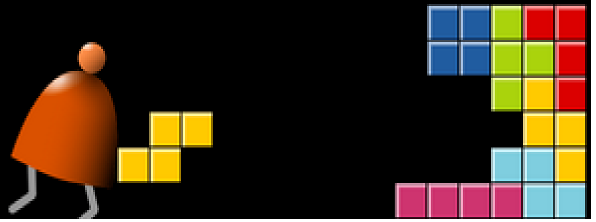
From Nand to Tetris

Building a Modern Computer from First Principles



Chapter 6

Assembler

These slides support chapter 6 of the book

The Elements of Computing Systems

By Noam Nisan and Shimon Schocken

MIT Press

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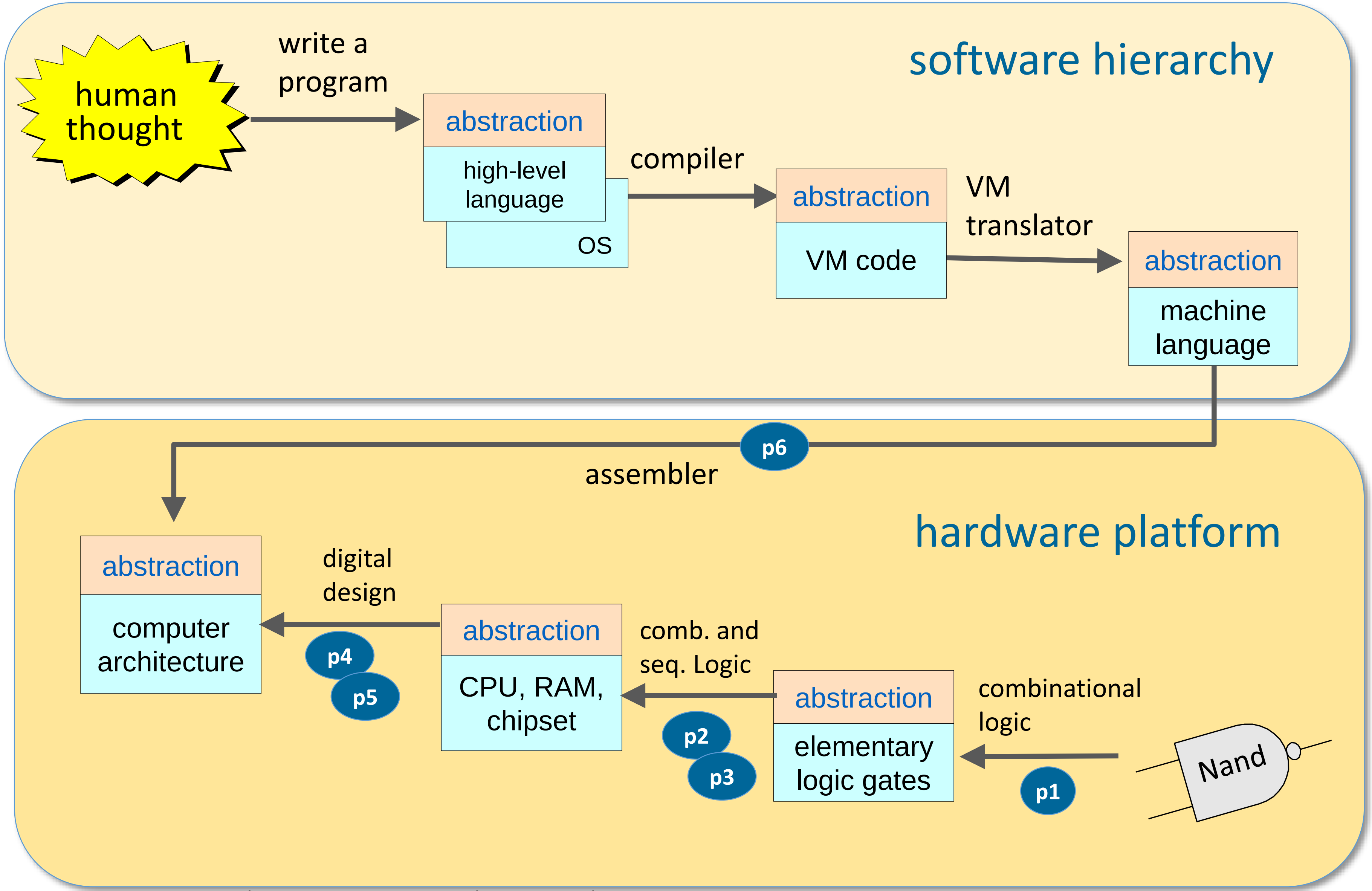
Happy teaching!

Noam Nisam / Shimon Schocken

Nand to Tetris: the big picture



Assembly process

Assembly Language

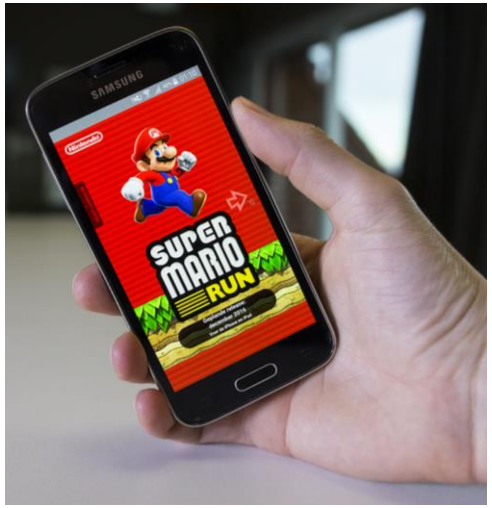
```
    @i
    M=1   // i = 1
    @sum
    M=0   // sum = 0
(LOOP)
    @i    // if i>RAM[0]
    D=M   // GOTP WRITE
    @R0
    D=D-M
    @WRITE
    D;JGT
    ...   // Etc.
```

assembler

Machine Language

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

run



Assembler: lecture plan

- ✓ The assembly process
- ➡ The Hack assembly language
- The assembly process: instructions
- The assembly process: symbols
- Developing an assembler
- Project 6 overview

The translator's challenge (overview)

Hack assembly code

(source language)

```
// Computes RAM[1]=1+...+RAM[0]
    @i
    M=1   // i = 1
    @sum
    M=0   // sum = 0

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

Assembler

What are the rules of the game?

Hack binary code

(source language)

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

The translator's challenge (overview)

Hack assembly code

(source language)

```
// Computes RAM[1]=1+...+RAM[0]
    @i
    M=1   // i = 1
    @sum
    M=0   // sum = 0

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

Assembler

Hack binary code

(source language)

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

<u>Based on the syntax rules of:</u>

- The source language
- The target language

Hack language specification: A-instruction

<u>Symbolic syntax:</u>

`@`*value*

Where *value* is either

- a non-negative decimal constant or
- a symbol referring to such a constant

Examples:

```
@21
```

```
@foo
```

<u>Binary syntax:</u>

`0`*valueInBinary*

Example:

```
0000000000010101
```

Hack language specification: C-instruction

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

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

Hack language specification: C-instruction

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

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

comp		c1	c2	c3	c4	c5	c6
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	d1	d2	d3	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
MD	0	1	1	RAM[A] and D register
A	1	0	0	A register
AM	1	0	1	A register and RAM[A]
AD	1	1	0	A register and D register
AMD	1	1	1	A register, RAM[A], and D register

jump	j1	j2	j3	effect:
null	0	0	0	no jump
JGT	0	0	1	if out > 0 jump
JEQ	0	1	0	if out = 0 jump
JGE	0	1	1	if out ≥ 0 jump
JLT	1	0	0	if out < 0 jump
JNE	1	0	1	if out ≠ 0 jump
JLE	1	1	0	if out ≤ 0 jump
JMP	1	1	1	Unconditional jump

Hack language specification: symbols

Pre-defined symbols:

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

Label declaration: (*label*)

Variable declaration: @*variableName*

The Hack language: a translator's perspective

Assembly program

```
// Computes RAM[1] = 1 + ... + RAM[0]
    @i
    M=1   // i = 1
    @sum
    M=0   // sum = 0

(LOOP)
    @i    // if i>RAM[0] goto STOP
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    @i    // sum += i
    D=M
    @sum
    M=D+M
    @i    // i++
    M=M+1
    @LOOP // goto LOOP
    0;JMP
(STOP)
    @sum
    D=M
    @R1
    M=D  // RAM[1] = the sum
(END)
    @END
    0;JMP
```

Assembly program elements:

- White space
  - Empty lines / indentation
  - Line comments
  - In-line comments
- Instructions
  - A-instructions
  - C-instructions
- Symbols
  - References
  - Label declarations

The Hack language: a translator’s perspective

Assembly program

```
// Computes RAM[1] = 1 + ... + RAM[0]
    @i
    M=1   // i = 1
    @sum
    M=0   // sum = 0

(LOOP)
    @i    // if i>RAM[0] goto STOP
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    @i    // sum += i
    D=M
    @sum
    M=D+M
    @i    // i++
    M=M+1
    @LOOP // goto LOOP
    0;JMP
(STOP)
    @sum
    D=M
    @R1
    M=D  // RAM[1] = the sum
(END)
    @END
    0;JMP
```

Assembler

Hack machine code

```
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
0000000000010010
1110001100000001
0000000000010000
1111110000010000
0000000000010001
1111000010001000
0000000000010000
1111110111001000
0000000000000100
1110101010000111
0000000000010001
1111110000010000
0000000000000001
1110001100001000
0000000000010110
1110101010000111
```

Challenges:

Handling…

- White space
- Instructions
- Symbols

Symbols

Program with symbols

```
// Computes RAM[1] = 1 + ... + RAM[0]
    @i
    M=1   // i = 1
    @sum
    M=0   // sum = 0

(LOOP)
    @i    // if i>RAM[0] goto STOP
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    @i    // sum += i
    D=M
    @sum
    M=D+M
    @i    // i++
    M=M+1
    @LOOP // goto LOOP
    0;JMP
(STOP)
    @sum
    D=M
    @R1
    M=D  // RAM[1] = the sum
(END)
    @END
    0;JMP
```

Challenges:

Handling…

- White space
- Instructions
- Symbols

Simplifying assumption:

Let’s deal with symbols later.

Handling programs without symbols

Assembly program (without symbols)

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

    @16   // if i>RAM[0] goto STOP
    D=M
    @0
    D=D-M
    @18
    D;JGT
    @16    // sum += i
    D=M
    @17
    M=D+M
    @16    // i++
    M=M+1
    @4     // goto LOOP
    0;JMP
    @17
    D=M
    @1
    M=D    // RAM[1] = the sum
    @22
    0;JMP
```

Assembler for symbol-less Hack programs

Hack machine code

```
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
0000000000010010
1110001100000001
0000000000010000
1111110000010000
0000000000010001
1111000010001000
0000000000010000
1111110111001000
0000000000000100
1110101010000111
0000000000010001
1111110000010000
0000000000000001
1110001100001000
0000000000010110
1110101010000111
```

Challenges:

Handling…

- White space
- Instructions

Handling white space

Assembly program (without symbols)

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

    @16   // if i>RAM[0] goto STOP
    D=M
    @0
    D=D-M
    @18
    D;JGT
    @16    // sum += i
    D=M
    @17
    M=D+M
    @16    // i++
    M=M+1
    @4     // goto LOOP
    0;JMP
    @17
    D=M
    @1
    M=D    // RAM[1] = the sum
    @22
    0;JMP
```

Assembler for symbol-less Hack programs

Hack machine code

```
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
0000000000010010
1110001100000001
0000000000010000
1111110000010000
0000000000010001
1111000010001000
0000000000010000
1111110111001000
0000000000000100
1110101010000111
0000000000010001
1111110000010000
0000000000000001
1110001100001000
0000000000010110
1110101010000111
```

Challenges:

Handling…

- White space
- Instructions

Handling white space

Assembly program (without symbols)

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

    @16    // if i>RAM[0] goto STOP
    D=M
    @0
    D=D-M
    @18
    D;JGT
    @16     // sum += i
    D=M
    @17
    M=D+M
    @16     // i++
    M=M+1
    @4      // goto LOOP
    0;JMP
    @17
    D=M
    @1
    M=D     // RAM[1] = the sum
    @22
    0;JMP
```

Assembler
for symbol-less
Hack programs

Hack machine code

```
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
0000000000010010
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1111000010001000
0000000000010000
1111110111001000
0000000000000100
1110101010000111
0000000000010001
1111110000010000
0000000000000001
1110001100001000
0000000000010110
1110101010000111
```

Challenges:

Handling…

- White space
- Instructions

Handling white space:

Ignore it!

Handling instructions

Assembly program (without symbols)

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

Assembler for symbol-less Hack programs

Hack machine code

```
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
0000000000010010
1110001100000001
0000000000010000
1111110000010000
0000000000010001
1111000010001000
0000000000010000
1111110111001000
0000000000000100
1110101010000111
0000000000010001
1111110000010000
0000000000000001
1110001100001000
0000000000010110
1110101010000111
```

Challenges:

Handling…

- ✓ White space
- Instructions

Translating A-instructions

Symbolic syntax:

```
@value
```

Examples:

```
@21
```

```
@foo
```

Where *value* is either

- a non-negative decimal constant or
- a symbol referring to such a constant (later)

Binary syntax:

```
0valueInBinary
```

Example:

```
0000000000010101
```

Translation to binary:

- If *value* is a decimal constant, generate the equivalent binary constant
- If *value* is a symbol, later.

Translating C-instructions

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

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

comp		c1	c2	c3	c4	c5	c6
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	d1	d2	d3	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
MD	0	1	1	RAM[A] and D register
A	1	0	0	A register
AM	1	0	1	A register and RAM[A]
AD	1	1	0	A register and D register
AMD	1	1	1	A register, RAM[A], and D register

jump	j1	j2	j3	effect:
null	0	0	0	no jump
JGT	0	0	1	if out > 0 jump
JEQ	0	1	0	if out = 0 jump
JGE	0	1	1	if out ≥ 0 jump
JLT	1	0	0	if out < 0 jump
JNE	1	0	1	if out ≠ 0 jump
JLE	1	1	0	if out ≤ 0 jump
JMP	1	1	1	Unconditional jump

Example:

Symbolic: `MD=D+1`

Binary:

Translating C-instructions

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

Binary syntax: $\boxed{1\ 1\ 1}$ a c1 c2 c3 c4 c5 c6 d1 d2 d3 j1 j2 j3

comp		c1	c2	c3	c4	c5	c6
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	d1	d2	d3	effect: the value is stored in:
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M	0	0	1	RAM[A]
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MD	0	1	1	RAM[A] and D register
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Example:

Symbolic: `MD=D+1`

Binary:

Translating C-instructions

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

Binary syntax: $\boxed{1\ 1\ 1}$ a c1 c2 c3 c4 c5 c6 d1 d2 d3 j1 j2 j3

comp		c1	c2	c3	c4	c5	c6
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						

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JLE	1	1	0	if out ≤ 0 jump
JMP	1	1	1	Unconditional jump

Example:

Symbolic: `MD=D+1`

Binary: `111`

Translating C-instructions

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

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

comp		c1	c2	c3	c4	c5	c6
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	d1	d2	d3	effect: the value is stored in:
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A	1	0	0	A register
AM	1	0	1	A register and RAM[A]
AD	1	1	0	A register and D register
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jump	j1	j2	j3	effect:
null	0	0	0	no jump
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JLT	1	0	0	if out < 0 jump
JNE	1	0	1	if out ≠ 0 jump
JLE	1	1	0	if out ≤ 0 jump
JMP	1	1	1	Unconditional jump

Example:

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Binary: `111`

Translating C-instructions

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

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

comp		c1	c2	c3	c4	c5	c6
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	d1	d2	d3	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
MD	0	1	1	RAM[A] and D register
A	1	0	0	A register
AM	1	0	1	A register and RAM[A]
AD	1	1	0	A register and D register
AMD	1	1	1	A register, RAM[A], and D register

jump	j1	j2	j3	effect:
null	0	0	0	no jump
JGT	0	0	1	if out > 0 jump
JEQ	0	1	0	if out = 0 jump
JGE	0	1	1	if out ≥ 0 jump
JLT	1	0	0	if out < 0 jump
JNE	1	0	1	if out ≠ 0 jump
JLE	1	1	0	if out ≤ 0 jump
JMP	1	1	1	Unconditional jump

Example:

Symbolic: `MD=D+1`

Binary: `111`

Translating C-instructions

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

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

comp		c1	c2	c3	c4	c5	c6
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	d1	d2	d3	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
MD	0	1	1	RAM[A] and D register
A	1	0	0	A register
AM	1	0	1	A register and RAM[A]
AD	1	1	0	A register and D register
AMD	1	1	1	A register, RAM[A], and D register

jump	j1	j2	j3	effect:
null	0	0	0	no jump
JGT	0	0	1	if out > 0 jump
JEQ	0	1	0	if out = 0 jump
JGE	0	1	1	if out ≥ 0 jump
JLT	1	0	0	if out < 0 jump
JNE	1	0	1	if out ≠ 0 jump
JLE	1	1	0	if out ≤ 0 jump
JMP	1	1	1	Unconditional jump

Example:

Symbolic: MD=D+1

Binary: 111

Translating C-instructions

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

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

comp		c1	c2	c3	c4	c5	c6
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	d1	d2	d3	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
MD	0	1	1	RAM[A] and D register
A	1	0	0	A register
AM	1	0	1	A register and RAM[A]
AD	1	1	0	A register and D register
AMD	1	1	1	A register, RAM[A], and D register

jump	j1	j2	j3	effect:
null	0	0	0	no jump
JGT	0	0	1	if out > 0 jump
JEQ	0	1	0	if out = 0 jump
JGE	0	1	1	if out ≥ 0 jump
JLT	1	0	0	if out < 0 jump
JNE	1	0	1	if out ≠ 0 jump
JLE	1	1	0	if out ≤ 0 jump
JMP	1	1	1	Unconditional jump

Example:

Symbolic: MD=D+1

Binary: 1110011111

Translating C-instructions

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

Binary syntax: 1 1 1 a c1 c2 c3 c4 c5 c6 $\boxed{\text{d1 d2 d3}}$ j1 j2 j3

comp		c1	c2	c3	c4	c5	c6
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	d1	d2	d3	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
MD	0	1	1	RAM[A] and D register
A	1	0	0	A register
AM	1	0	1	A register and RAM[A]
AD	1	1	0	A register and D register
AMD	1	1	1	A register, RAM[A], and D register

jump	j1	j2	j3	effect:
null	0	0	0	no jump
JGT	0	0	1	if out > 0 jump
JEQ	0	1	0	if out = 0 jump
JGE	0	1	1	if out ≥ 0 jump
JLT	1	0	0	if out < 0 jump
JNE	1	0	1	if out ≠ 0 jump
JLE	1	1	0	if out ≤ 0 jump
JMP	1	1	1	Unconditional jump

Example:

Symbolic: `MD=D+1`

Binary: `1110011111`

Translating C-instructions

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

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

comp		c1	c2	c3	c4	c5	c6
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	d1	d2	d3	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
MD	0	1	1	RAM[A] and D register
A	1	0	0	A register
AM	1	0	1	A register and RAM[A]
AD	1	1	0	A register and D register
AMD	1	1	1	A register, RAM[A], and D register

jump	j1	j2	j3	effect:
null	0	0	0	no jump
JGT	0	0	1	if out > 0 jump
JEQ	0	1	0	if out = 0 jump
JGE	0	1	1	if out ≥ 0 jump
JLT	1	0	0	if out < 0 jump
JNE	1	0	1	if out ≠ 0 jump
JLE	1	1	0	if out ≤ 0 jump
JMP	1	1	1	Unconditional jump

Example:

Symbolic: $\boxed{\text{MD}}$=D+1

Binary: 1110011111

Translating C-instructions

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

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

comp		c1	c2	c3	c4	c5	c6
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	d1	d2	d3	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
MD	0	1	1	RAM[A] and D register
A	1	0	0	A register
AM	1	0	1	A register and RAM[A]
AD	1	1	0	A register and D register
AMD	1	1	1	A register, RAM[A], and D register

jump	j1	j2	j3	effect:
null	0	0	0	no jump
JGT	0	0	1	if out > 0 jump
JEQ	0	1	0	if out = 0 jump
JGE	0	1	1	if out ≥ 0 jump
JLT	1	0	0	if out < 0 jump
JNE	1	0	1	if out ≠ 0 jump
JLE	1	1	0	if out ≤ 0 jump
JMP	1	1	1	Unconditional jump

Example:

Symbolic: MD=D+1

Binary: 1110011111

Translating C-instructions

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

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

comp		c1	c2	c3	c4	c5	c6
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	d1	d2	d3	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
MD	0	1	1	RAM[A] and D register
A	1	0	0	A register
AM	1	0	1	A register and RAM[A]
AD	1	1	0	A register and D register
AMD	1	1	1	A register, RAM[A], and D register

jump	j1	j2	j3	effect:
null	0	0	0	no jump
JGT	0	0	1	if out > 0 jump
JEQ	0	1	0	if out = 0 jump
JGE	0	1	1	if out ≥ 0 jump
JLT	1	0	0	if out < 0 jump
JNE	1	0	1	if out ≠ 0 jump
JLE	1	1	0	if out ≤ 0 jump
JMP	1	1	1	Unconditional jump

Example:

Symbolic: MD=D+1

Binary: 1110011111011000

Translating C-instructions

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

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

comp		c1	c2	c3	c4	c5	c6
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	d1	d2	d3	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
MD	0	1	1	RAM[A] and D register
A	1	0	0	A register
AM	1	0	1	A register and RAM[A]
AD	1	1	0	A register and D register
AMD	1	1	1	A register, RAM[A], and D register

jump	j1	j2	j3	effect:
null	0	0	0	no jump
JGT	0	0	1	if out > 0 jump
JEQ	0	1	0	if out = 0 jump
JGE	0	1	1	if out ≥ 0 jump
JLT	1	0	0	if out < 0 jump
JNE	1	0	1	if out ≠ 0 jump
JLE	1	1	0	if out ≤ 0 jump
JMP	1	1	1	Unconditional jump

Example:

Symbolic: `MD=D+1`

Binary: `1110011111011`

Translating C-instructions

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

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

comp		c1	c2	c3	c4	c5	c6
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	d1	d2	d3	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
MD	0	1	1	RAM[A] and D register
A	1	0	0	A register
AM	1	0	1	A register and RAM[A]
AD	1	1	0	A register and D register
AMD	1	1	1	A register, RAM[A], and D register

jump	j1	j2	j3	effect:
null	0	0	0	no jump
JGT	0	0	1	if out > 0 jump
JEQ	0	1	0	if out = 0 jump
JGE	0	1	1	if out ≥ 0 jump
JLT	1	0	0	if out < 0 jump
JNE	1	0	1	if out ≠ 0 jump
JLE	1	1	0	if out ≤ 0 jump
JMP	1	1	1	Unconditional jump

Example:

Symbolic: MD=D+1

Binary: 1110011111011

Translating C-instructions

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

Binary syntax: 1 1 1 a c1 c2 c3 c4 c5 c6 d1 d2 d3 $\boxed{\text{j1 j2 j3}}$

comp (a=0)	*comp* (a=1)	c1	c2	c3	c4	c5	c6
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	d1	d2	d3	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
MD	0	1	1	RAM[A] and D register
A	1	0	0	A register
AM	1	0	1	A register and RAM[A]
AD	1	1	0	A register and D register
AMD	1	1	1	A register, RAM[A], and D register

jump	j1	j2	j3	effect:
null	0	0	0	no jump
JGT	0	0	1	if out > 0 jump
JEQ	0	1	0	if out = 0 jump
JGE	0	1	1	if out ≥ 0 jump
JLT	1	0	0	if out < 0 jump
JNE	1	0	1	if out ≠ 0 jump
JLE	1	1	0	if out ≤ 0 jump
JMP	1	1	1	Unconditional jump

Example: Symbolic: MD=D+1 Binary: 1110011111011

Translating C-instructions

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

Binary syntax: 1 1 1 a c1 c2 c3 c4 c5 c6 d1 d2 d3 $\boxed{\text{j1 j2 j3}}$

comp		c1	c2	c3	c4	c5	c6
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	d1	d2	d3	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
MD	0	1	1	RAM[A] and D register
A	1	0	0	A register
AM	1	0	1	A register and RAM[A]
AD	1	1	0	A register and D register
AMD	1	1	1	A register, RAM[A], and D register

jump	j1	j2	j3	effect:
null	0	0	0	no jump
JGT	0	0	1	if out > 0 jump
JEQ	0	1	0	if out = 0 jump
JGE	0	1	1	if out ≥ 0 jump
JLT	1	0	0	if out < 0 jump
JNE	1	0	1	if out ≠ 0 jump
JLE	1	1	0	if out ≤ 0 jump
JMP	1	1	1	Unconditional jump

Example:

Symbolic: MD=D+1

Binary: 111001111101100
0

Translating C-instructions

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

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

comp		c1	c2	c3	c4	c5	c6
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	d1	d2	d3	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
MD	0	1	1	RAM[A] and D register
A	1	0	0	A register
AM	1	0	1	A register and RAM[A]
AD	1	1	0	A register and D register
AMD	1	1	1	A register, RAM[A], and D register

jump	j1	j2	j3	effect:
null	0	0	0	no jump
JGT	0	0	1	if out > 0 jump
JEQ	0	1	0	if out = 0 jump
JGE	0	1	1	if out ≥ 0 jump
JLT	1	0	0	if out < 0 jump
JNE	1	0	1	if out ≠ 0 jump
JLE	1	1	0	if out ≤ 0 jump
JMP	1	1	1	Unconditional jump

Example:

Symbolic: MD=D+1

Binary: 111001111101100 0

The overall assembly logic

Assembly program

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

For each instruction

- Parse the instruction:
  break it into its underlying fields
- A-instruction:
  translate the decimal value into a binary value
- C-instruction:
  for each field in the instruction, generate the corresponding binary code;
- Assemble the translated binary codes into a complete 16-bit machine instruction
- Write the 16-bit instruction to the output file.

The overall assembly logic

Assembly program

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

Resulting code:

Hack machine code

```
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
0000000000010010
1110001100000001
0000000000010000
1111110000010000
0000000000010001
1111000010001000
0000000000010000
1111110111001000
0000000000000100
1110101010000111
0000000000010001
1111110000010000
0000000000000001
1110001100001000
0000000000010110
1110101010000111
```

The overall assembly logic

Assembly program

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

Resulting code:

Hack machine code

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0000000000010000
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0000000000010000
1111110111001000
0000000000000100
1110101010000111
0000000000010001
1111110000010000
0000000000000001
1110001100001000
0000000000010110
1110101010000111
```

Disclaimer

The source code contains no symbols

Assembler: lecture plan

- ✓ Assembler logic (basic)
- ✓ The Hack assembly language
- ✓ The assembly process: instructions
- ➡ The assembly process: symbols
- Developing an assembler
- Project 6 overview

Hack Assembler

Assembly program

```
// Computes RAM[1] = 1 + ... + RAM[0]
    @i
    M=1   // i = 1
    @sum
    M=0   // sum = 0

(LOOP)
    @i    // if i>RAM[0] goto STOP
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    @i    // sum += i
    D=M
    @sum
    M=D+M
    @i    // i++
    M=M+1
    @LOOP // goto LOOP
    0;JMP
(STOP)
    @sum
    D=M
    @R1
    M=D  // RAM[1] = the sum
(END)
    @END
    0;JMP
```

Assembler

Hack machine code

```
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
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1111000010001000
0000000000010000
1111110111001000
0000000000000100
1110101010000111
0000000000010001
1111110000010000
0000000000000001
1110001100001000
0000000000010110
1110101010000111
```

Challenges:

Handling…

- White space
- Instructions
- Symbols

Hack Assembler

Assembly program

```
// Computes RAM[1] = 1 + ... + RAM[0]
    @i
    M=1   // i = 1
    @sum
    M=0   // sum = 0

(LOOP)
    @i    // if i>RAM[0] goto STOP
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    @i    // sum += i
    D=M
    @sum
    M=D+M
    @i    // i++
    M=M+1
    @LOOP // goto LOOP
    0;JMP
(STOP)
    @sum
    D=M
    @R1
    M=D  // RAM[1] = the sum
(END)
    @END
    0;JMP
```

Assembler

Hack machine code

```
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
0000000000010010
1110001100000001
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0000000000000100
1110101010000111
0000000000010001
1111110000010000
0000000000000001
1110001100001000
0000000000010110
1110101010000111
```

Challenges:

Handling…

- ✓ White space
- ✓ Instructions
- Symbols

Handling symbols

Assembly program

```
// Computes RAM[1] = 1 + ... + RAM[0]
    @i
    M=1   // i = 1
    @sum
    M=0   // sum = 0

(LOOP)
    @i    // if i>RAM[0] goto STOP
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    @i    // sum += i
    D=M
    @sum
    M=D+M
    @i    // i++
    M=M+1
    @LOOP // goto LOOP
    0;JMP
(STOP)
    @sum
    D=M
    @R1
    M=D  // RAM[1] = the sum
(END)
    @END
    0;JMP
```

Pre-defined symbols:

represent special memory locations

label symbols:

represent destinations of goto instructions

variable symbols:

represent memory locations where the programmer wants to maintain values

Handling pre-defined symbols

Assembly program

```
// Computes RAM[1] = 1 + ... + RAM[0]
    @i
    M=1   // i = 1
    @sum
    M=0   // sum = 0

(LOOP)
    @i    // if i>RAM[0] goto STOP
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    @i    // sum += i
    D=M
    @sum
    M=D+M
    @i    // i++
    M=M+1
    @LOOP // goto LOOP
    0;JMP
(STOP)
    @sum
    D=M
    @R1
    M=D  // RAM[1] = the sum
(END)
    @END
    0;JMP
```

The Hack language specification describes 23 *pre-defined symbols*:

symbol	value
R0	0
R1	1
R2	2
...	...
R15	15
SCREEN	16384
KBD	24576

symbol	value
SP	0
LCL	1
ARG	2
THIS	3
THAT	4

Translating *@preDefinedSymbol* :

Replace *preDefinedSymbol* with its value.

Handling symbols that denote labels

Assembly program

```
    // Computes RAM[1] = 1 + ... + RAM[0]
 0      @i
 1      M=1   // i = 1
 2      @sum
 3      M=0   // sum = 0

    (LOOP)
 4      @i    // if i>RAM[0] goto STOP
 5      D=M
 6      @R0
 7      D=D-M
 8      @STOP
 9      D;JGT
10      @i    // sum += i
11      D=M
12      @sum
13      M=D+M
14      @i    // i++
15      M=M+1
16      @LOOP // goto LOOP
17      0;JMP
    (STOP)
18      @sum
19      D=M
20      @R1
21      M=D  // RAM[1] = the sum
    (END)
22      @END
23      0;JMP
```

Label symbols

- Used to label destinations of goto commands
- Declared by the pseudo-command `(xxx)`
- This directive defines the symbol xxx to refer to the memory location holding the next instruction in the program

symbol	value
LOOP	4
STOP	18
END	22

Translating *@labelSymbol* :

Replace *labelSymbol* with its value

Handling symbols that denote variables

Assembly program

```
// Computes RAM[1] = 1 + ... + RAM[0]
    @i
    M=1   // i = 1
    @sum
    M=0   // sum = 0

(LOOP)
    @i    // if i>RAM[0] goto STOP
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    @i    // sum += i
    D=M
    @sum
    M=D+M
    @i    // i++
    M=M+1
    @LOOP // goto LOOP
    0;JMP
(STOP)
    @sum
    D=M
    @R1
    M=D  // RAM[1] = the sum
(END)
    @END
    0;JMP
```

Variable symbols

- Any symbol xxx appearing in an assembly program which is not pre-defined and is not defined elsewhere using the `(xxx)` directive is treated as a *variable*
- Each variable is assigned a unique memory address, starting at 16

symbol	value
i	16
sum	17

Translating *@variableSymbol* :

- If seen for the first time, assign a unique memory address
- Replace *variableSymbol* with this address

Symbol table

Assembly program

```
// Computes RAM[1] = 1 + ... + RAM[0]
    @i
    M=1   // i = 1
    @sum
    M=0   // sum = 0

(LOOP)
    @i    // if i>RAM[0] goto STOP
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    @i    // sum += i
    D=M
    @sum
    M=D+M
    @i    // i++
    M=M+1
    @LOOP // goto LOOP
    0;JMP
(STOP)
    @sum
    D=M
    @R1
    M=D  // RAM[1] = the sum
(END)
    @END
    0;JMP
```

Symbol table

Assembly program

```
// Computes RAM[1] = 1 + ... + RAM[0]
    @i
    M=1   // i = 1
    @sum
    M=0   // sum = 0

(LOOP)
    @i    // if i>RAM[0] goto STOP
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    @i    // sum += i
    D=M
    @sum
    M=D+M
    @i    // i++
    M=M+1
    @LOOP // goto LOOP
    0;JMP
(STOP)
    @sum
    D=M
    @R1
    M=D  // RAM[1] = the sum
(END)
    @END
    0;JMP
```

Symbol table

symbol	value

Symbol table

Assembly program

```
// Computes RAM[1] = 1 + ... + RAM[0]
    @i
    M=1   // i = 1
    @sum
    M=0   // sum = 0

(LOOP)
    @i    // if i>RAM[0] goto STOP
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    @i    // sum += i
    D=M
    @sum
    M=D+M
    @i    // i++
    M=M+1
    @LOOP // goto LOOP
    0;JMP
(STOP)
    @sum
    D=M
    @R1
    M=D  // RAM[1] = the sum
(END)
    @END
    0;JMP
```

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

Initialization:
Add the pre-defined symbols

Symbol table

Assembly program

```
   // Computes RAM[1] = 1 + ... + RAM[0]
0      @i
1      M=1   // i = 1
2      @sum
3      M=0   // sum = 0

   (LOOP)
4      @i    // if i>RAM[0] goto STOP
5      D=M
6      @R0
7      D=D-M
8      @STOP
9      D;JGT
10     @i    // sum += i
11     D=M
12     @sum
13     M=D+M
14     @i    // i++
15     M=M+1
16     @LOOP // goto LOOP
17     0;JMP
   (STOP)
18     @sum
19     D=M
20     @R1
21     M=D  // RAM[1] = the sum
   (END)
22     @END
23     0;JMP
```

Symbol table

symbol	value
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Initialization:
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Symbol table

Assembly program

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     // Computes RAM[1] = 1 + ... + RAM[0]
0        @i
1        M=1    // i = 1
2        @sum
3        M=0    // sum = 0

     (LOOP)
4        @i     // if i>RAM[0] goto STOP
5        D=M
6        @R0
7        D=D-M
8        @STOP
9        D;JGT
10       @i     // sum += i
11       D=M
12       @sum
13       M=D+M
14       @i     // i++
15       M=M+1
16       @LOOP  // goto LOOP
17       0;JMP
     (STOP)
18       @sum
19       D=M
20       @R1
21       M=D   // RAM[1] = the sum
     (END)
22       @END
23       0;JMP
```

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
END	22

Initialization:
Add the pre-defined symbols

First pass:
Add the label symbols

Symbol table

Assembly program

```
// Computes RAM[1] = 1 + ... + RAM[0]
    @i
    M=1   // i = 1
    @sum
    M=0   // sum = 0

(LOOP)
    @i    // if i>RAM[0] goto STOP
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    @i    // sum += i
    D=M
    @sum
    M=D+M
    @i    // i++
    M=M+1
    @LOOP // goto LOOP
    0;JMP
(STOP)
    @sum
    D=M
    @R1
    M=D  // RAM[1] = the sum
(END)
    @END
    0;JMP
```

Symbol table

symbol	value
R0	0
R1	1
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SCREEN	16384
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LOOP	4
STOP	18
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Initialization:
Add the pre-defined symbols

First pass:
Add the label symbols

Symbol table

Assembly program

```
// Computes RAM[1] = 1 + ... + RAM[0]
    @i
    M=1   // i = 1
    @sum
    M=0   // sum = 0

(LOOP)
    @i    // if i>RAM[0] goto STOP
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    @i    // sum += i
    D=M
    @sum
    M=D+M
    @i    // i++
    M=M+1
    @LOOP // goto LOOP
    0;JMP
(STOP)
    @sum
    D=M
    @R1
    M=D  // RAM[1] = the sum
(END)
    @END
    0;JMP
```

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
END	22
i	16
sum	17

Initialization:
Add the pre-defined symbols

First pass:
Add the label symbols

Second pass:
Add the var. symbols

Usage:

To resolve a symbol, look up its value in the symbol table

The assembly process

Initialization:

- Construct an empty symbol table
- Add the pre-defined symbols to the symbol table

First pass:

Scan the entire program;

For each "instruction" of the form `(xxx)`:

- Add the pair (`xxx`, *address*) to the symbol table,
  where *address* is the number of the instruction following `(xxx)`

Second pass:

Set *n* to 16

Scan the entire program again; for each instruction:

- If the instruction is *@symbol*, look up *symbol* in the symbol table;
  - If (*symbol*, *value*) is found, use *value* to complete the instruction's translation;
  - If not found:
    - Add (*symbol*, *n*) to the symbol table,
    - Use *n* to complete the instruction's translation,
    - *n*++
- If the instruction is a C-instruction, complete the instruction's translation
- Write the translated instruction to the output file.

Hack Assembler

Assembly program

```
// Computes RAM[1] = 1 + ... + RAM[0]
    @i
    M=1   // i = 1
    @sum
    M=0   // sum = 0

(LOOP)
    @i    // if i>RAM[0] goto STOP
    D=M
    @R0
    D=D-M
    @STOP
    D;JGT
    @i    // sum += i
    D=M
    @sum
    M=D+M
    @i    // i++
    M=M+1
    @LOOP // goto LOOP
    0;JMP
(STOP)
    @sum
    D=M
    @R1
    M=D  // RAM[1] = the sum
(END)
    @END
    0;JMP
```

Assembler

Hack machine code

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1110111111001000
0000000000010001
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0000000000010000
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0000000000000000
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0000000000000100
1110101010000111
0000000000010001
1111110000010000
0000000000000001
1110001100001000
0000000000010110
1110101010000111
```

Challenges:

Handling…

- ✓ White space
- ✓ Instructions
- ✓ Symbols

Assembler: lecture plan

- ✓ Assembler logic (basic)
- ✓ The Hack assembly language
- ✓ The assembly process: instructions
- ✓ The assembly process: symbols
- ➡ Developing an assembler
- Project 6 overview

Sub-tasks that need to be done

- Reading and parsing commands
- Converting mnemonics → code
- Handling symbols

Reading and Parsing Commands

No need to understand the *meaning* of anything

Reading and Parsing Commands

- Start reading a file with a given name

Reading and Parsing Commands

- Start reading a file with a given name
  - E.g. Constructor for a **Parser** object that accepts a string specifying a file name.
  - Need to know how to read text files

Reading and Parsing Commands

- Start reading a file with a given name

- Move to the next command in the file

Reading and Parsing Commands

- Start reading a file with a given name

- Move to the next command in the file

  - Are we finished? `boolean hasMoreCommands()`
  - Get the next command: `void advance()`
  - Need to read one line at a time
  - Need to skip whitespace including comments

Reading and Parsing Commands

- Start reading a file with a given name

- Move to the next command in the file

- Get the fields of the current command

Reading and Parsing Commands

- Start reading a file with a given name

- Move to the next command in the file

- Get the fields of the current command
  - Type of current command (A-Command, C-Command, or Label)

Reading and Parsing Commands

- Start reading a file with a given name

- Move to the next command in the file

- Get the fields of the current command
  - Type of current command (A-Command, C-Command, or Label)
  - Easy access to the fields:

```
D=M+1; JGT                @sum
```

D | M + 1 | J G T   s u m

Reading and Parsing Commands

- Start reading a file with a given name

- Move to the next command in the file

- Get the fields of the current command
  - Type of current command (A-Command, C-Command, or Label)
  - Easy access to the fields:

```
D=M+1; JGT                      @sum
```

D	M + 1	J G T	s u m

```
String dest();  String comp();  String jump();      String label();
```

Translating Mnemonic to Code: overview

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

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

Translating Mnemonic to Code: overview

No need to worry about how the mnemonic fields were obtained

Translating Mnemonic to Code: destination

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

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

dest	d1	d2	d3
null	0	0	0
M	0	0	1
D	0	1	0
MD	0	1	1
A	1	0	0
AM	1	0	1
AD	1	1	0
AMD	1	1	1

Translating Mnemonic to Code: jump

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

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

jump	j1	j2	j3
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

Translating Mnemonic to Code: computation

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

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

comp		c1	c2	c3	c4	c5	c6
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						

Recap: Parsing + Translating

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

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

```
// Assume that current command is
//      D = M+1; JGT

String c=parser.comp();  // "M+1"
String d=parser.dest();  // "D"
String j=parser.jump();  // "JGT"

String cc = Code.comp(c);  // "1110111"
String dd = Code.dest(d);  // "010"
String jj = Code.jump(j);  // "001"

String out = "111" + cc + dd + jj;
```

The Symbol Table

Symbol	Address
loop	73
sum	12

No need to worry about what these symbols mean

The Symbol Table

Symbol	Address
loop	73
sum	12

- Create an new empty table
- Add a (*symbol* , *address*) pair to the table
- Does the table contain a given symbol?
- What is the address associated with a given symbol?

Using the Symbol Table

- Create a new empty table
- Add all the pre-defined symbols to the table
- While reading the input, add labels and new variables to the table
- Whenever you see a "@*xxx*" command, where *xxx* is not a number, consult the table to replace the symbol *xxx* with its address.

Using the Symbol Table: adding symbols

- …
- …
- While reading the input, add labels and new variables to the table
  - **Labels:** when you see a "`(`*xxx*`)`" command, add the symbol *xxx* and the address of the next machine language command
    - Comment 1: this requires maintaining this running address
    - Comment 2: this may need to be done in a first pass
  - **Variables:** when you see an "`@`*xxx*" command, where *xxx* is not a number and not already in the table, add the symbol *xxx* and the next free address for variable allocation

Overall logic

- Initialization
  - Of Parser
  - Of Symbol Table
- First Pass: Read all commands, only paying attention to labels and updating the symbol table
- Restart reading and translating commands
- Main Loop:
  - Get the next Assembly Language Command and parse it
  - For A-commands: Translate symbols to binary addresses
  - For C-commands: get code for each part and put them together
  - Output the resulting machine language command

`Parser` module: proposed API

Routine	Arguments	Returns	Function
Constructor / initializer	Input file or stream	—	Opens the input file/stream and gets ready to parse it.
`hasMoreCommands`	—	boolean	Are there more lines in the input?
`advance`	—	—	• Reads the next command from the input, and makes it the current command. • Takes care of whitespace, if necessary. • Should be called only if `hasMoreCommands()` is true. • Initially there is no current command.
`commandType`	—	`A_COMMAND`, `C_COMMAND`, `L_COMMAND`	Returns the type of the current command: `A_COMMAND` for @*xxx* where *xxx* is either a symbol or a decimal number `C_COMMAND` for *dest* = *comp* ; *jump* `L_COMMAND` for (*xxx*) where *xxx* is a symbol.
`symbol`	—	string	• Returns the symbol or decimal *xxx* of the current command @*xxx* or (*xxx*). • Should be called only when `commandType()` is `A_COMMAND` or `L_COMMAND`.
`dest`	—	string	• Returns the *dest* mnemonic in the current *C*-command (8 possibilities). • Should be called only when `commandType()` is `C_COMMAND`.
`comp`	—	string	• Returns the *comp* mnemonic in the current *C*-command (28 possibilities). • Should be called only when `commandType()` is `C_COMMAND`.
`jump`	—	string	• Returns the jump mnemonic in the current *C*-command (8 possibilities). • Should be called only when `commandType()` is `C_COMMAND`.

`Code` module: proposed API

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

`SymbolTable` module: proposed API

Routine	Arguments	Returns	Function
Constructor	—	—	Creates a new empty symbol table.
`addEntry`	symbol (string), address (int)	—	Adds the pair (symbol, address) to the table.
`contains`	symbol (string)	boolean	Does the symbol table contain the given symbol?
`getAddress`	symbol (string)	integer	Returns the address associated with the symbol.

Assembler: lecture plan

- ✓ The assembly process
- ✓ The Hack assembly language
- ✓ The assembly process: instructions
- ✓ The assembly process: symbols
- ✓ Developing an assembler
- ➡ Project 6 overview

Developing a Hack Assembler

Contract

- Develop an *assembler* that translates Hack assembly programs into executable Hack binary code
- The source program is supplied in a text file named `Xxx.asm`
- The generated code is written into a text file named `Xxx.hack`
- Assumption: `Xxx.asm` is error-free

Usage

```
prompt> java HackAssembler Xxx.asm
```

This command should create a new `Xxx.hack` file that can be executed as-is on the Hack computer.

Proposed design

The assembler can be implemented in any high-level language

Proposed software design

- `Parser`: unpacks each instruction into its underlying fields
- `Code`: translates each field into its corresponding binary value
- `SymbolTable`: manages the symbol table
- `Main`: initializes I/O files and drives the process.

Proposed Implementation

Staged development

- Develop a basic assembler that can translate assembly programs without symbols
- Develop an ability to handle symbols
- Morph the basic assembler into an assembler that can translate any assembly program

Supplied test programs

```
Add.asm
Max.asm         MaxL.asm
Rectangle.asm   RectangleL.asm
Pong.asm        PongL.asm
```

Test program: `Add`

Add.asm

```
// Computes RAM[0] = 2 + 3

@2
D=A
@3
D=D+A
@0
M=D
```

Basic test of handling:

- White space
- Instructions

Test program: `Max`

Max.asm

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

   @R0
   D=M            // D = RAM[0]
   @R1
   D=D-M          // D = RAM[0] - RAM[1]
   @OUTPUT_RAM0
   D;JGT          // if D>0 goto output R

   // Output RAM[1]
   @R1
   D=M
   @R2
   M=D            // RAM[2] = RAM[1]
   @END
   0;JMP

(OUTPUT_RAM0)
   @R0
   D=M
   @R2
   M=D            // RAM[2] = RAM[0]

(END)
   @END
   0;JMP
```

with labels

MaxL.asm

```
// Symbol-less version

   @0
   D=M            // D = RAM[0]
   @1
   D=D-M          // D = RAM[0] - RAM[1]
   @12
   D;JGT          // if D>0 goto output RAM[0]

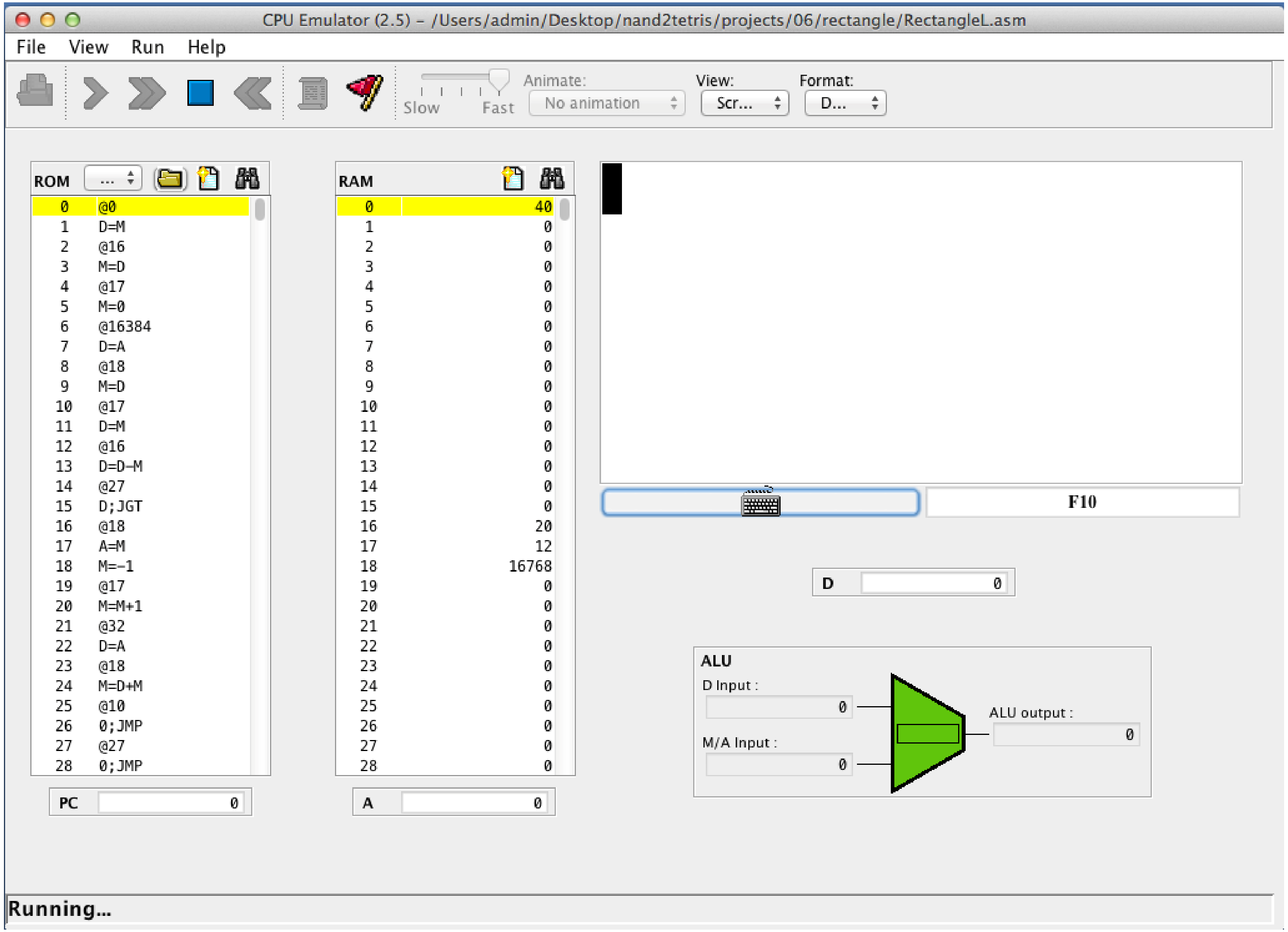
   // Output RAM[1]
   @1
   D=M
   @2
   M=D            // RAM[2] = RAM[1]
   @16
   0;JMP

   @0
   D=M
   @2
   M=D            // RAM[2] = RAM[0]

   @16
   0;JMP
```

without labels

Test program: `Rectangle`



Test program: `Rectangle`

Rectangle.asm

```
// Rectangle.asm

   @R0
   D=M
   @n
   M=D  // n = RAM[0]

   @i
   M=0  // i = 0

   @SCREEN
   D=A
   @address
   M=D  // base address of the Hack scre

(LOOP)
   @i
   D=M
   @n
   D=D-M
   @END
   D;JGT  // if i>n goto END
   ...
```

with symbols

RectangleL.asm

```
// Symbol-less version

   @0
   D=M
   @16
   M=D   // n = RAM[0]

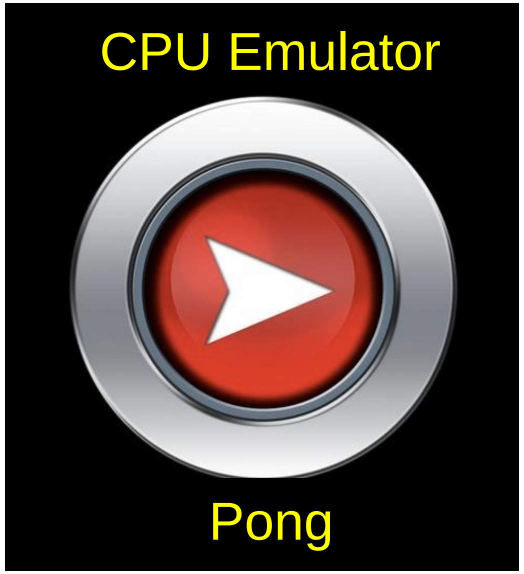
   @17
   M=0   // i = 0

   @16384
   D=A
   @18
   M=D   // base address of the Hack screen

   @17
   D=M
   @16
   D=D-M
   @27
   D;JGT  // if i>n goto END
   ...
```

without symbols

Test program: Pong



Test program: Pong

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
0;JMP
@R15
M=D
...
```

Observations:

- Source code originally written in the Jack language
- The Hack code was generated by the Jack compiler and the Hack assembler
- The resulting code is 28,374 instructions long

  (includes the Jack OS)

Machine generated code:

- No white space
- "Strange" addresses
- "Strange" labels
- "Strange" pre-defined symbols

Testing options

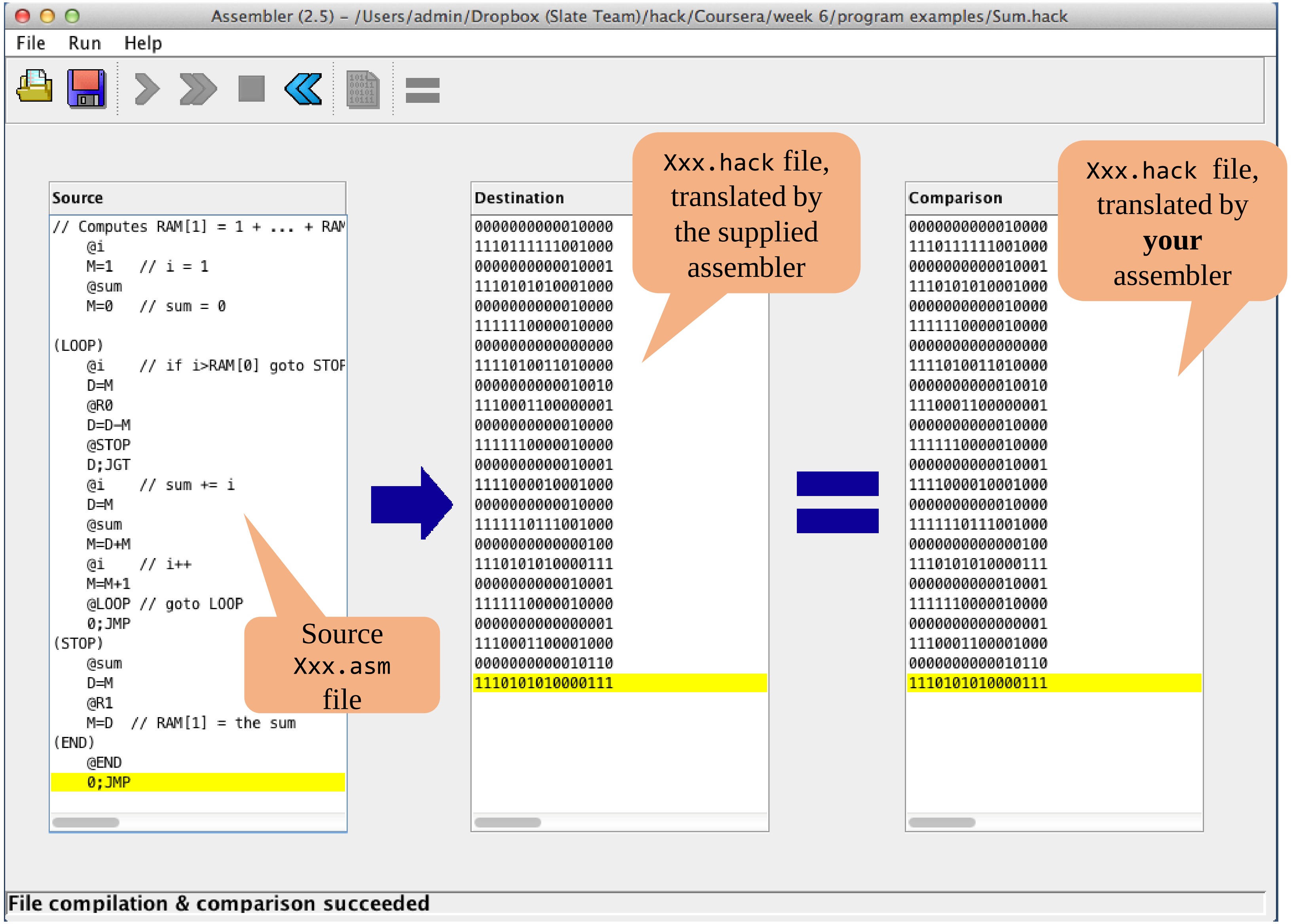
Use your assembler to translate `Xxx.asm`,
generating the executable file `Xxx.hack`

Hardware simulator:
load `Xxx.hack` into the Hack `Computer` chip, then execute it

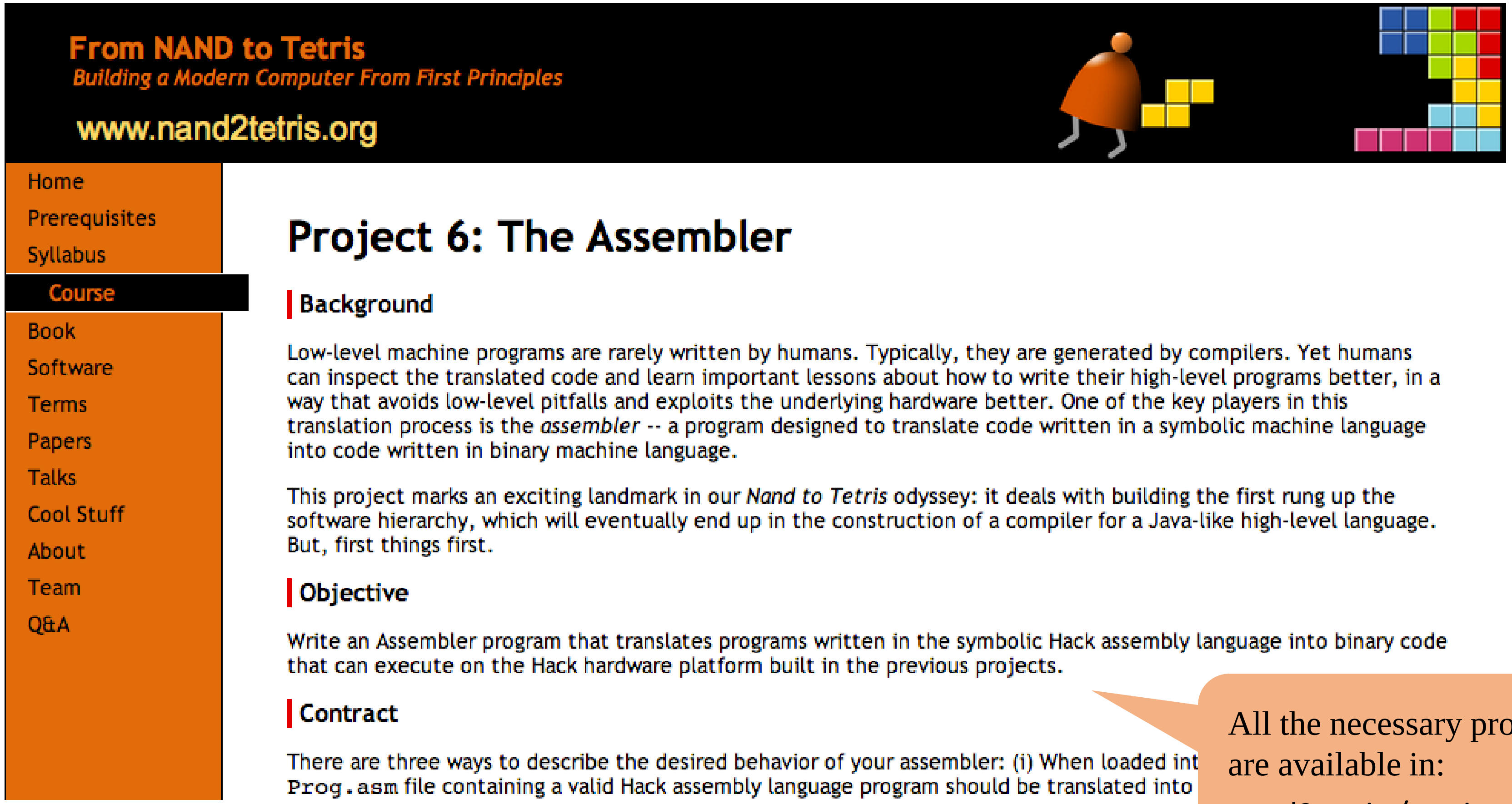
CPU Emulator:
load `Xxx.hack` into the supplied `CPUEmulator`, then execute it

Assembler:
use the supplied `Assembler` to translate `Xxx.asm`;
Compare the resulting code to the binary code generated by *your* assembler.

Testing your assembler using the supplied assembler



Project 6 Resources



From NAND to Tetris

Building a Modern Computer From First Principles

www.nand2tetris.org

- Home
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- Syllabus
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Project 6: The Assembler

Background

Low-level machine programs are rarely written by humans. Typically, they are generated by compilers. Yet humans can inspect the translated code and learn important lessons about how to write their high-level programs better, in a way that avoids low-level pitfalls and exploits the underlying hardware better. One of the key players in this translation process is the *assembler* -- a program designed to translate code written in a symbolic machine language into code written in binary machine language.

This project marks an exciting landmark in our *Nand to Tetris* odyssey: it deals with building the first rung up the software hierarchy, which will eventually end up in the construction of a compiler for a Java-like high-level language. But, first things first.

Objective

Write an Assembler program that translates programs written in the symbolic Hack assembly language into binary code that can execute on the Hack hardware platform built in the previous projects.

Contract

There are three ways to describe the desired behavior of your assembler: (i) When loaded int `Prog.asm` file containing a valid Hack assembly language program should be translated into

All the necessary project 6 files are available in:

nand2tetris / projects / 06

More resources

- Supplied Assembler
- Supplied CPU emulator
- Assembler Tutorial
- Proposed Assembler API
- nand2tetris Q&A forum

All available in: `www.nand2tetris.org`

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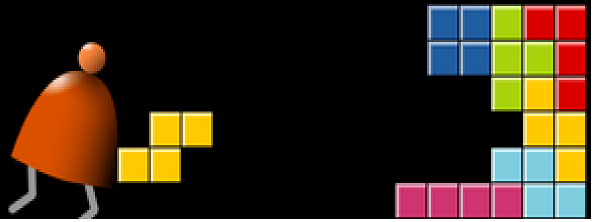

Chapter 6

Assembler

These slides support chapter 6 of the book

<u>The Elements of Computing Systems</u>

By Noam Nisan and Shimon Schocken

MIT Press