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

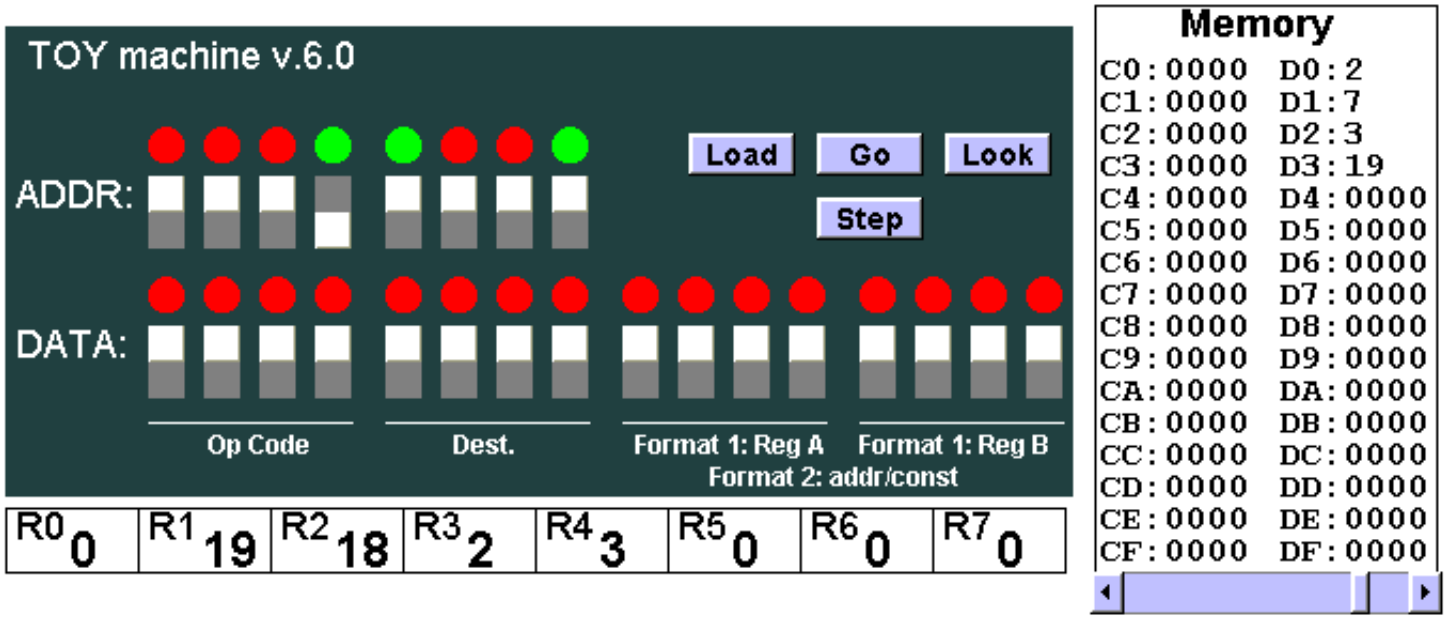
Why Study Machine Language Programming Today

- 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

Outline

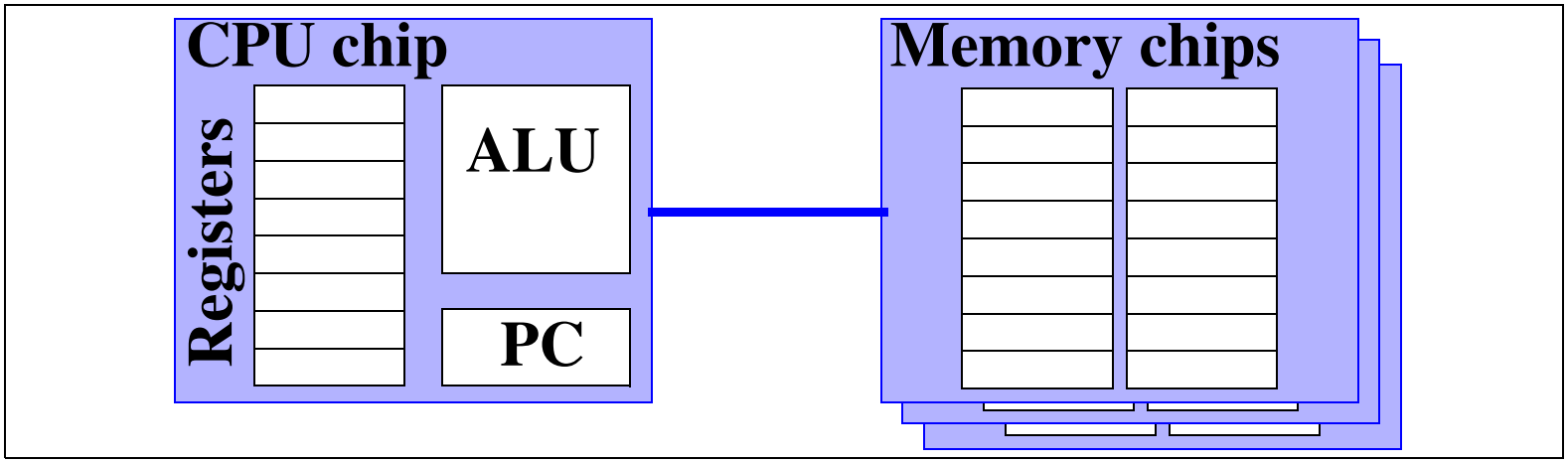
- ~~Introduction~~
- **Toy machine**
- Machine language instructions
- Example machine language programs
- Conclusions

Toy Machine



- 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
.				12	11				7	6	5			2	1	0
.				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

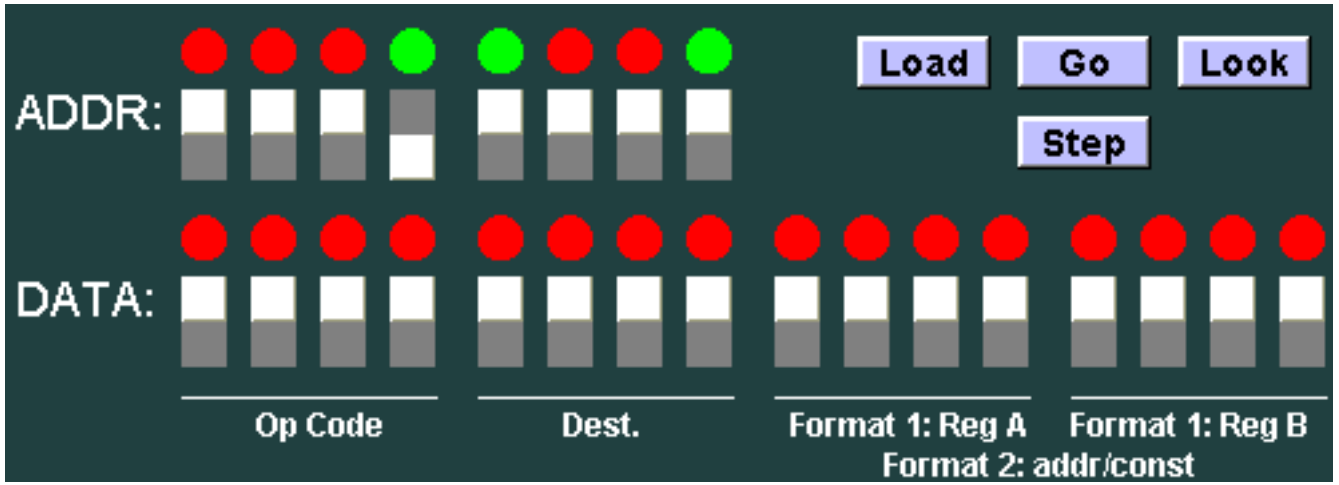
Instruction:

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)

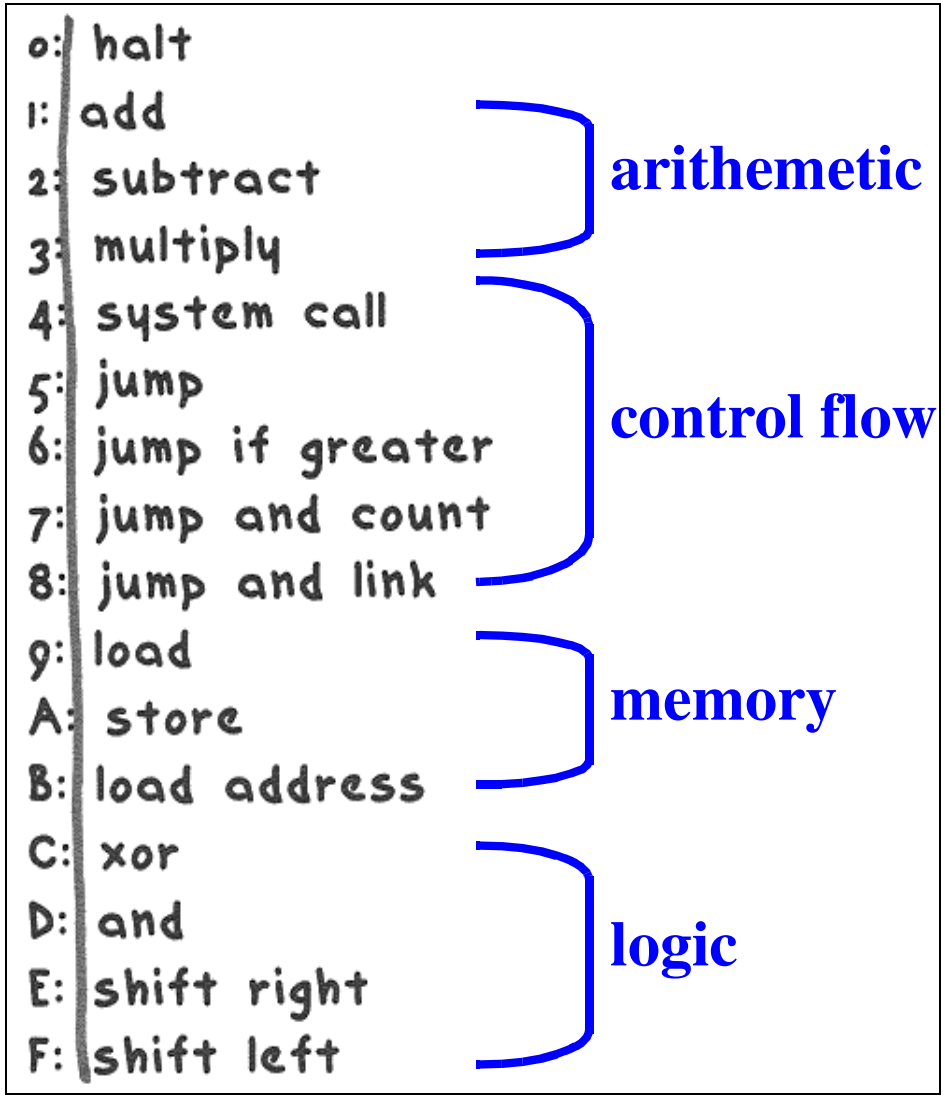
"Output:"

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

Outline

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

TOY Instructions



- 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 R_3 and R_4

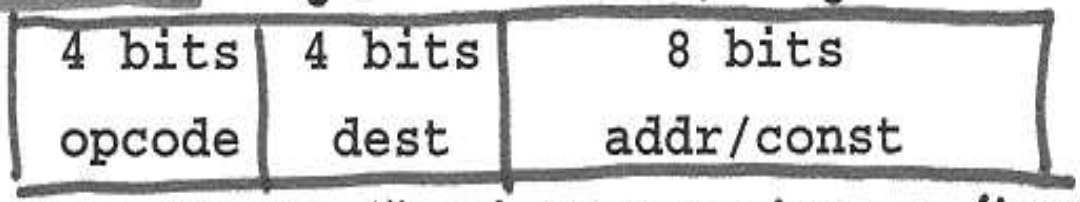
put the result in R_2

$R_2 \leftarrow R_3 + R_4$

Other instrs: sub, mult, xor, and

Instruction Format 2

FORMAT 2: register-memory, register-immediate



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

```
R2 <- mem[34]
```

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

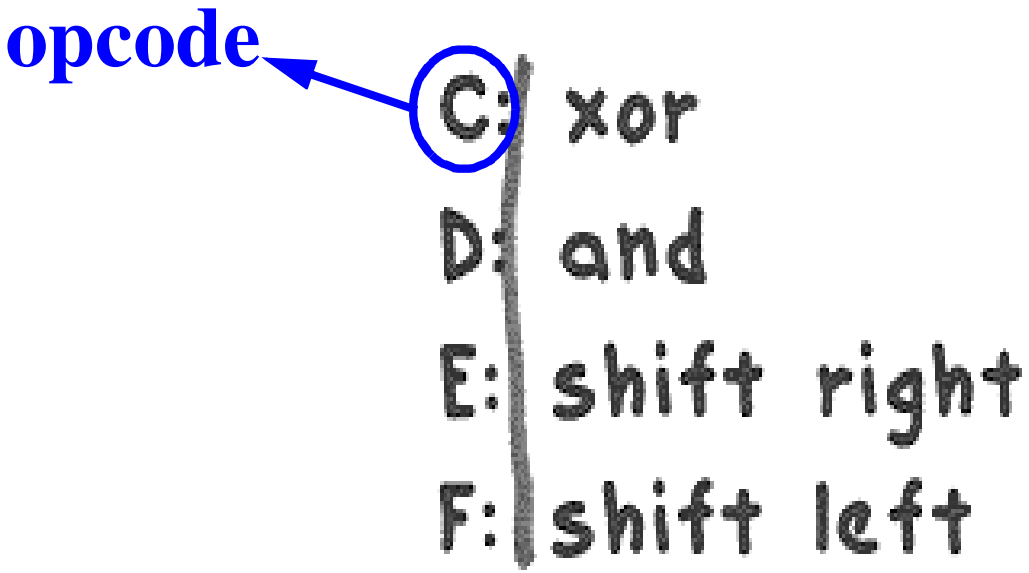
```
mem[34] <- R2
```

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

```
R2 <- 0034
```

Other instrs: shifts, halt, system call, jumps

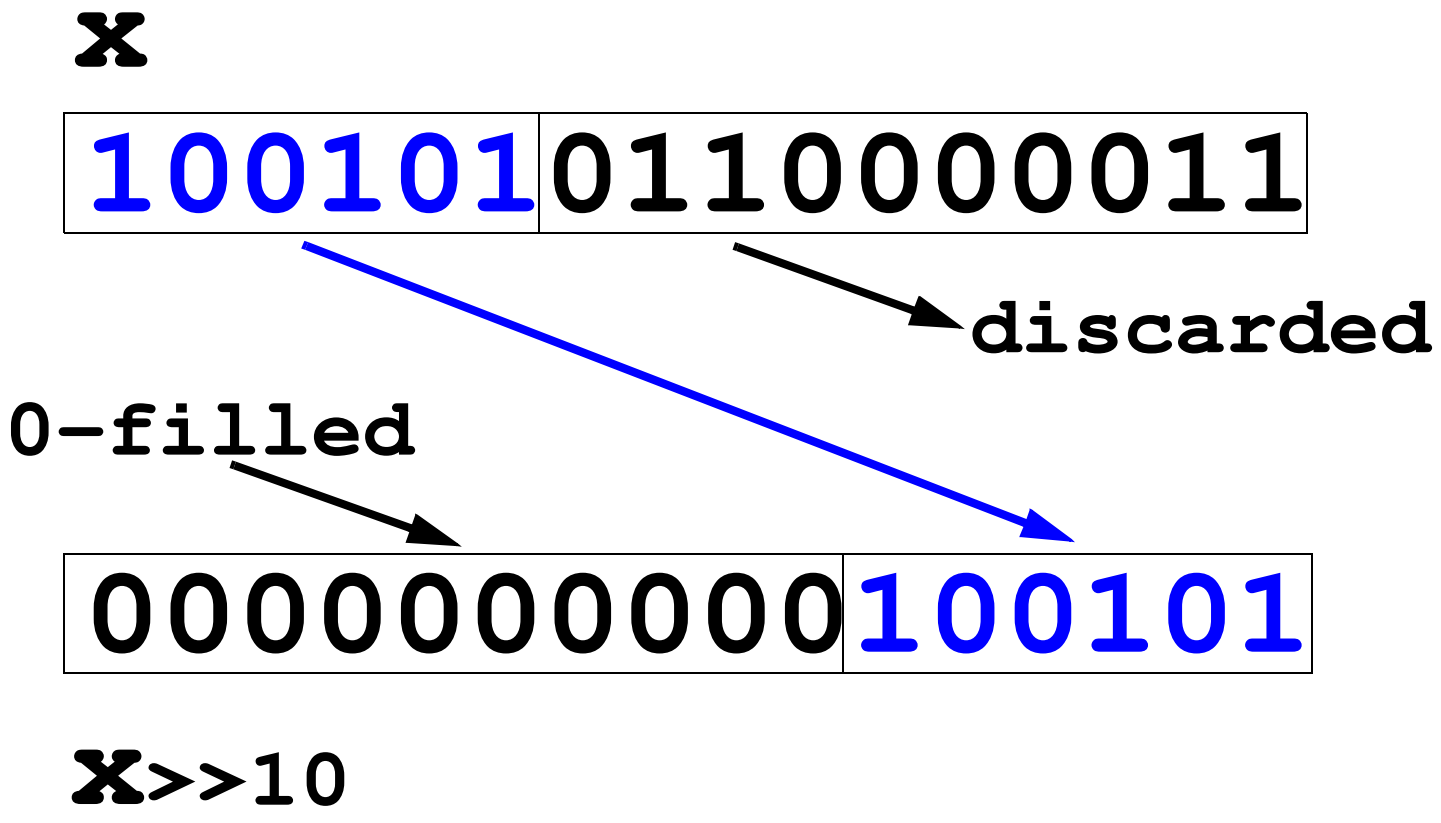
Logical Instructions



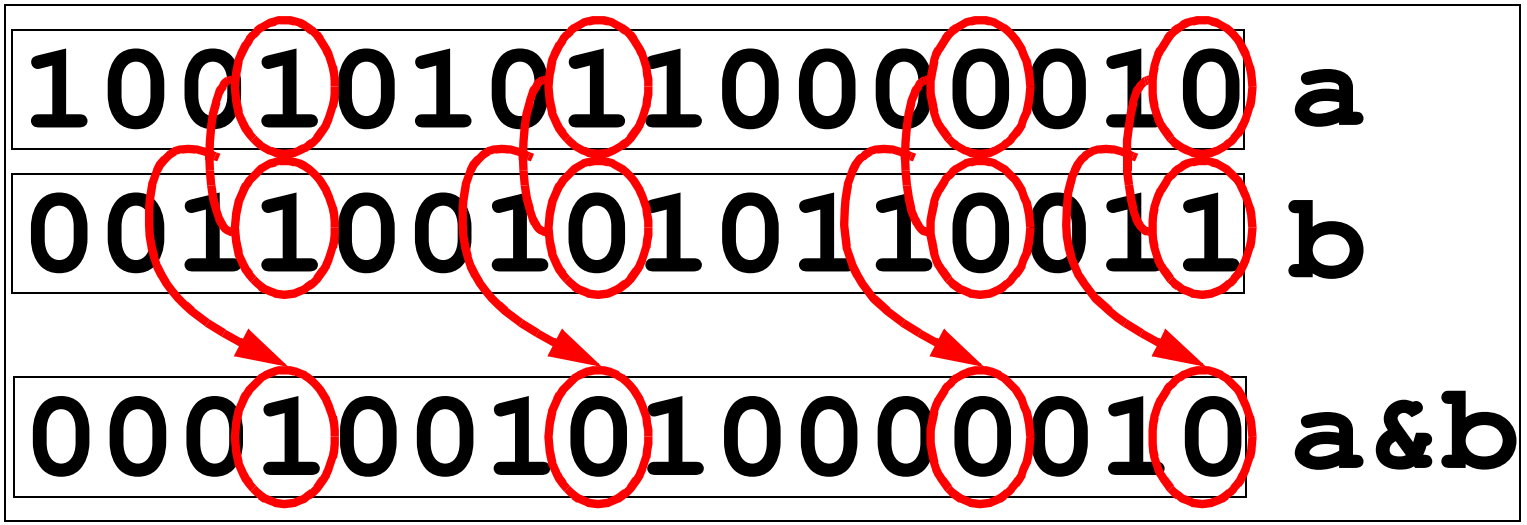
xor, and: bit-by-bit operations

shift: move bits

Right-Shift


x
100101
0110000011
discarded
0-filled
0000000000
100101
x>>10

Bit-by-Bit-And



MASKing with "and instruction"

a	1010010x01111010
b	0000000100000000
a & b	0000000x00000000

Other Logical Operations

- Can implement other logical operations

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

Outline

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

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

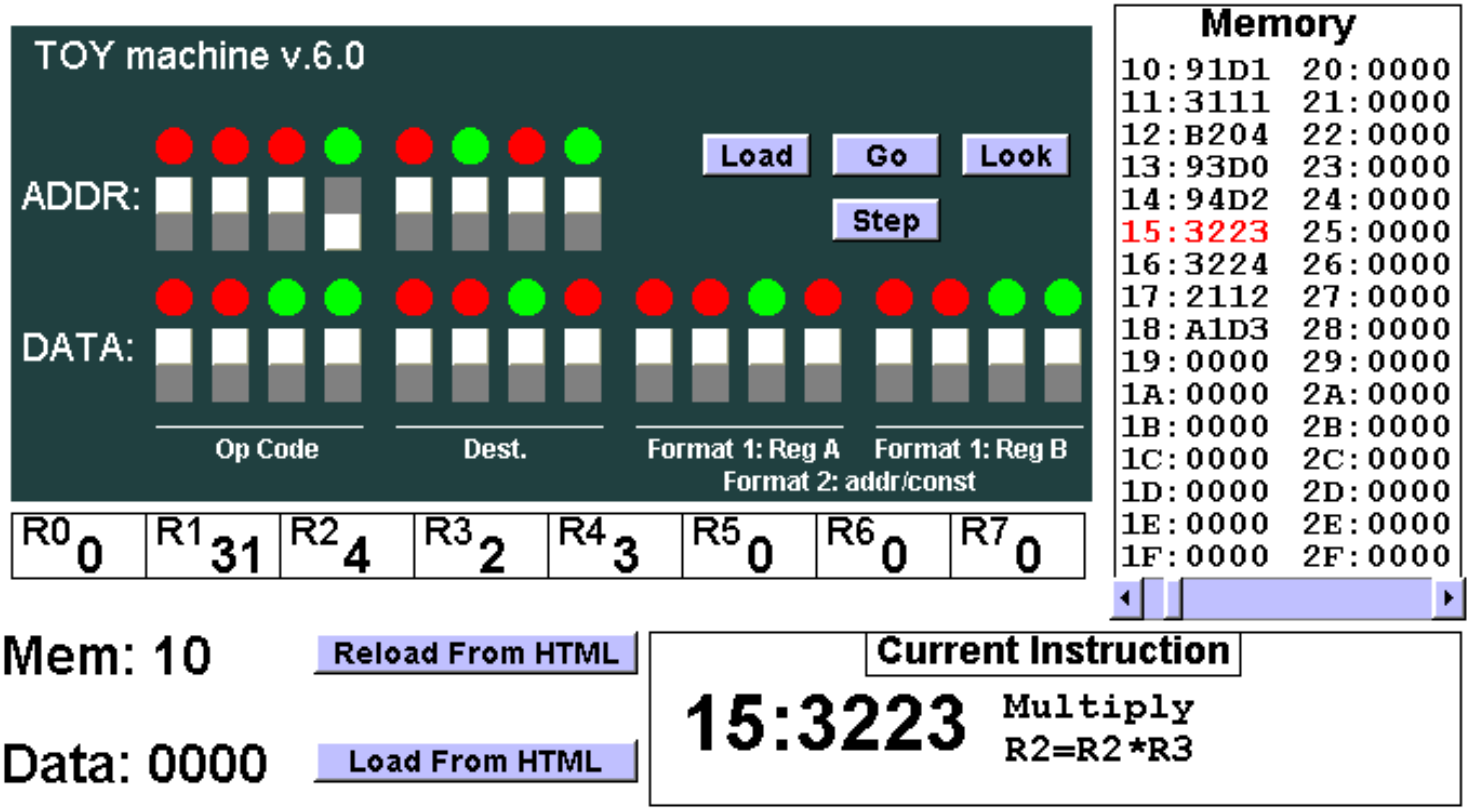
- Suppose memory locations 10-19 contain

```
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


TOY machine v.6.0
ADDR:
DATA:
Load
Go
Look
Step
Op Code
Dest.
Format 1: Reg A
Format 1: Reg B
Format 2: addr/const
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
Reload From HTML
Data: 0000
Load From HTML
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
```

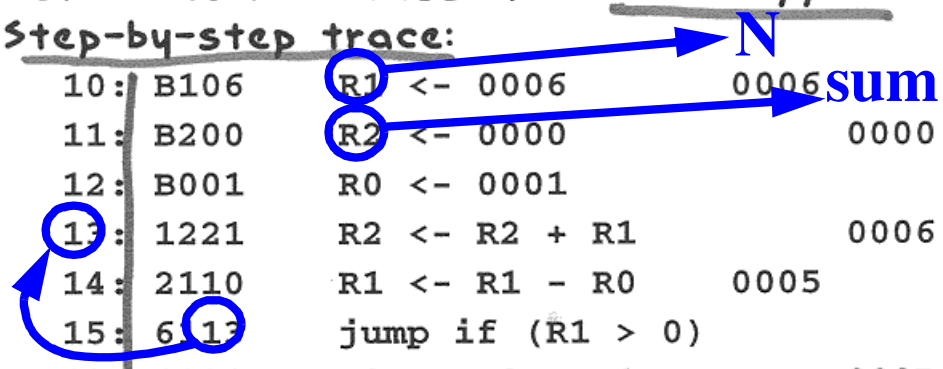
Computes 1 + 2 + 3 + 4 + 5 + 6 = 21

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:




```
10: B106    R1 <- 0006          0006
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)

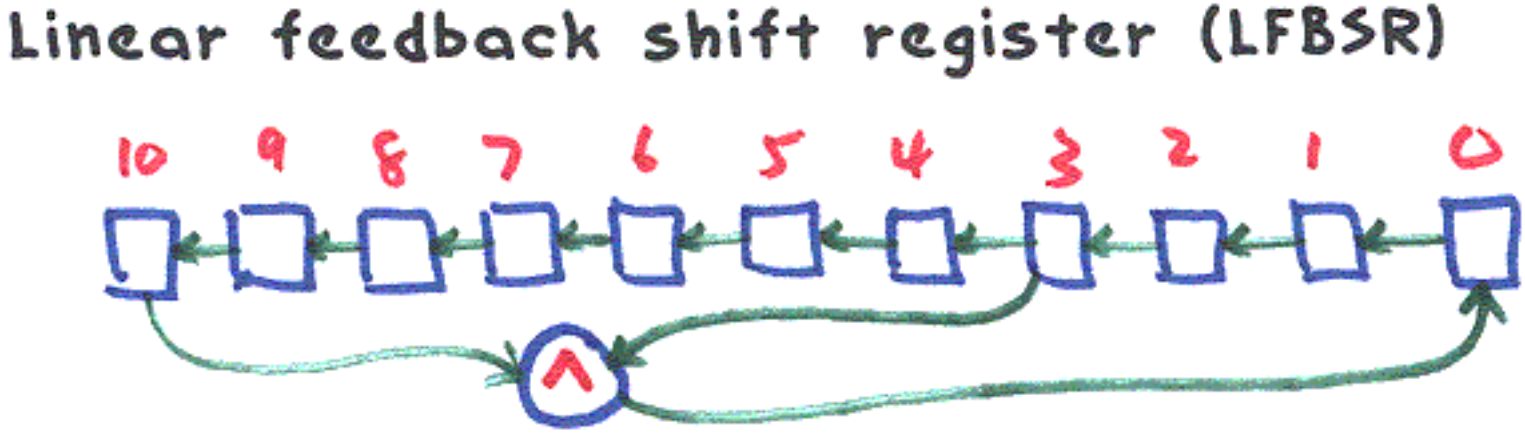
- **Efficient algorithm (Horner's method):**
  rewrite ax^3+bx^2+cx+d as $((ax+b)x+c)x+d$

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



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
11: B000    R0 <- 0000
12: 1210    R2 <- R1 + R0    0000011010000100
13: 1310    R3 <- R1 + R0    0000011010000100
14: E203    R2 <- R2 >> 3    0000000011010000
15: E30A    R3 <- R3 >> 10   0000000000000001
16: C323    R3 <- R2 ^ R3    0000000011010001
17: B401    R4 <- 0001       0000000000000001
18: D334    R3 <- R3 & R4    0000000000000001
19: F101    R1 <- R1 << 1    0000110100001000
1A: C113    R1 <- R1 ^ R3    0000110100001001
1B: 0000    halt
```

R1 is LFBSR content

R2 is a copy of R1

So is R3

Get 3rd bit to the right end

Get 10th bit to the right end

Only right-most bit of xor

Left shift LFBSR

Put in the new right-most bi

- Simulates one step of LFBSR of Lecture 1

Outline

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

Basic Characteristics of TOY Machine

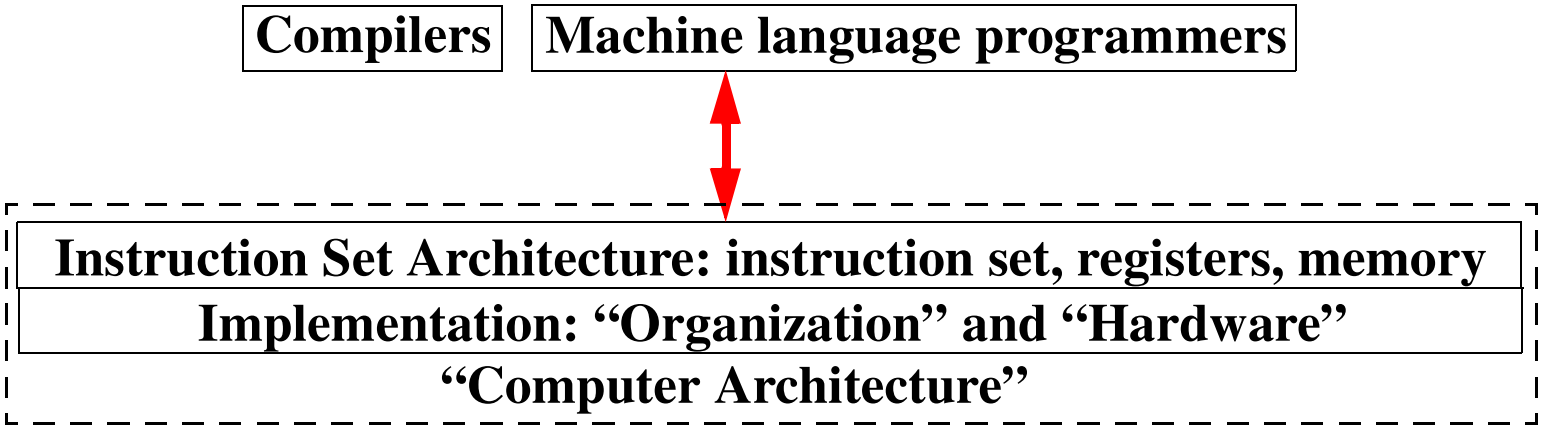
TOY is a "general purpose" computer

- "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"



- 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