CS 126 Lecture A1:
TOY Machine

Outline

- **Introduction**
- Toy machine
- Machine language instructions
- Example machine language programs
- Conclusions

Brief History Leading to the Dominance of von Neumann Architecture

- 1940s, Atanasoff, Iowa State, first **special-purpose** electronic computer, binary representation of numbers
- ~1946, ENIAC, Eckert and Mauchly, UPenn, first general-purpose electronic computer
  - 100 ft long, 8.5 ft high, several ft wide, 18000 vacuum tubes
  - conditional jumps, **programmable**
  - code: setting switches, data: punch cards
  - Used to compute artillery firing tables
- 1944, von Neumann, visited ENIAC, the **“von Neumann Memo”**, concept of a “stored-program” computer
- 1949, Wilkes, EDSAC, first **stored-program** computer
- 1946, von Neumann, Goldstine, Burks, IAS machine, Princeton, the report pioneered most modern computer architecture concepts

Why Study Machine Language Programming Today

- Learn how computers really work
- There are still (a few) situations where machine language programming is necessary
- The first step towards understanding how to build better computers

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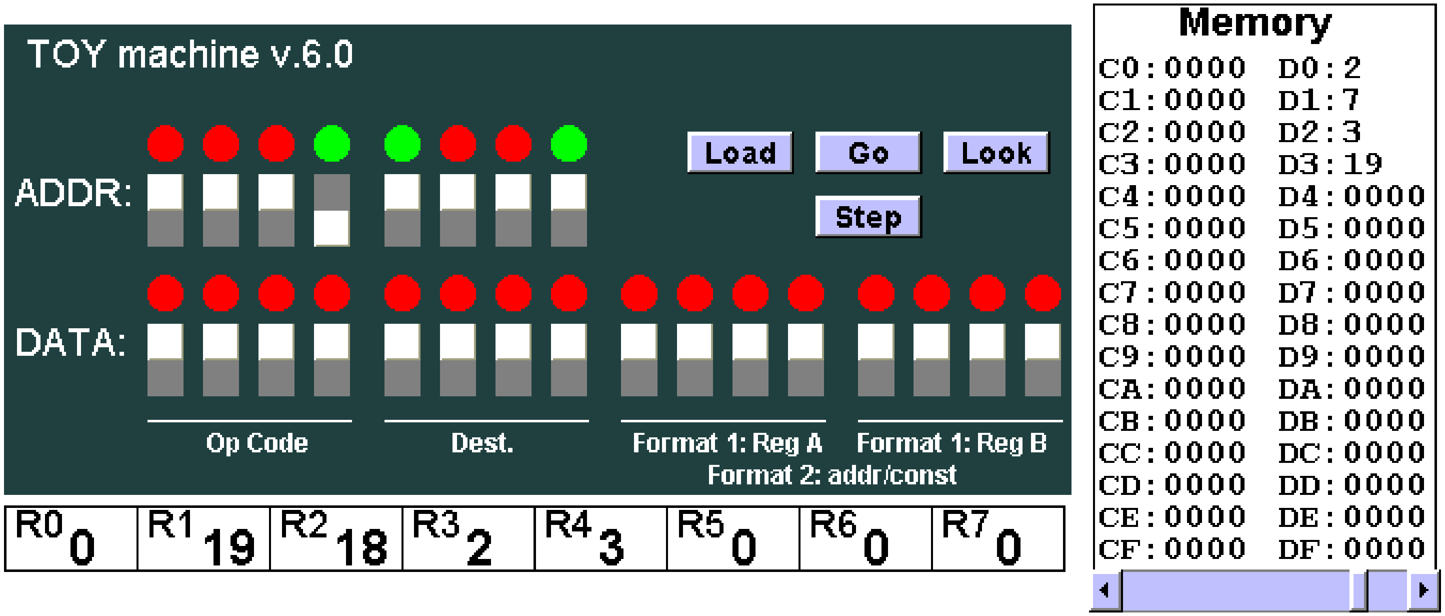
Toy Machine

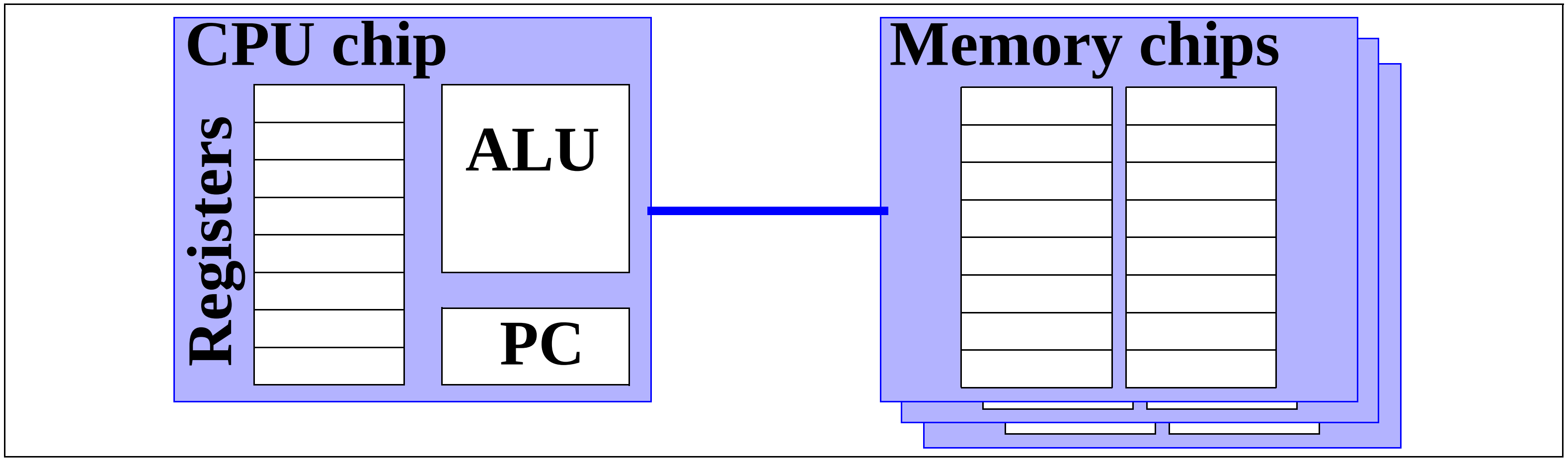


R0	R1	R2	R3	R4	R5	R6	R7
0	19	18	2	3	0	0	0

```
C0:0000  D0:2
C1:0000  D1:7
C2:0000  D2:3
C3:0000  D3:19
C4:0000  D4:0000
C5:0000  D5:0000
C6:0000  D6:0000
C7:0000  D7:0000
C8:0000  D8:0000
C9:0000  D9:0000
CA:0000  DA:0000
CB:0000  DB:0000
CC:0000  DC:0000
CD:0000  DD:0000
CE:0000  DE:0000
CF:0000  DF:0000
```

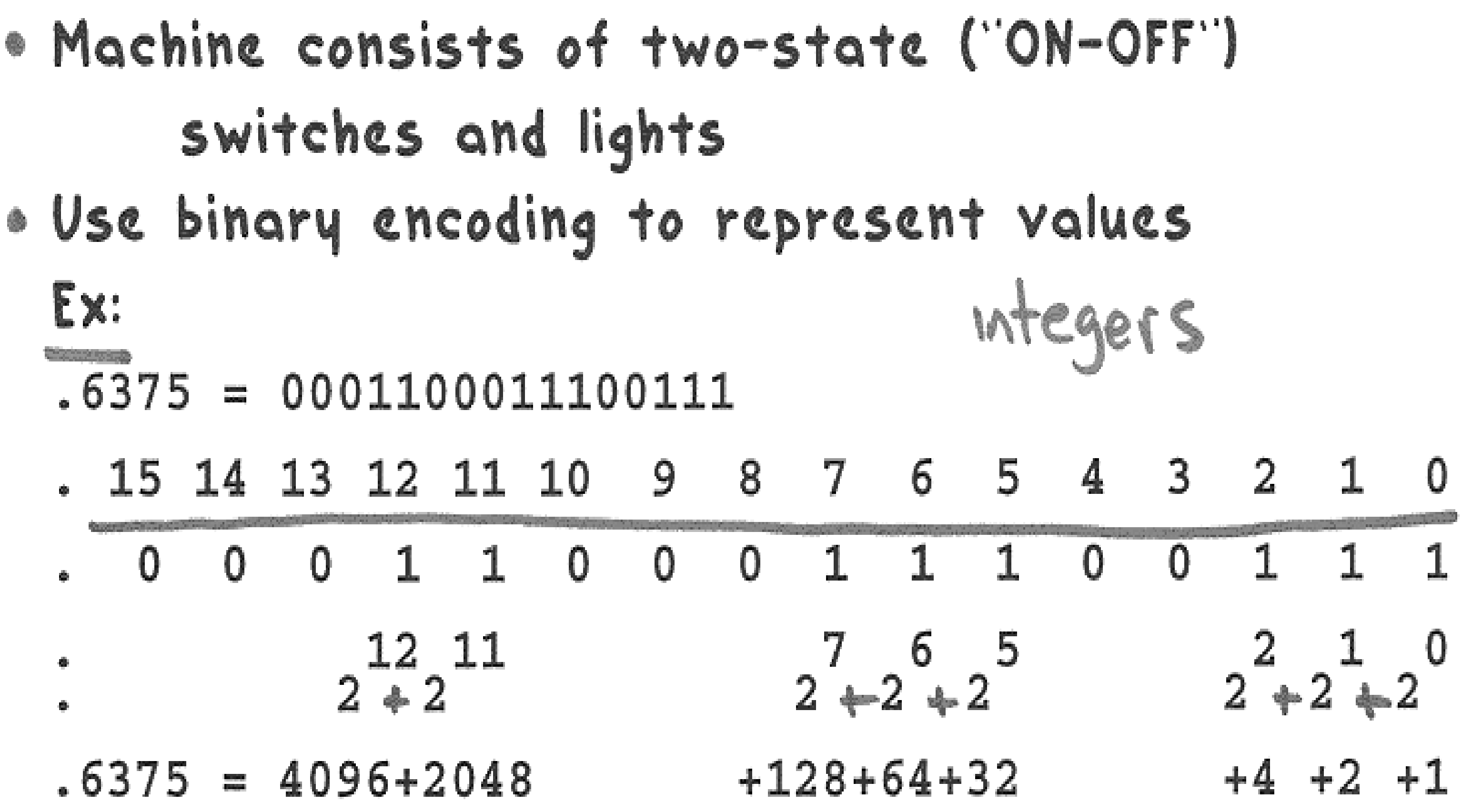
- An imaginary machine, similar to
  - ancient early computers
  - today's microprocessers
- Box with switches and lights, maybe TTY

Inside the Box



- ALU (arithmetic logic unit) -- executes instructions to manipulate date
- 8 registers -- the fastest form of storage, on-chip in modern computers, used as scratch space during computation
- PC (program counter) -- a register with special meaning, keeps track of the next instruction to be executed
- 256 16-bit words of memory -- stores both code and data

Binary Numbers



- Machine consists of two-state ("ON-OFF") switches and lights
- Use binary encoding to represent values

Ex: integers

.6375 = 0001100011100111

.	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

. $2^{12}+2^{11}$ $2^{7}+2^{6}+2^{5}$ $2^{2}+2^{1}+2^{0}$

.6375 = 4096+2048 +128+64+32 +4 +2 +1

Hexadecimal Numbers

- Hexadecimal (base-16) notation provides shorthand binary code four bits at a time

0000	0001	0010	0011	0100	0101	0110	0111
0	1	2	3	4	5	6	7
1000	1001	1010	1011	1100	1101	1110	1111
8	9	A	B	C	D	E	F

Ex:

6375 =	0001	1000	1110	0111
	1	8	E	7

- $6375 = 1*16^3 + 8*16^2 + 14*16^1 + 7*16^0$
- $= 4096 + 2048 + 224 + 7$

TOY machine memory

Contents of machine in hexadecimal (``dump'')

```
PC: 0010

   R0:  R1:  R2:  R3:  R4:  R5:  R6:  R7:
   0000 0788 B700 0010 0401 0002 0003 00A0

00: 0000 0000 0000 0000 0000 0000 0000 0000
08: 0000 0000 0000 0000 0000 0000 0000 0000
10: 9222 9120 1121 A120 1121 A121 7211 0000
18: 0000 0001 0002 0003 0004 0005 0006 0007
20: 0008 0009 000A 000B 000C 000D 000E 000F
28: 0000 0000 0000 FE10 FACE CAFE ACED CEDE
 .
 .
 .
E8: 1234 5678 9ABC DEF0 0000 0000 F00D 0000
F0: 0000 0000 EEEE 1111 EEEE 1111 0000 0000
F8: B1B2 F1F5 0000 0000 0000 0000 0000 0000
```

16

EE

- Programmers still look at dumps, even today
- Contents of memory
  - record of what program has done
  - determines (with PC) what machine will do

Program and Data

Program: sequence of instructions

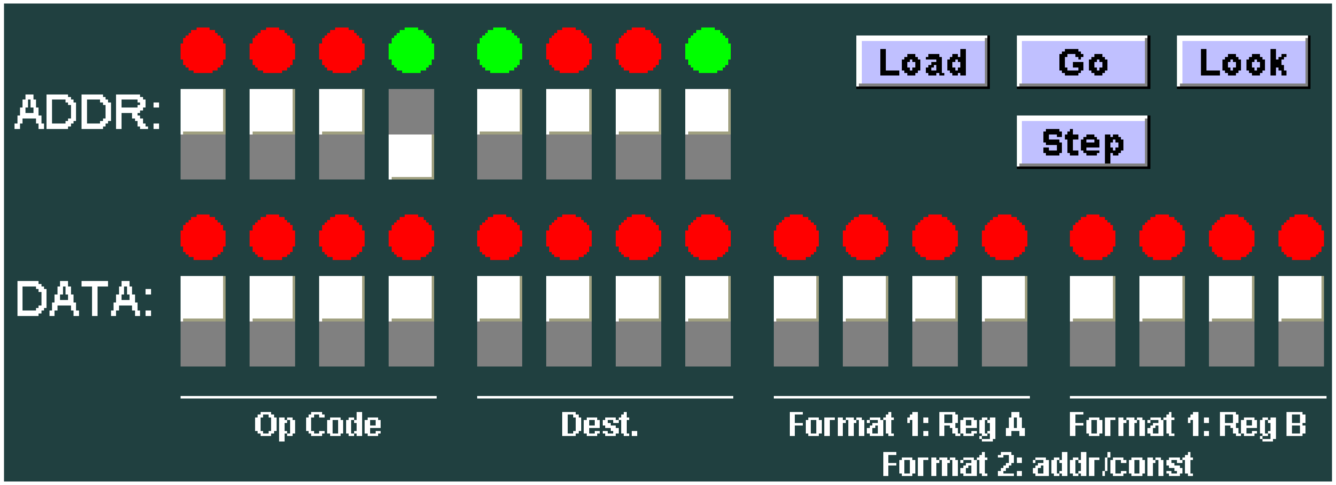
Instruction:

16-bit word (interpreted one way)

Data:

16-bit word (interpreted other ways)

How to Use the TOY Machine



To run a program

- load the program and data
  (set switches, press LOAD for each wor
- set switches to address of first instruction
- press GO

How to Use the TOY Machine

GO button

* loads PC from address switches
* initiates FETCH-INCREMENT-EXECUTE cycle
* machine runs until halt instruction hit

FETCH (get instruction from memory into CPU)
INCREMENT program counter (PC)
EXECUTE (may require data from or to memory)

"**Output:**"

- read contents of memory word in lights
- system call can write output
  to an output device (tty)

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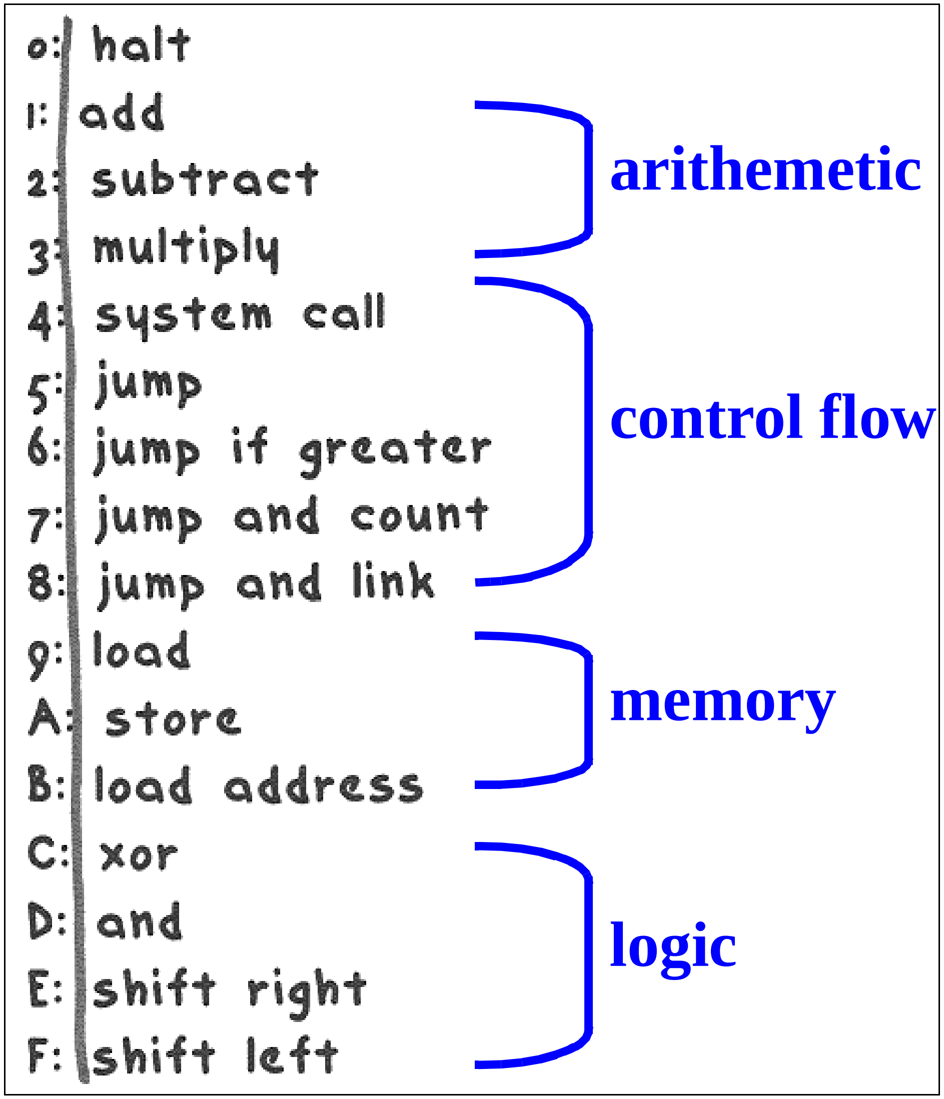
TOY Instructions



0: halt
1: add
2: subtract
3: multiply
4: system call
5: jump
6: jump if greater
7: jump and count
8: jump and link
9: load
A: store
B: load address
C: xor
D: and
E: shift right
F: shift left

arithemetic

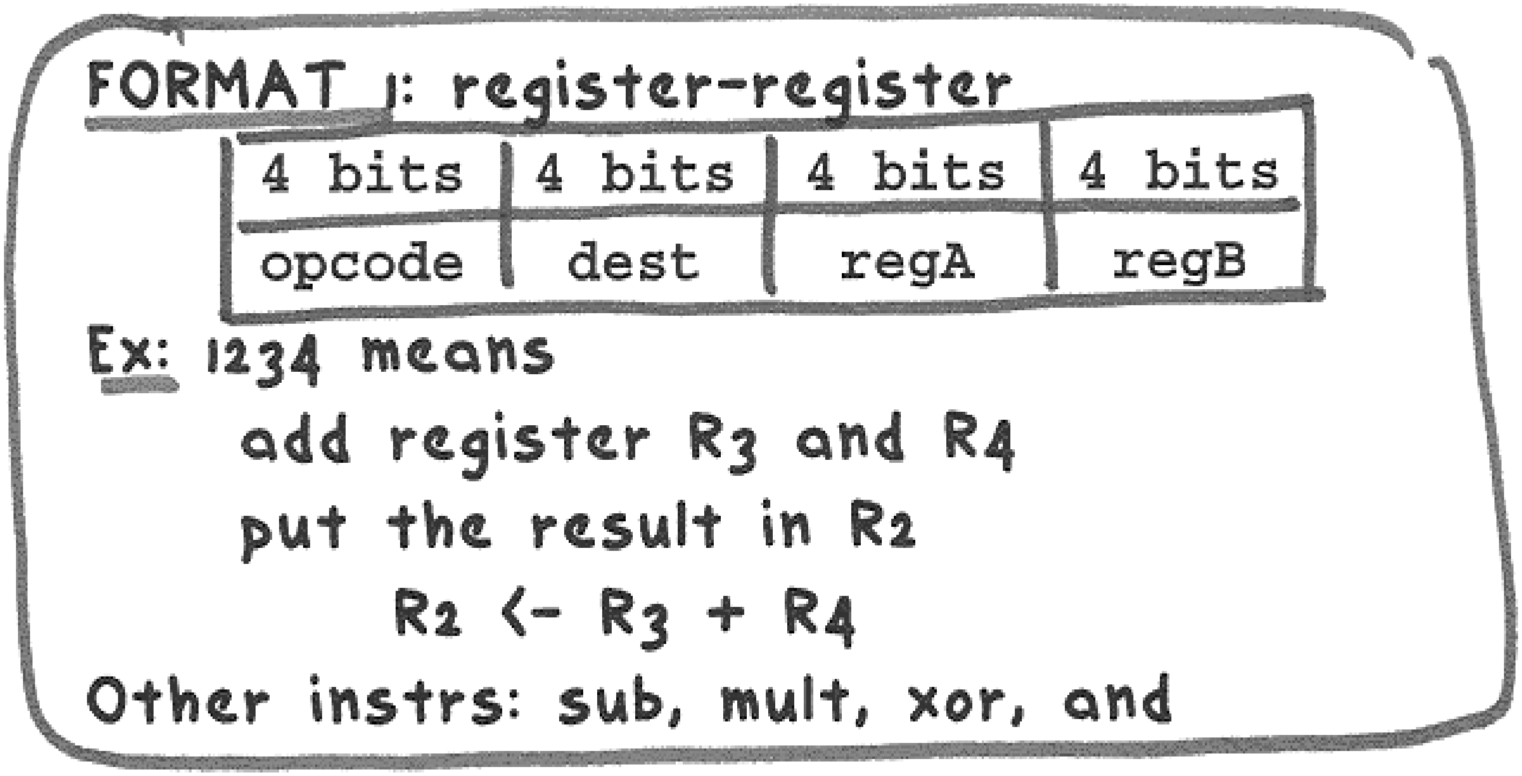
control flow

memory

logic

- Encode each of these instructions using 16 bits
- Need to divide up the 16 bits to denote components of each type of instructions
- Instruction formats - different ways of dividing up the 16 bits

Instruction Format 1



FORMAT 1: register-register

4 bits	4 bits	4 bits	4 bits
opcode	dest	regA	regB

Ex: 1234 means

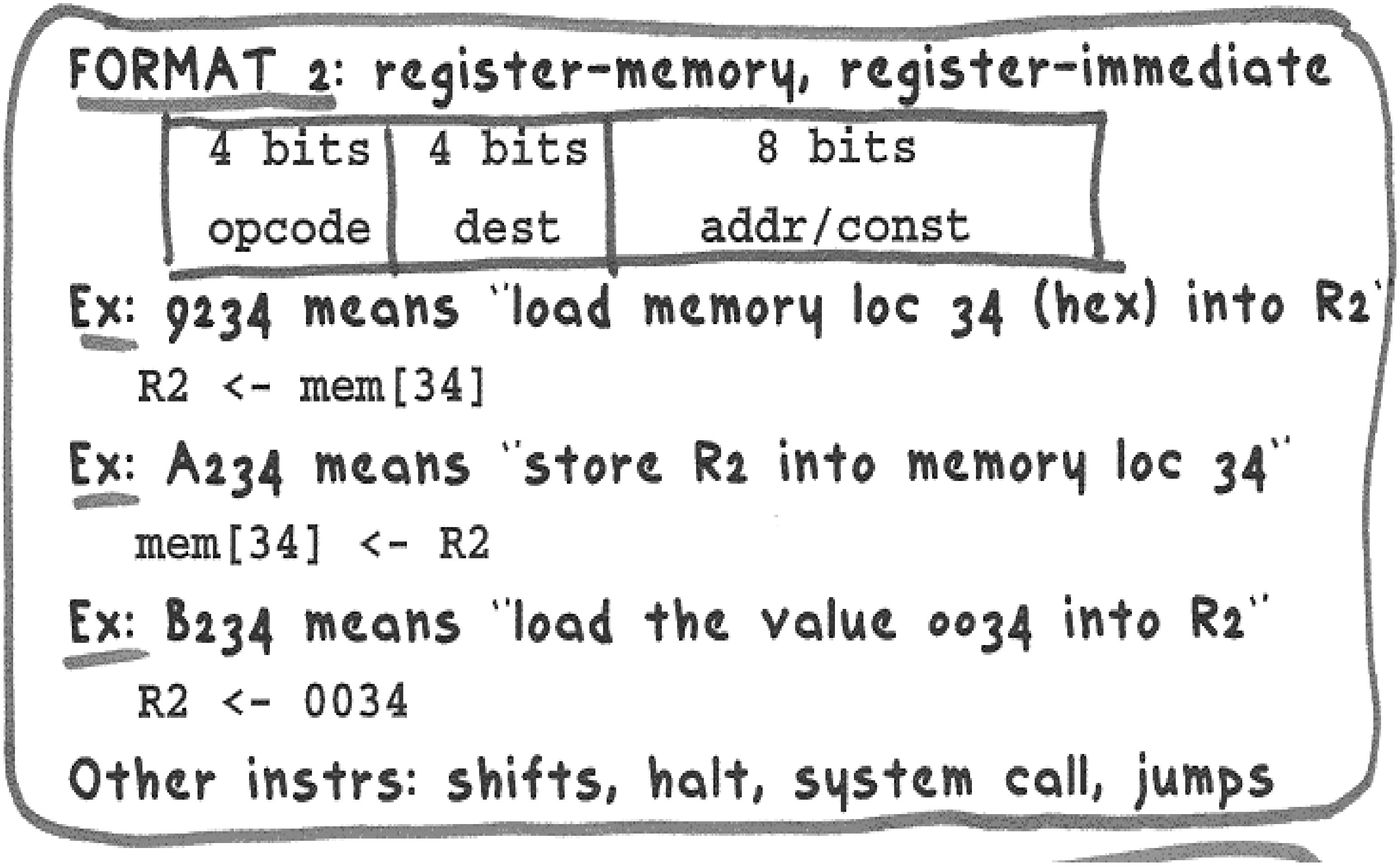
add register R3 and R4

put the result in R2

R2 <- R3 + R4

Other instrs: sub, mult, xor, and

Instruction Format 2



FORMAT 2: register-memory, register-immediate

4 bits	4 bits	8 bits
opcode	dest	addr/const

Ex: 9234 means "load memory loc 34 (hex) into R2"

R2 <- mem[34]

Ex: A234 means "store R2 into memory loc 34"

mem[34] <- R2

Ex: B234 means "load the value 0034 into R2"

R2 <- 0034

Other instrs: shifts, halt, system call, jumps

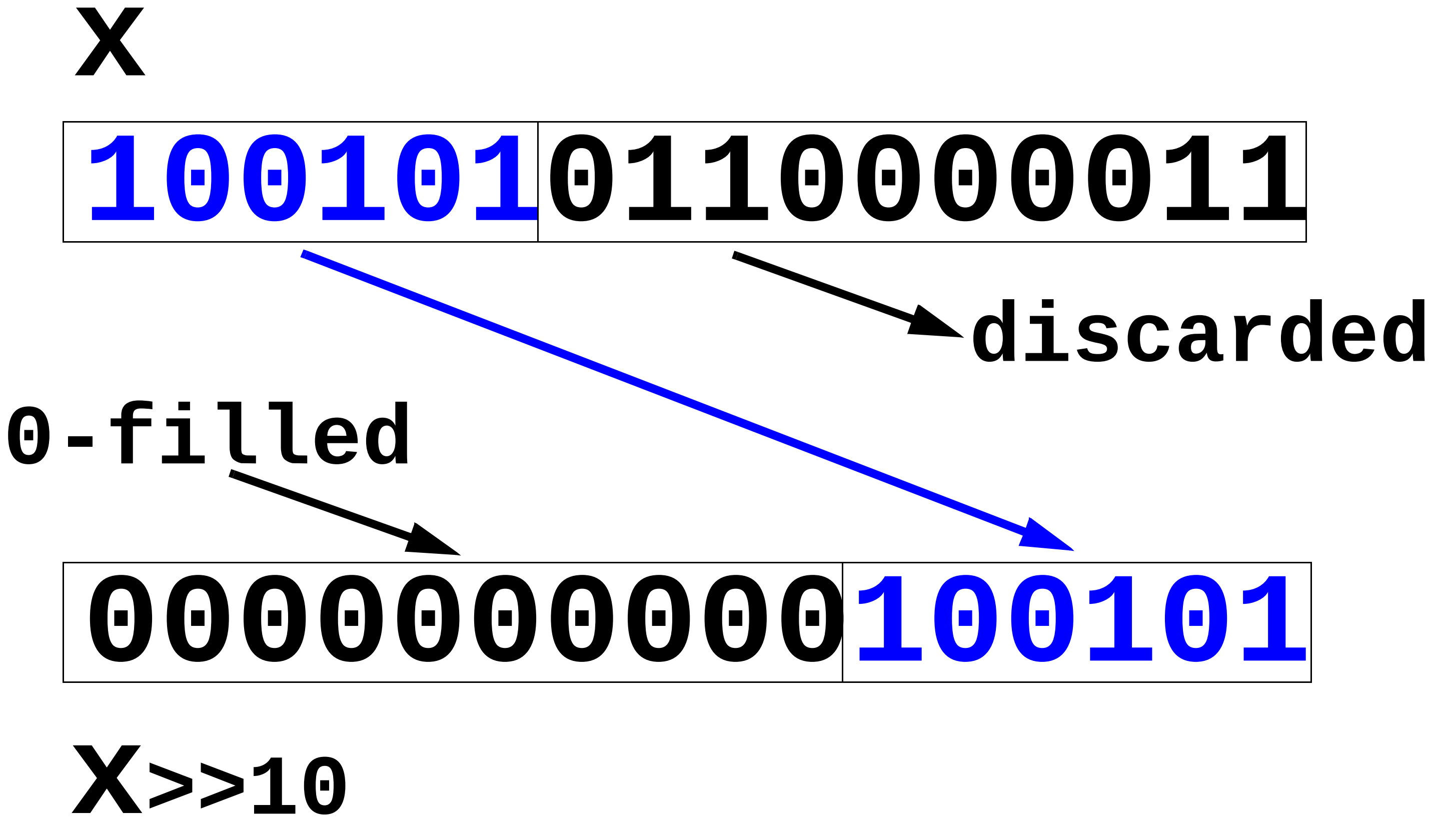
Logical Instructions

opcode

C: xor
D: and
E: shift right
F: shift left

xor, and: bit-by-bit operations
shift: move bits

Right-Shift



X

1001010110000011

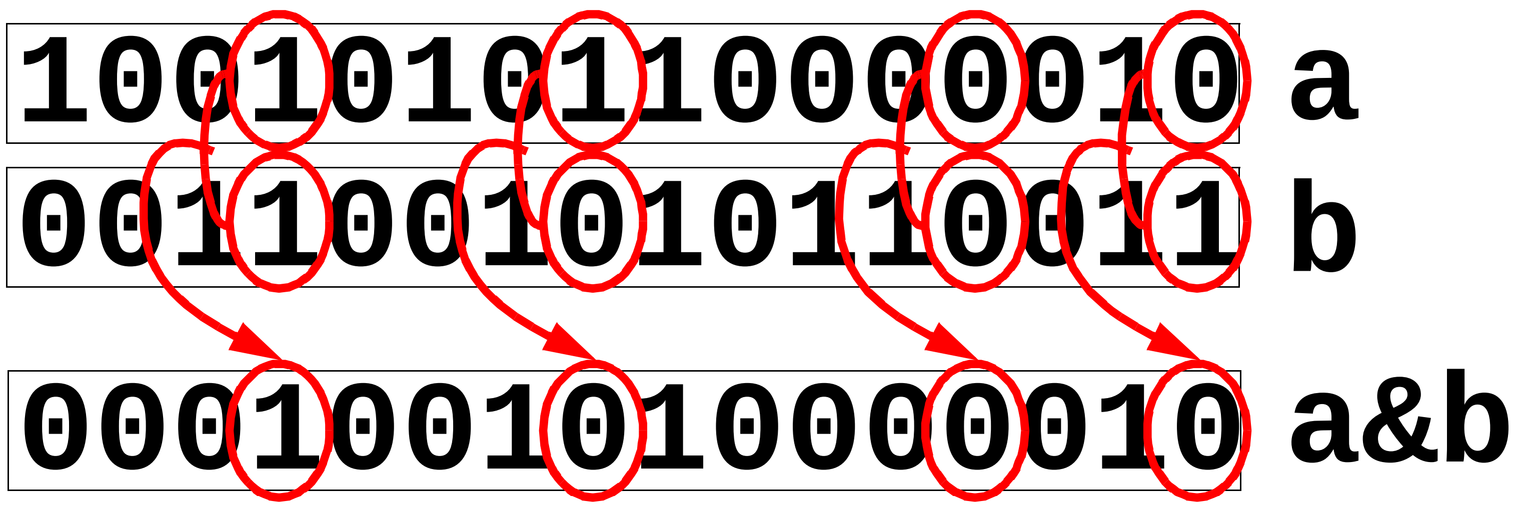
discarded

0-filled

0000000000100101

X>>10

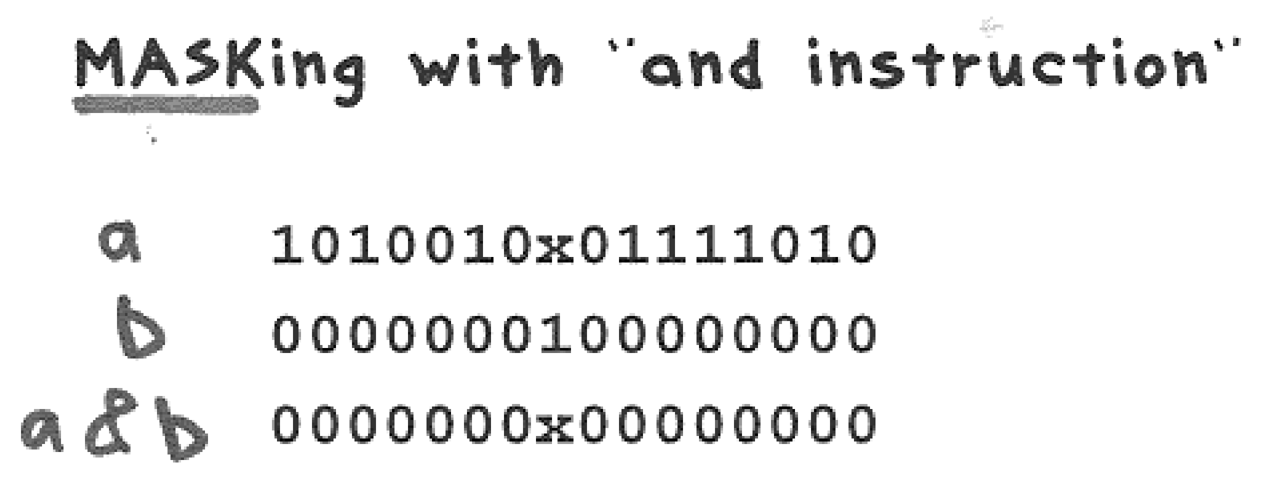
Bit-by-Bit-And



1001010110000010 a

0011001010110011 b

0001001010000010 a&b



MASKing with "and instruction"

a 1010010x01111010

b 0000000100000000

a&b 0000000x00000000

Other Logical Operations

- Can implement other logical operations

		and	xor	or
a	b	&	^	(a & b) ^ (a ^ b)
0	0	0	0	0
0	1	0	1	1
1	0	0	1	1
1	1	1	0	1

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Sample TOY program 0: arithmetic

Ex: TOY code for C expression t = b*b - 4*a*c

memory loc D0 is used for storing a
D1 for b
D2 for c
D3 for t

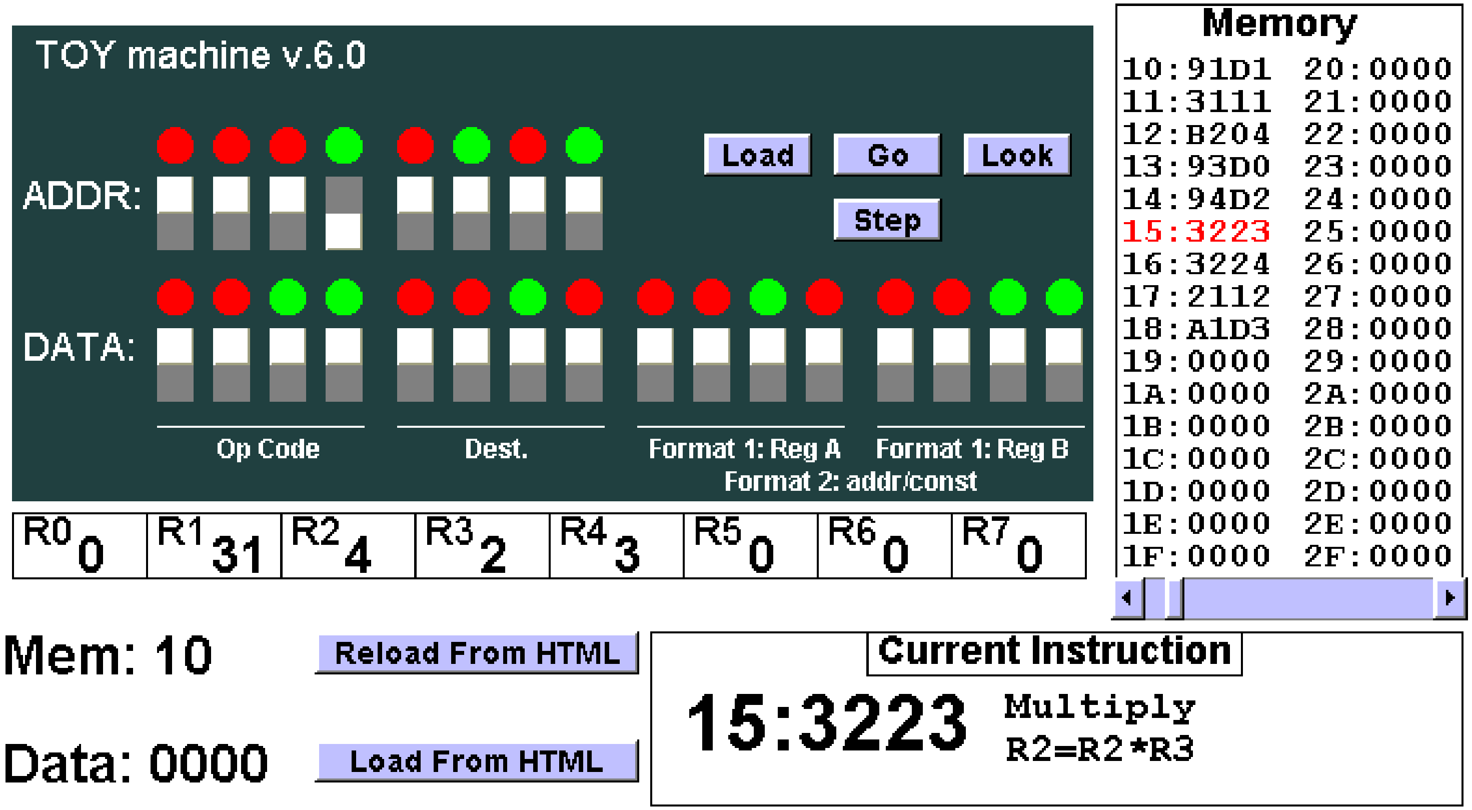
- Suppose memory locations 10-19 contain

```
10: 91D1 3111 B204 93D0 94D2 3223 3224 2112
18: A1D3 0000
```

- Set PC to 10; Press GO. TOY computes the value.
- Step-by-step trace:

```
10: 91D1     R1 <- b
11: 3111     R1 <- b*b
12: B204     R2 <- 4
13: 93D0     R3 <- a
14: 94D2     R4 <- c
15: 3223     R2 <- 4*a
16: 3224     R2 <- (4*a)*c
17: 2112     R2 <- (b*b) - (4*a*c)
18: A1D3     t  <- (b*b - 4*a*c)
19: 0000     halt
```

TOY Demo



```
R0 0   R1 31   R2 4   R3 2   R4 3   R5 0   R6 0   R7 0
```

```
Memory
10:91D1  20:0000
11:3111  21:0000
12:B204  22:0000
13:93D0  23:0000
14:94D2  24:0000
15:3223  25:0000
16:3224  26:0000
17:2112  27:0000
18:A1D3  28:0000
19:0000  29:0000
1A:0000  2A:0000
1B:0000  2B:0000
1C:0000  2C:0000
1D:0000  2D:0000
1E:0000  2E:0000
1F:0000  2F:0000
```

Mem: 10

Data: 0000

Current Instruction

15:3223 Multiply
R2=R2*R3

Sample TOY program 1: more arithmetic

Ex: Suppose memory locations 10-1F contain

```
10: B001 B200 B101 1221 1110 1221 1110 1221
18: 1110 1221 1110 1221 1110 1221 0000 0000
```

- Set PC to 10. Press GO. What happens?
- Step-by-step trace:

```
10: B001    R0 <- 0001
11: B200    R2 <- 0000                0000
12: B101    R1 <- 0001         0001
13: 1221    R2 <- R2 + R1             0001
14: 1110    R1 <- R1 + R0      0002
15: 1221    R2 <- R2 + R1             0003
16: 1110    R1 <- R1 + R0      0003
17: 1221    R2 <- R2 + R1             0006
18: 1110    R1 <- R1 + R0      0004
19: 1221    R2 <- R2 + R1             000A
1A: 1110    R1 <- R1 + R0      0005
1B: 1221    R2 <- R2 + R1             000F
1C: 1110    R1 <- R1 + R0      0006
1D: 1221    R2 <- R2 + R1             0015
1E: 0000    halt
```

Computes 1 + 2 + 3 + 4 + 5 + 6 = 21

Sample TOY program 2: loop

- Suppose memory locations 10-17 contain

```
10: B106 B200 B001 1221 2110 6113 0000 0000
```

- Set PC to 10. Press GO. What happens?
- Step-by-step trace:

```
                                       N
10: B106    R1 <- 0006             0006 sum
11: B200    R2 <- 0000                  0000
12: B001    R0 <- 0001
13: 1221    R2 <- R2 + R1               0006
14: 2110    R1 <- R1 - R0          0005
15: 6113    jump if (R1 > 0)
13: 1221    R2 <- R2 + R1               000B
14: 2110    R1 <- R1 - R0          0004
15: 6113    jump if (R1 > 0)
13: 1221    R2 <- R2 + R1               000F
14: 2110    R1 <- R1 - R0          0003
15: 6113    jump if (R1 > 0)
13: 1221    R2 <- R2 + R1               0012
14: 2110    R1 <- R1 - R0          0002
15: 6113    jump if (R1 > 0)
13: 1221    R2 <- R2 + R1               0014
14: 2110    R1 <- R1 - R0          0001
15: 6113    jump if (R1 > 0)
13: 1221    R2 <- R2 + R1               0015
14: 2110    R1 <- R1 - R0          0000
15: 6113    jump if (R1 > 0)
16: 0000    halt
```

Computes

$$N + (N-1) + \ldots + 3 + 2 + 1 = N(N+1)/2$$

for *any* value N loaded into R1

Horner's Method

Problem:

- evaluate 2x^3 + 3x^2 + 9x + 7 at x = 10
  assume "data" stored in locations 30--34

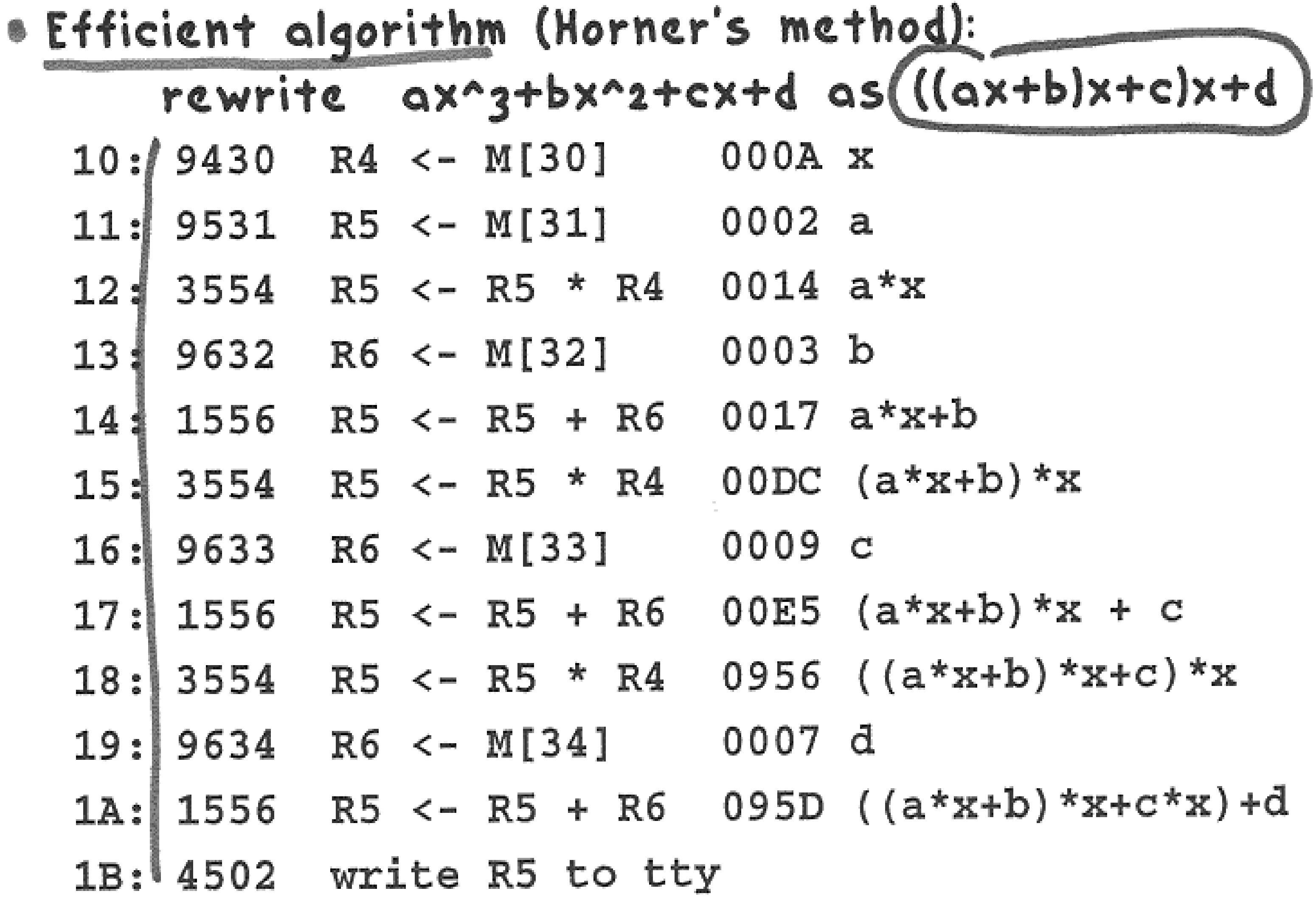
```
         x     a     b     c     d
30: 000A  0002  0003  0009  0007  0000  0000  0000
```

First try:

- compute x^3, mult. by a; compute x^2, ...
  (cumbersome, inefficient)

- **Efficient algorithm** (Horner's method):
  rewrite ax^3+bx^2+cx+d as ((ax+b)x+c)x+d

Sample TOY Program 3: Horner's Method



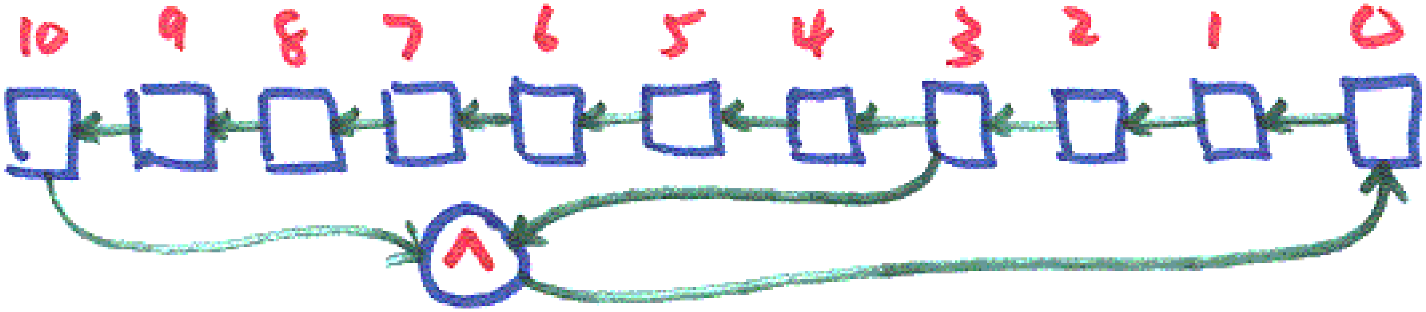
- Efficient algorithm (Horner's method):

  rewrite ax^3+bx^2+cx+d as ((ax+b)x+c)x+d

```
10: 9430   R4 <- M[30]      000A x
11: 9531   R5 <- M[31]      0002 a
12: 3554   R5 <- R5 * R4    0014 a*x
13: 9632   R6 <- M[32]      0003 b
14: 1556   R5 <- R5 + R6    0017 a*x+b
15: 3554   R5 <- R5 * R4    00DC (a*x+b)*x
16: 9633   R6 <- M[33]      0009 c
17: 1556   R5 <- R5 + R6    00E5 (a*x+b)*x + c
18: 3554   R5 <- R5 * R4    0956 ((a*x+b)*x+c)*x
19: 9634   R6 <- M[34]      0007 d
1A: 1556   R5 <- R5 + R6    095D ((a*x+b)*x+c*x)+d
1B: 4502   write R5 to tty
```

LFBSR

Linear feedback shift register (LFBSR)



Sample TOY program 4: bit manipulation

Ex: suppose that memory locations 10-15 contain

```
10: 911F B000 1210 1310 E203 E30A C323 B401
18: D334 F101 C113 0000 0000 0000 0000 0684
```

- Set PC to 10. Press GO. What happens?

- Step-by-step:

```
10: 911F    R1 <- 0684        0000011010000100   R1 is LFBSR content
11: B000    R0 <- 0000
12: 1210    R2 <- R1 + R0     0000011010000100   R2 is a copy of R1
13: 1310    R3 <- R1 + R0     0000011010000100   So is R3
14: E203    R2 <- R2 >> 3     0000000011010000   Get 3rd bit to the right end
15: E30A    R3 <- R3 >> 10    0000000000000001   Get 10th bit to the right en
16: C323    R3 <- R2 ^ R3     0000000011010001
17: B401    R4 <- 0001        0000000000000001   Only right-most bit of xor
18: D334    R3 <- R3 & R4     0000000000000001
19: F101    R1 <- R1 << 1     0000110100001000   Left shift LFBSR
1A: C113    R1 <- R1 ^ R3     0000110100001001   Put in the new right-most bi
1B: 0000    halt
```

- Simulates one step of LFBSR of Lecture 1

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Basic Characteristics of TOY Machine

TOY is a "general purpose" computer

- "von Neumann" machine
  - instructions and data in same memory
  - can change program (control) w/o rewiring

    immediate applications

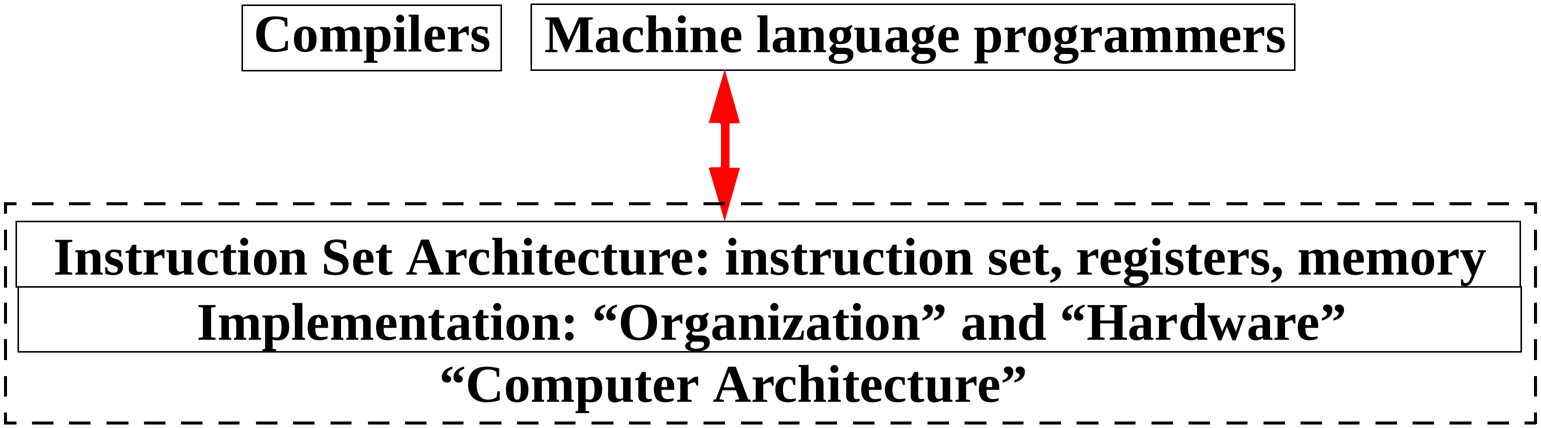
    profound implications

- sufficient power to perform any computation
  - limited only by amount of memory (and time)

    [stay tuned]

- similar to real machines

“Computer Architecture”



Compilers **Machine language programmers**

Instruction Set Architecture: instruction set, registers, memory

Implementation: “Organization” and “Hardware”

“Computer Architecture”

- Interface--“instruction set architecture” (ISA)
  - visible to machine language programmers
  - boundary between software and hardware
- Implementation
  - “Organization”: interaction of high-level components
  - “Hardware”: low level specifics such as detailed logic design
- Abstractions
  - Can change hardware without changing organization
  - Can change implementation without changing ISA