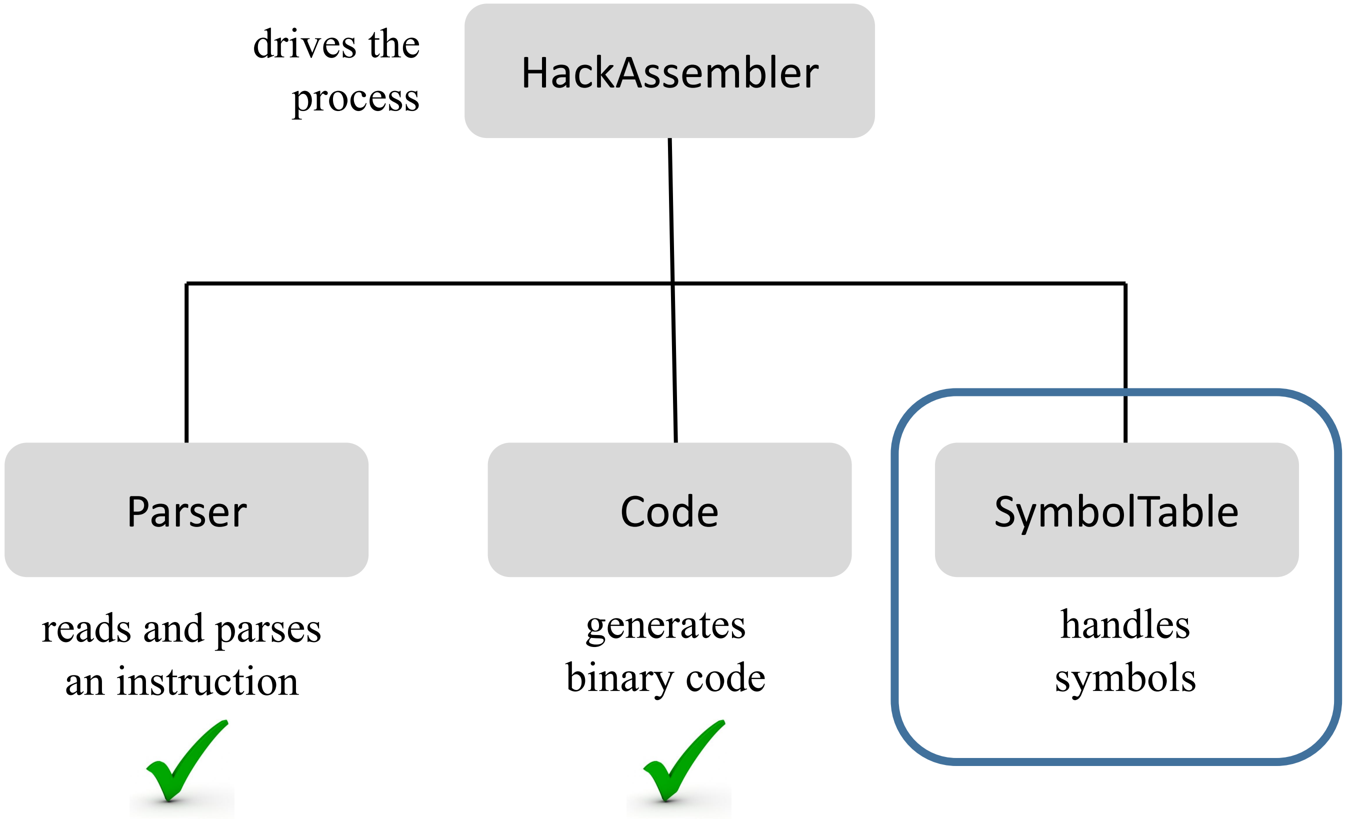
`dest("DM")` returns `"011"`

`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)

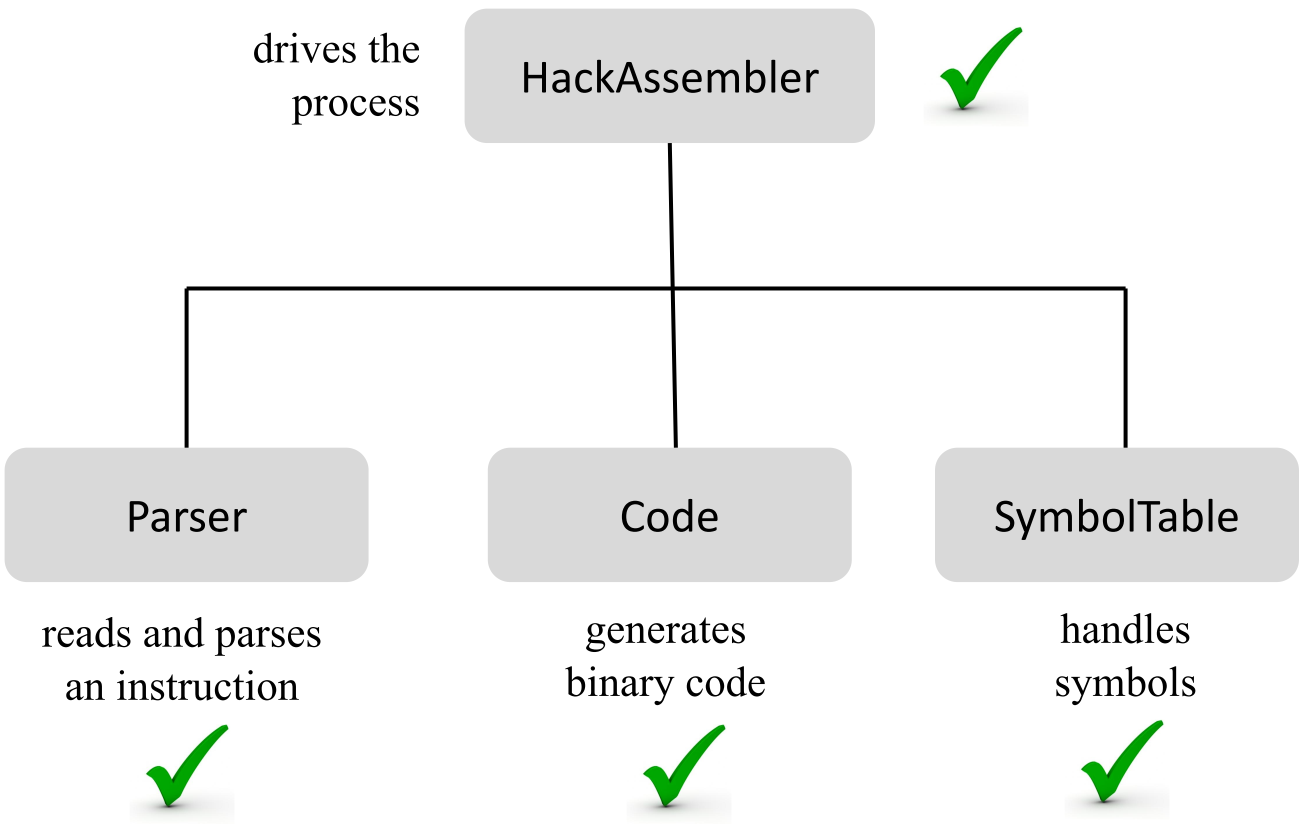
`contains(symbol` (string)**`):`** Checks if `symbol` exists in the table (boolean)

`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:

Implement the main program as you see fit.

Chapter 6: Assembler

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

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

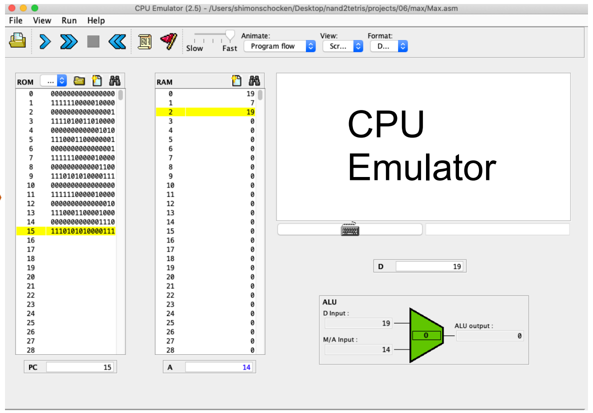
```
// Computes R1 = 1 + ... + R0
    // i = 1
    @i
    M=1
    // sum = 0
    @sum
    M=0
(LOOP)
    // if i > R0 goto STOP
    @i
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    ...
```

Your assembler

Prog.hack

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

Load / Run



<u>Test programs</u>

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

(with symbols)

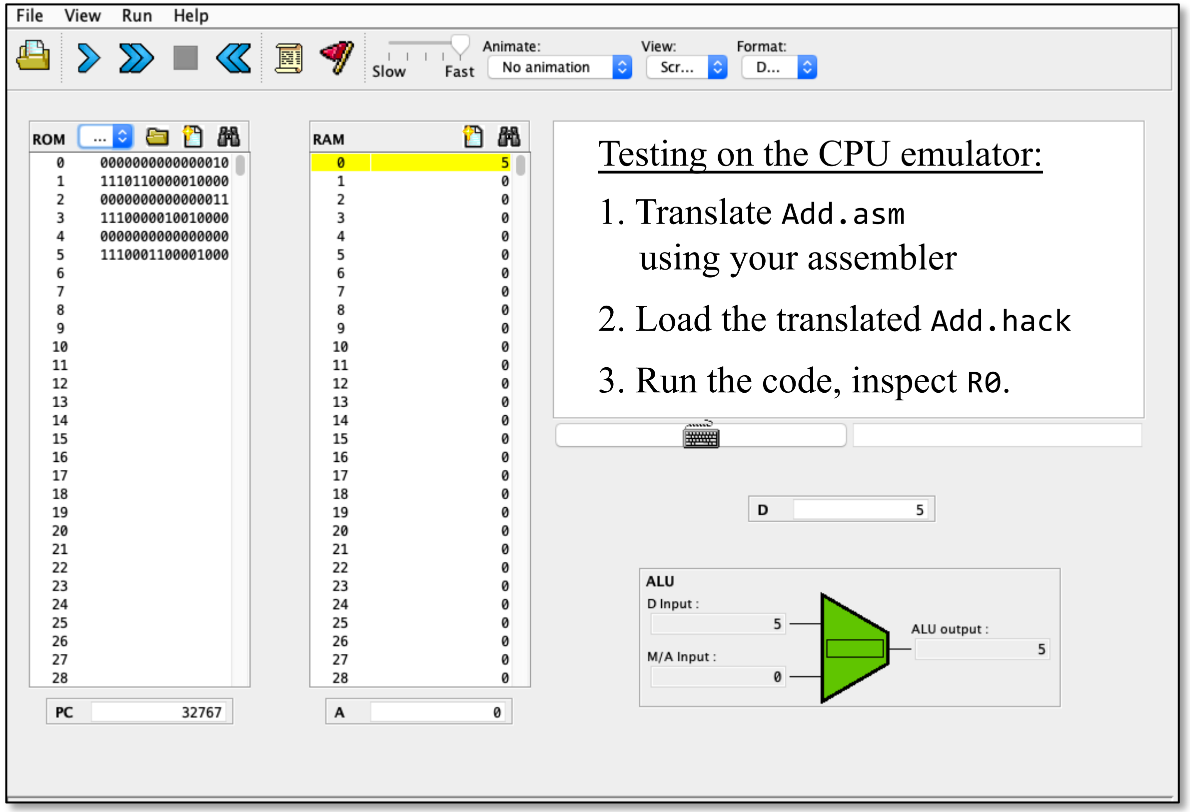
- `MaxL.asm`
- `RectL.asm`
- `PongL.asm`

(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
```



Testing on the CPU emulator:

1. Translate `Add.asm` using your assembler
2. Load the translated `Add.hack`
3. Run the code, inspect `R0`.

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 "binary" from the `ROM` menu.

Testing

Max.asm

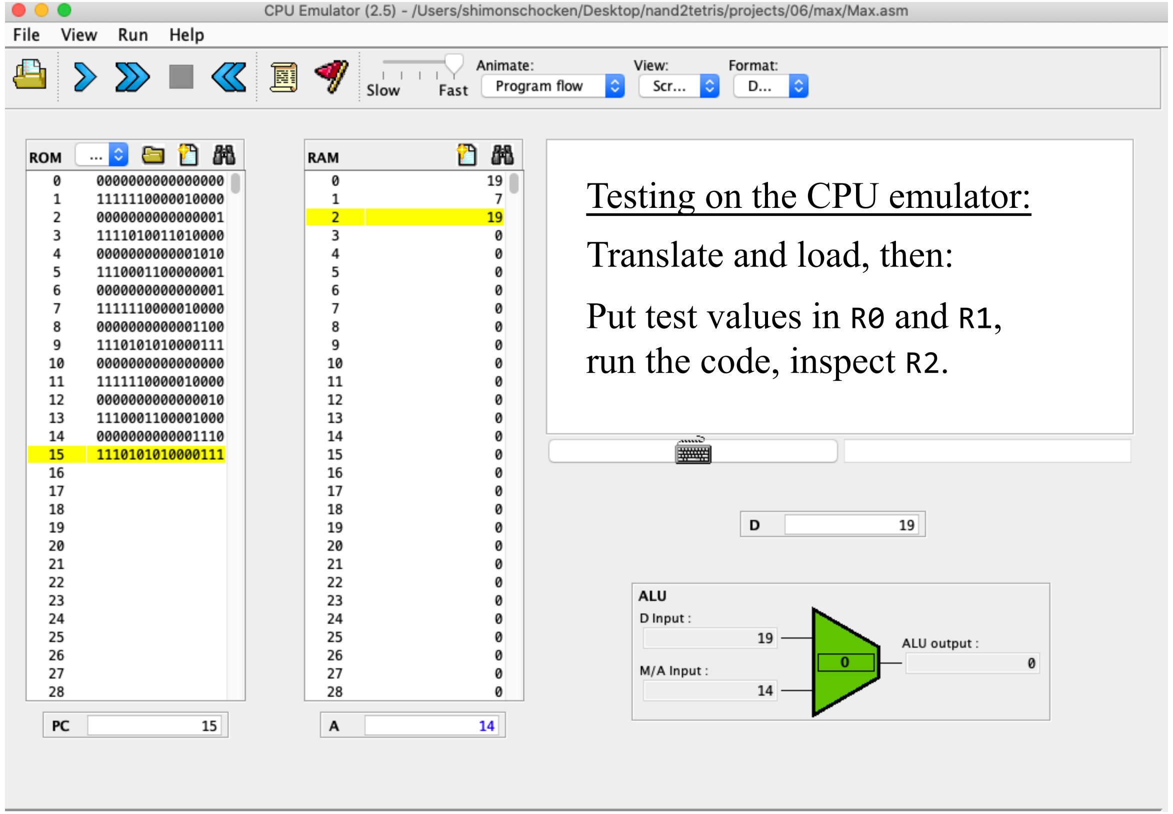
```
// Computes RAM[2] =
// max(RAM[0],RAM[1])

   @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)

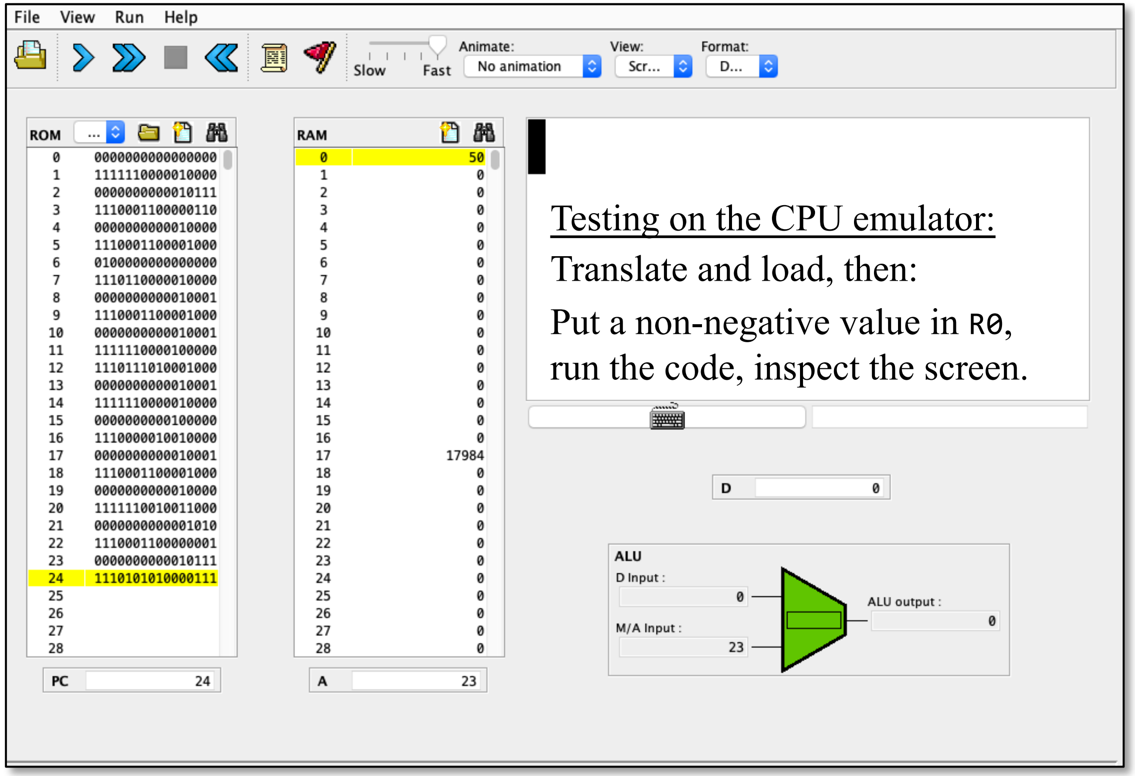
Testing

`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
   ...
```

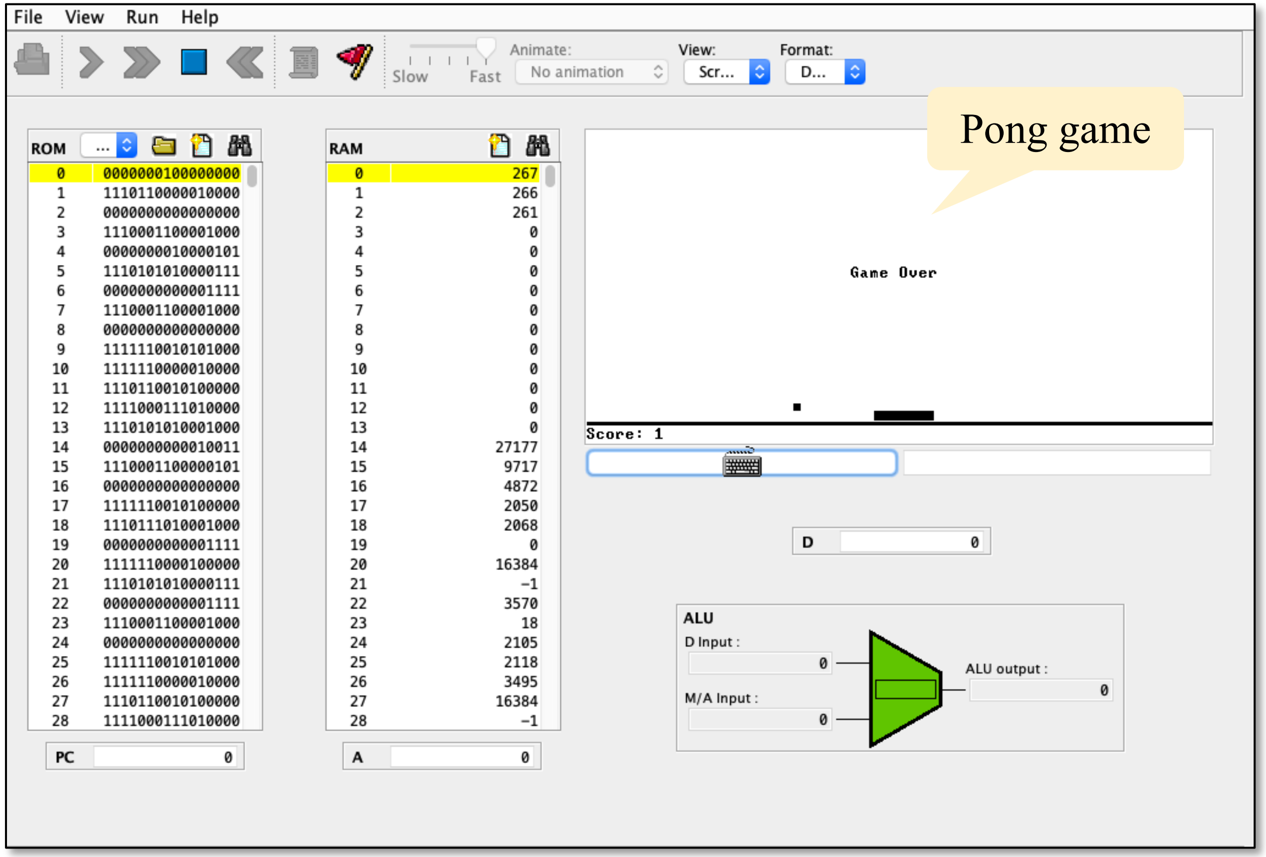
without symbols

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

<u>Background</u>

The original `Pong` program was written in the high-level Jack language

The computer's operating system is also written in Jack

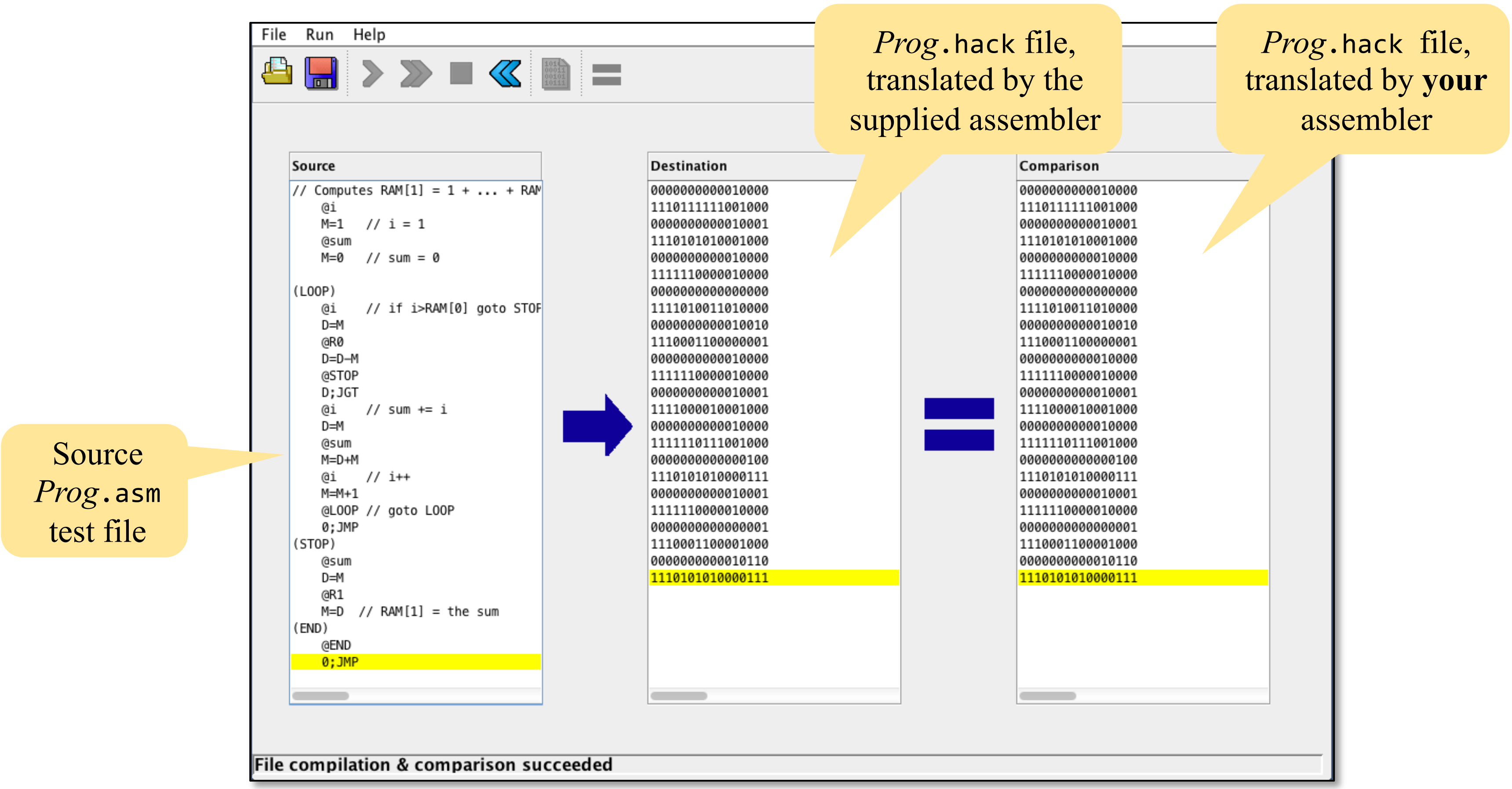
The `Pong` code + the OS code were compiled by the Jack compiler, creating a single `Pong.asm` file

The compiled code (`Pong.asm`) has compiler-generated addresses and symbols (which may be hard to read).

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.