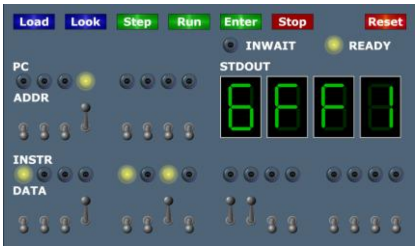
5. The TOY Machine



What is TOY?

An imaginary machine similar to:

- Ancient computers.
- Today's microprocessors.

Why Study TOY?

Machine language programming.

- How do Java programs relate to computer?
- Key to understanding Java references.
- Still some situations today where it is really necessary.

multimedia, computer games, scientific computing, SSE, AVX

Computer architecture.

- How does it work?
- How is a computer put together?

TOY machine. Optimized for simplicity, not cost or performance.

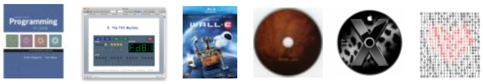
Data and Programs Are Encoded in Binary

Each bit consists of two states:

- 1 or 0; true or false.
- Switch is on or off; wire has high voltage or low voltage.

Everything stored in a computer is a sequence of bits.

- Data and programs.
- Text, documents, pictures, sounds, movies, executables, …



Binary Encoding

How to represent integers?

- Use binary encoding.
- Ex: $6375_{10} = 0001100011100111_2$

Dec	Bin
0	0000
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111

Dec	Bin
8	1000
9	1001
10	1010
11	1011
12	1100
13	1101
14	1110
15	1111

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	1	0	0	0	1	1	1	0	0	1	1	1

$$6375_{10} = +2^{12} +2^{11} +2^{7} +2^{6} +2^{5} +2^{2} +2^{1} +2^{0}$$
$$= 4096 +2048 +128 +64 +32 +4 +2 +1$$

Hexadecimal Encoding

How to represent integers?

- Use hexadecimal encoding.
- Ex: $6375_{10} = 0001100011100111_2$
  $= 18E7_{16}$

binary code, 4 bits at a time

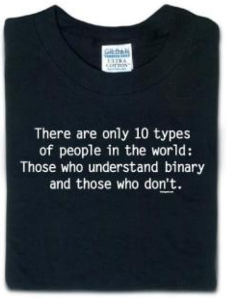
Dec	Bin	Hex
0	0000	0
1	0001	1
2	0010	2
3	0011	3
4	0100	4
5	0101	5
6	0110	6
7	0111	7

Dec	Bin	Hex
8	1000	8
9	1001	9
10	1010	A
11	1011	B
12	1100	C
13	1101	D
14	1110	E
15	1111	F

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	1	0	0	0	1	1	1	0	0	1	1	1
1				8				E				7			

$$6375_{10} = 1 \times 16^3 + 8 \times 16^2 + 14 \times 16^1 + 7 \times 16^0$$
$$= 4096 + 2048 + 224 + 7$$

Binary People



http://www.thinkgeek.com/tshirts-apparel/unisex/frustrations/5aa9

Inside the TOY Box

Switches. Input data and programs.

Lights. View data.

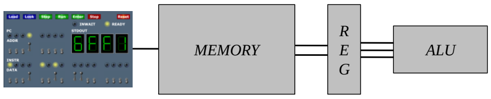
Memory.
- Stores data and programs.
- 256 16-bit "words."
- Special word for stdin / stdout.

Program counter (PC).
- An extra 8-bit register.
- Next instruction to be executed.

Registers.
- Fastest form of storage.
- Scratch space during computation.
- 16 16-bit registers.
- Register 0 is always 0.

Arithmetic-logic unit (ALU). Manipulate data stored in registers.

Standard input, standard output. Interact with outside world.



TOY Machine "Core" Dump

A core dump is the contents of machine at a particular place and time.
- Record of what program has done.
- Completely determines what machine will do.

Registers

R0	R1	R2	R3
0000	0000	0000	0000
R4	R5	R6	R7
0000	0000	0000	0000
R8	R9	RA	RB
0000	0000	0000	0000
RC	RD	RE	RF
0000	0000	0000	0000

pc

10

index of next instruction

data

program

variables

Memory

00:	0008	0005	0000	0000	0000	0000	0000	0000
08:	0000	0000	0000	0000	0000	0000	0000	0000
10:	8A00	8B01	1CAB	9C02	0000	0000	0000	0000
18:	0000	0000	0000	0000	0000	0000	0000	0000
20:	0000	0000	0000	0000	0000	0000	0000	0000
28:	0000	0000	0000	0000	0000	0000	0000	0000
.								
.								
E8:	0000	0000	0000	0000	0000	0000	0000	0000
F0:	0000	0000	0000	0000	0000	0000	0000	0000
F8:	0000	0000	0000	0000	0000	0000	0000	0000

A Sample Program

A sample program. Adds 0008 + 0005 = 000D.

RA	RB	RC
0000	0000	0000

Registers

pc
10

Program counter

TOY memory (program and data)

comments

```
00: 0008   8
01: 0005   5
02: 0000   0

10: 8A00   RA ← mem[00]
11: 8B01   RB ← mem[01]
12: 1CAB   RC ← RA + RB
13: 9C02   mem[02] ← RC
14: 0000   halt
```

add.toy

A Sample Program

Program counter. The pc is initially 10, so the machine interprets 8A00 as an instruction.

RA	RB	RC
0000	0000	0000

Registers

pc
10

Program counter

index of next instruction to execute

```
00: 0008   8
01: 0005   5
02: 0000   0

10: 8A00   RA ← mem[00]
11: 8B01   RB ← mem[01]
12: 1CAB   RC ← RA + RB
13: 9C02   mem[02] ← RC
14: 0000   halt
```

add.toy

Load

Load. [opcode 8]
- Loads the contents of some memory location into a register.
- 8A00 means load the contents of memory cell 00 into register A.

RA	RB	RC
0000	0000	0000

Registers

pc
10

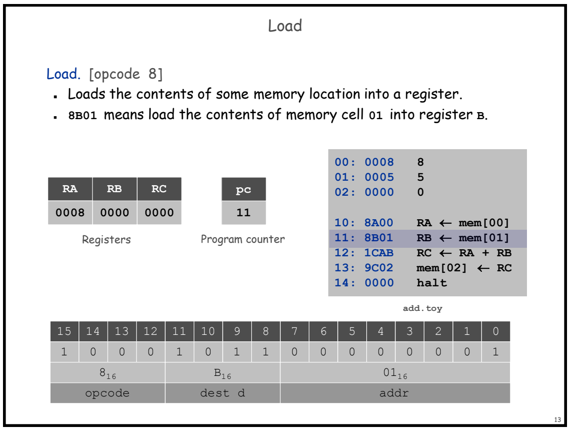
Program counter

```
00: 0008   8
01: 0005   5
02: 0000   0

10: 8A00   RA ← mem[00]
11: 8B01   RB ← mem[01]
12: 1CAB   RC ← RA + RB
13: 9C02   mem[02] ← RC
14: 0000   halt
```

add.toy

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
8_{16}				A_{16}				00_{16}							
opcode				dest d				addr							



Load

Load. [opcode 8]
- Loads the contents of some memory location into a register.
- 8B01 means load the contents of memory cell 01 into register B.

RA	RB	RC
0008	0000	0000

Registers

pc
11

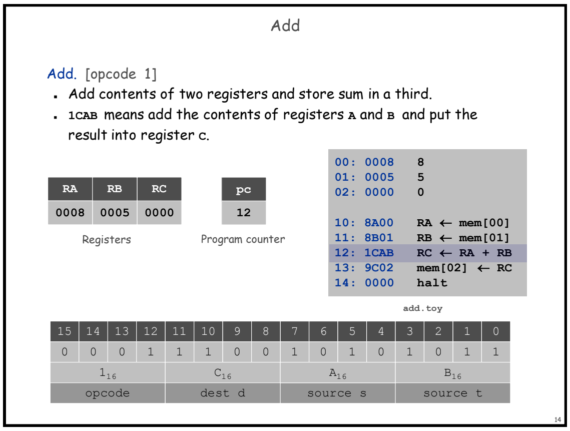
Program counter

```
00: 0008   8
01: 0005   5
02: 0000   0

10: 8A00   RA ← mem[00]
11: 8B01   RB ← mem[01]
12: 1CAB   RC ← RA + RB
13: 9C02   mem[02] ← RC
14: 0000   halt
```

add.toy

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	0	1	0	1	1	0	0	0	0	0	0	0	1
8_{16}				B_{16}				01_{16}							
opcode				dest d				addr							



Add

Add. [opcode 1]
- Add contents of two registers and store sum in a third.
- 1CAB means add the contents of registers A and B and put the result into register C.

RA	RB	RC
0008	0005	0000

Registers

pc
12

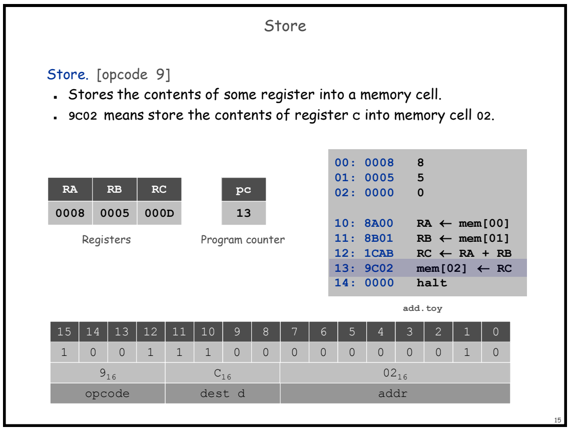
Program counter

```
00: 0008   8
01: 0005   5
02: 0000   0

10: 8A00   RA ← mem[00]
11: 8B01   RB ← mem[01]
12: 1CAB   RC ← RA + RB
13: 9C02   mem[02] ← RC
14: 0000   halt
```

add.toy

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	1	1	0	0	1	0	1	0	1	0	1	1
1_{16}				C_{16}				A_{16}				B_{16}			
opcode				dest d				source s				source t			



Store

Store. [opcode 9]
- Stores the contents of some register into a memory cell.
- 9C02 means store the contents of register C into memory cell 02.

RA	RB	RC
0008	0005	000D

Registers

pc
13

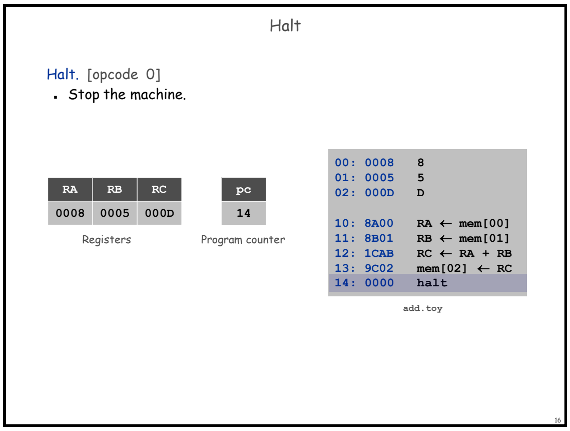
Program counter

```
00: 0008   8
01: 0005   5
02: 0000   0

10: 8A00   RA ← mem[00]
11: 8B01   RB ← mem[01]
12: 1CAB   RC ← RA + RB
13: 9C02   mem[02] ← RC
14: 0000   halt
```

add.toy

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	1	1	1	0	0	0	0	0	0	0	0	1	0
9_{16}				C_{16}				02_{16}							
opcode				dest d				addr							



Halt

Halt. [opcode 0]
- Stop the machine.

RA	RB	RC
0008	0005	000D

Registers

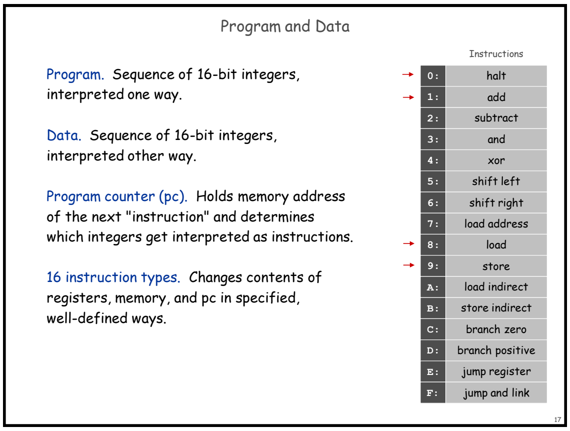
pc
14

Program counter

```
00: 0008   8
01: 0005   5
02: 000D   D

10: 8A00   RA ← mem[00]
11: 8B01   RB ← mem[01]
12: 1CAB   RC ← RA + RB
13: 9C02   mem[02] ← RC
14: 0000   halt
```

add.toy



Program and Data

Program. Sequence of 16-bit integers, interpreted one way.

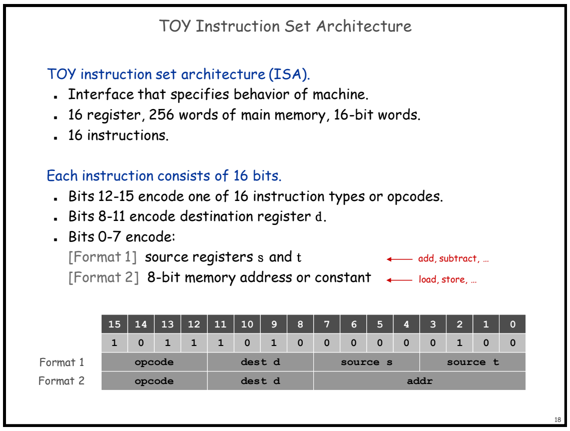
Data. Sequence of 16-bit integers, interpreted other way.

Program counter (pc). Holds memory address of the next "instruction" and determines which integers get interpreted as instructions.

16 instruction types. Changes contents of registers, memory, and pc in specified, well-defined ways.

Instructions

→	0:	halt
→	1:	add
	2:	subtract
	3:	and
	4:	xor
	5:	shift left
	6:	shift right
	7:	load address
→	8:	load
→	9:	store
	A:	load indirect
	B:	store indirect
	C:	branch zero
	D:	branch positive
	E:	jump register
	F:	jump and link



TOY Instruction Set Architecture

TOY instruction set architecture (ISA).
- Interface that specifies behavior of machine.
- 16 register, 256 words of main memory, 16-bit words.
- 16 instructions.

Each instruction consists of 16 bits.
- Bits 12-15 encode one of 16 instruction types or opcodes.
- Bits 8-11 encode destination register d.
- Bits 0-7 encode:

  [Format 1] source registers s and t ← add, subtract, ...

  [Format 2] 8-bit memory address or constant ← load, store, ...

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
	1	0	1	1	1	0	1	0	0	0	0	0	0	1	0	0
Format 1	opcode				dest d				source s				source t			
Format 2	opcode				dest d				addr							

Interfacing with the TOY Machine

To enter a program or data:

- Set 8 memory address switches.
- Set 16 data switches.
- Press `Load`: data written into addressed word of memory.

To view the results of a program:

- Set 8 memory address switches.
- Press `Look`: contents of addressed word appears in lights.

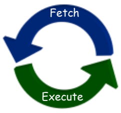
Interfacing with the TOY Machine

To execute the program:

- Set 8 memory address switches to address of first instruction.
- Press `Look` to set `pc` to first instruction.
- Press `Run` to repeat fetch-execute cycle until halt opcode.

Fetch-execute cycle.

- Fetch: get instruction from memory.
- Execute: update `pc`, move data to or from memory and registers, perform calculations.



Flow Control

Flow control.

- To harness the power of TOY, need loops and conditionals.
- Manipulate `pc` to control program flow.

```
if (boolean expression) {
    statement 1;
    statement 2;
}
```

```
while (boolean expression) {
    statement 1;
    statement 2;
}
```

Branch if zero. [opcode C]

- Changes `pc` depending on whether value of some register is zero.
- Used to implement: `for`, `while`, `if-else`.

Branch if positive. [opcode D]

- Changes `pc` depending on whether value of some register is positive.
- Used to implement: `for`, `while`, `if-else`.

An Example: Multiplication

Multiply. Given integers `a` and `b`, compute `c` = `a` × `b`.

TOY multiplication. No direct support in TOY hardware.

Brute-force multiplication algorithm:

- Initialize `c` to `0`.
- Add `b` to `c`, `a` times.

```
int a = 3;
int b = 9;
int c = 0;

while (a != 0) {
   c = c + b;
   a = a - 1;
}
```

brute force multiply in Java

Issues ignored. Slow, overflow, negative numbers.

Multiply

```
     0A: 0003   3  ← inputs
     0B: 0009   9
     0C: 0000   0  ← output

     0D: 0000   0  ← constants
     0E: 0001   1

     10: 8A0A   RA ← mem[0A]               a = 3;
     11: 8B0B   RB ← mem[0B]               b = 9;
     12: 8C0D   RC ← mem[0D]               c = 0;

     13: 810E   R1 ← mem[0E]               always 1

     14: CA18   if (RA == 0) pc ← 18       while (a != 0) {
loop 15: 1CCB   RC ← RC + RB                  c = c + b;
     16: 2AA1   RA ← RA - R1                  a = a - 1;
     17: C014   pc ← 14                    }

     18: 9C0C   mem[0C] ← RC
     19: 0000   halt
```

multiply.toy

Step-By-Step Trace

```
                                     R1     RA     RB     RC
10: 8A0A  RA ← mem[0A]                      0003
11: 8B0B  RB ← mem[0B]                             0009
12: 8C0D  RC ← mem[0D]                                    0000
13: 810E  R1 ← mem[0E]               0001
14: CA18  if (RA == 0) pc ← 18
15: 1CCB  RC ← RC + RB                                    0009
16: 2AA1  RA ← RA - R1                      0002
17: C014  pc ← 14
14: CA18  if (RA == 0) pc ← 18
15: 1CCB  RC ← RC + RB                                    0012
16: 2AA1  RA ← RA - R1                      0001
17: C014  pc ← 14
14: CA18  if (RA == 0) pc ← 18
15: 1CCB  RC ← RC + RB                                    001B
16: 2AA1  RA ← RA - R1                      0000
17: C014  pc ← 14
14: CA18  if (RA == 0) pc ← 18
18: 9C0C  mem[0C] ← RC
19: 0000  halt
```

multiply.toy

A Little History

Electronic Numerical Integrator and Calculator (ENIAC).

- First widely known general purpose electronic computer.
- Conditional jumps, programmable.
- Programming: change switches and cable connections.
- Data: enter numbers using punch cards.

30 tons
30 x 50 x 8.5 ft
17,468 vacuum tubes
300 multiply/sec
15,000 watts

John Mauchly (left) and J. Presper Eckert (right)
http://cs.swau.edu/~durkin/articles/history_computing.html

ENIAC, Ester Gerston (left), Gloria Gordon (right)
US Army photo: http://ftp.arl.mil/ftp/historic-computers

Basic Characteristics of TOY Machine

TOY is a general-purpose computer.

- Sufficient power to perform any computation.
- Limited only by amount of memory and time.

Stored-program computer. [von Neumann memo, 1944]

- Data and program encoded in binary.
- Data and program stored in same memory.
- Can change program without rewiring.

Outgrowth of Alan Turing's work.

All modern computers are general-purpose computers and have same (von Neumann) architecture.

John von Neumann

Maurice Wilkes (left)
EDSAC (right)

TOY Reference Card

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Format 1	opcode				dest d				source s				source t			
Format 2	opcode				dest d				addr							

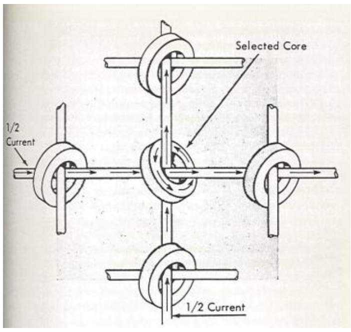
#	Operation	Fmt	Pseudocode
0:	halt	1	exit(0)
1:	add	1	R[d] ← R[s] + R[t]
2:	subtract	1	R[d] ← R[s] - R[t]
3:	and	1	R[d] ← R[s] & R[t]
4:	xor	1	R[d] ← R[s] ^ R[t]
5:	shift left	1	R[d] ← R[s] << R[t]
6:	shift right	1	R[d] ← R[s] >> R[t]
7:	load addr	2	R[d] ← addr
8:	load	2	R[d] ← mem[addr]
9:	store	2	mem[addr] ← R[d]
A:	load indirect	1	R[d] ← mem[R[t]]
B:	store indirect	1	mem[R[t]] ← R[d]
C:	branch zero	2	if (R[d] == 0) pc ← addr
D:	branch positive	2	if (R[d] > 0) pc ← addr
E:	jump register	2	pc ← R[d]
F:	jump and link	2	R[d] ← pc; pc ← addr

Register 0 always reads 0.
Loads from mem[FF] from stdin.
Stores to mem[FF] to stdout.

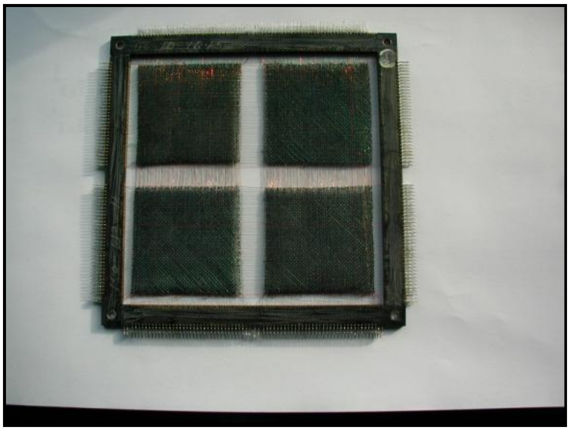
16-bit registers.
16-bit memory.
8-bit program counter.

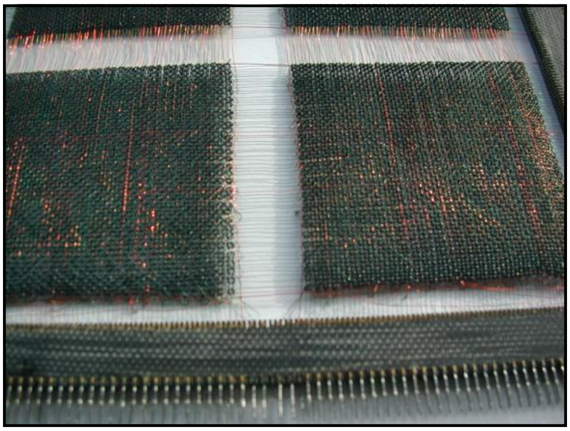
5: Supplemental Notes

Why do They Call it "Core"?



http://www.columbia.edu/acis/history/core.html





An Efficient Multiplication Algorithm

Inefficient multiply.

- Brute force multiplication algorithm loops a times.
- In worst case, 65,535 additions!

"Grade-school" multiplication.

- Always 16 additions to multiply 16-bit integers.

```
Decimal          1 2 3 4             Binary        1 0 1 1
               * 1 5 1 2                         * 1 1 0 1
                 2 4 6 8                           1 0 1 1
               1 2 3 4                           0 0 0 0
             6 1 7 0                           1 0 1 1
           1 2 3 4                           1 0 1 1
         0 1 8 6 5 8 0 8                     1 0 0 0 1 1 1 1
```

Binary Multiplication

Grade school binary multiplication algorithm to compute c = a × b.

- Initialize c = 0.
- Loop over i bits of b. ⇐ b_i = ith bit of b
  - if b_i = 0, do nothing
  - if b_i = 1, shift a left i bits and add to c

```
        1 0 1 1   a
      * 1 1 0 1   b
        1 0 1 1   a << 0
      0 0 0 0
    1 0 1 1       a << 2
  1 0 1 1         a << 3
1 0 0 0 1 1 1 1   c
```

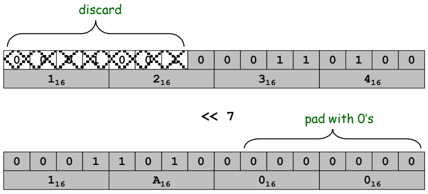
Implement with built-in TOY shift instructions.

```
int c = 0;
for (int i = 15; i >= 0; i--)
   if (((b >> i) & 1) == 1)      ⇐ b_i = ith bit of b
      c = c + (a << i);
```

Shift Left

Shift left. (opcode 5)

- Move bits to the left, padding with zeros as needed.
- 1234_{16} << 7_{16} = $1A00_{16}$



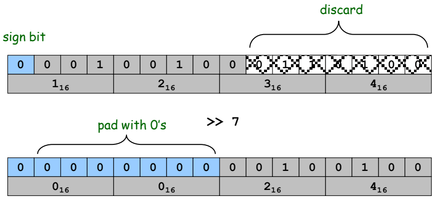
0	0	0	1	0	0	1	0	0	0	1	1	0	1	0	0
1_{16}				2_{16}				3_{16}				4_{16}			

0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0
1_{16}				A_{16}				0_{16}				0_{16}			

Shift Right

Shift right. (opcode 6)

- Move bits to the right, padding with sign bit as needed.
- 1234_{16} >> 7_{16} = 0024_{16}



0	0	0	1	0	0	1	0	0	0	1	1	0	1	0	0
1_{16}				2_{16}				3_{16}				4_{16}			

0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0
0_{16}				0_{16}				2_{16}				4_{16}			

Bitwise AND

Logical AND. (opcode B)

- Logic operations are BITWISE.
- 0024_{16} & 0001_{16} = 0000_{16}

x	y	&
0	0	0
0	1	0
1	0	0
1	1	1

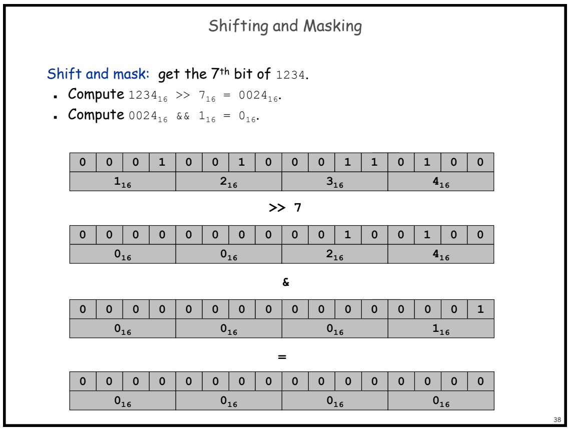
0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0
0_{16}				0_{16}				2_{16}				4_{16}			

&

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0_{16}				0_{16}				0_{16}				1_{16}			

=

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0_{16}				0_{16}				0_{16}				0_{16}			



Shifting and Masking

Shift and mask: get the 7th bit of 1234.

- Compute 1234_{16} >> 7_{16} = 0024_{16}.
- Compute 0024_{16} && 1_{16} = 0_{16}.

0	0	0	1	0	0	1	0	0	0	1	1	0	1	0	0
1_{16}				2_{16}				3_{16}				4_{16}			

>> 7

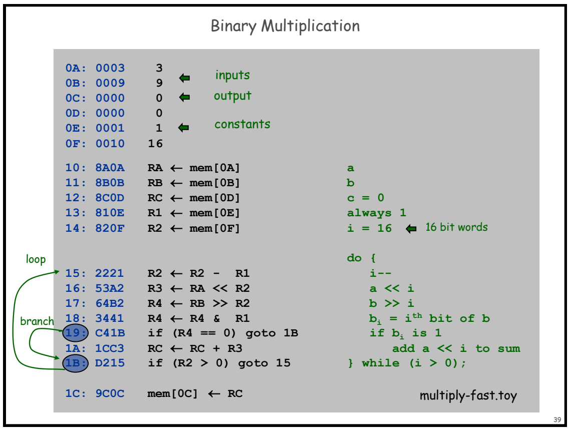
0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0
0_{16}				0_{16}				2_{16}				4_{16}			

&

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0_{16}				0_{16}				0_{16}				1_{16}			

=

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0_{16}				0_{16}				0_{16}				0_{16}			



Binary Multiplication

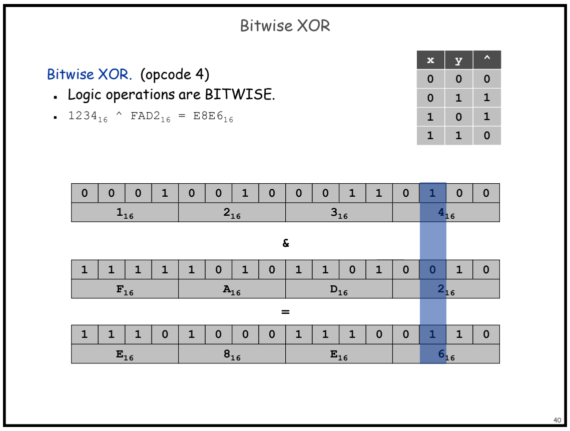
```
0A: 0003     3   ⇦  inputs
0B: 0009     9
0C: 0000     0   ⇦  output
0D: 0000     0
0E: 0001     1   ⇦  constants
0F: 0010    16

10: 8A0A    RA ← mem[0A]          a
11: 8B0B    RB ← mem[0B]          b
12: 8C0D    RC ← mem[0D]          c = 0
13: 810E    R1 ← mem[0E]          always 1
14: 820F    R2 ← mem[0F]          i = 16  ⇦ 16 bit words

                                  do {
15: 2221    R2 ← R2 -  R1           i--
16: 53A2    R3 ← RA << R2           a << i
17: 64B2    R4 ← RB >> R2           b >> i
18: 3441    R4 ← R4 &  R1           b_i = i^th bit of b
19: C41B    if (R4 == 0) goto 1B    if b_i is 1
1A: 1CC3    RC ← RC + R3              add a << i to sum
1B: D215    if (R2 > 0) goto 15   } while (i > 0);

1C: 9C0C    mem[0C] ← RC
```

multiply-fast.toy



Bitwise XOR

Bitwise XOR. (opcode 4)

- Logic operations are BITWISE.
- 1234_{16} ^ $FAD2_{16}$ = $E8E6_{16}$

x	y	^
0	0	0
0	1	1
1	0	1
1	1	0

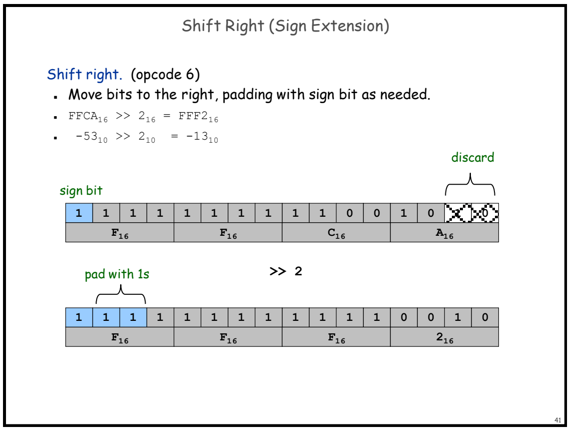
0	0	0	1	0	0	1	0	0	0	1	1	0	1	0	0
1_{16}				2_{16}				3_{16}				4_{16}			

&

1	1	1	1	1	0	1	0	1	1	0	1	0	0	1	0
F_{16}				A_{16}				D_{16}				2_{16}			

=

1	1	1	0	1	0	0	0	1	1	1	0	0	1	1	0
E_{16}				8_{16}				E_{16}				6_{16}			



Shift Right (Sign Extension)

Shift right. (opcode 6)

- Move bits to the right, padding with sign bit as needed.
- $FFCA_{16}$ >> 2_{16} = $FFF2_{16}$
- -53_{10} >> 2_{10} = -13_{10}

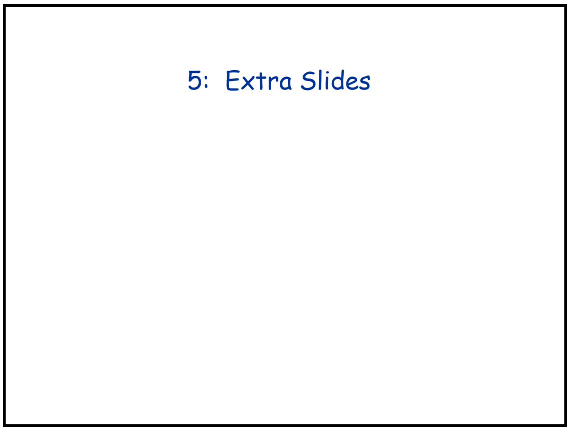
discard
sign bit

1	1	1	1	1	1	1	1	1	1	0	0	1	0	1	0
F_{16}				F_{16}				C_{16}				A_{16}			

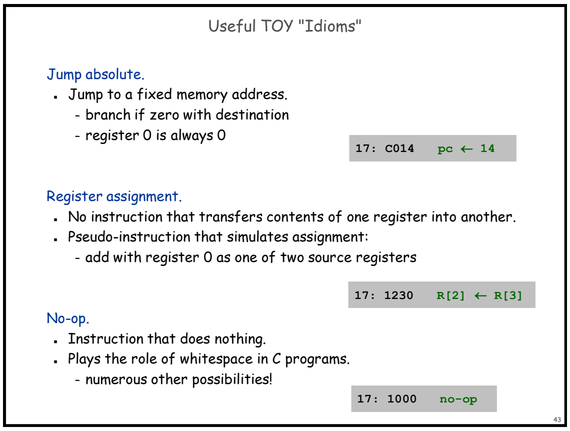
>> 2

pad with 1s

1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0
F_{16}				F_{16}				F_{16}				2_{16}			



5: Extra Slides



Useful TOY "Idioms"

Jump absolute.

- Jump to a fixed memory address.
  - branch if zero with destination
  - register 0 is always 0

```
17: C014    pc ← 14
```

Register assignment.

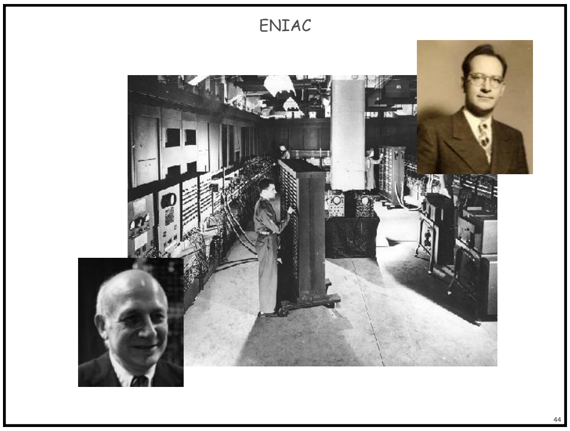
- No instruction that transfers contents of one register into another.
- Pseudo-instruction that simulates assignment:
  - add with register 0 as one of two source registers

```
17: 1230    R[2] ← R[3]
```

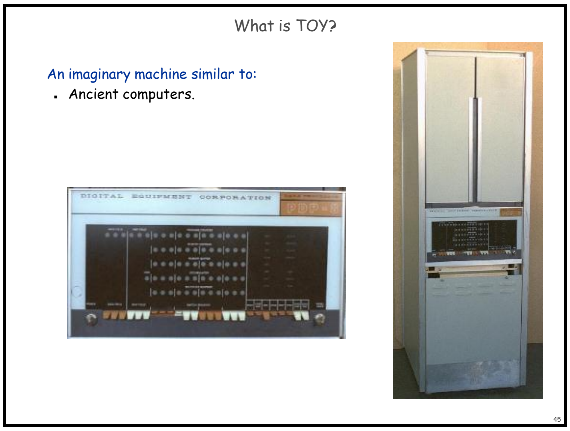
No-op.

- Instruction that does nothing.
- Plays the role of whitespace in C programs.
  - numerous other possibilities!

```
17: 1000    no-op
```



ENIAC



What is TOY?

An imaginary machine similar to:

- Ancient computers.