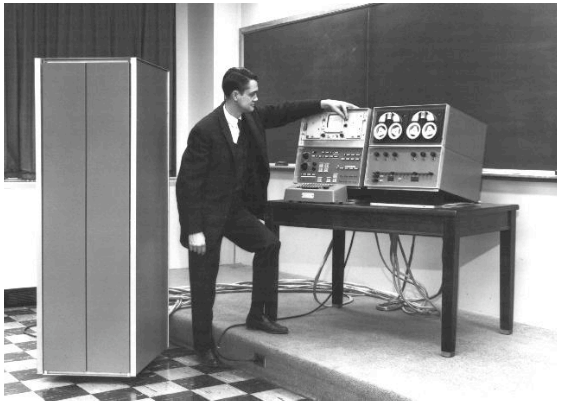
Lecture 9: TOY II



LINC

What We've Learned About TOY

Data representation.
- Binary and hex.

TOY: what's in it, how to use it.
- Box with switches and lights.
- 4,328 bits = (255 × 16) + (15 × 16) + (8). 541 bytes!
- von Neumann architecture.

TOY instruction set architecture.
- 16 instruction types.

Sample TOY machine language programs.
- Arithmetic.
- Loops.

What We Do Today

Binary add, subtract.

Standard input, standard output.

Manipulate addresses.
- References (pointers).
- Arrays.

TOY simulator in Java.

How to add and subtract binary numbers

Binary addition facts:
- 0 + 0 = 0
- 0 + 1 = 1 + 0 = 1
- 1 + 1 = 10
- 1 + 1 + 1 = 11 (needed for carries)

Bigger numbers example:

```
                   carries
  1 <-------------         ---------> 1  1
  013                 0  0  0  0  1  1  0  1
+ 092               + 0  1  0  1  1  1  0  0
-----               -------------------------
  105                 0  1  1  0  1  0  0  1
```

OK, but: subtract?
- Subtract by adding a negative integer (e.g., 6 - 4 = 6 + (-4))
- OK, but: negative integers?

How to Represent Negative Integers

TOY words are 16 bits each.

- We could use 16 bits to represent 0 to $2^{16} - 1$.
- But we want negative integers too.
- Reserving half the possible bit-patterns for negative seems fair.

Highly desirable property:

- If X is a positive integer, then the representation of -X, when added to X, had better yield zero.

```
    x       0 0 1 1 0 1 0 0
+(-x)     + ? ? ? ? ? ? ? ?
    0       0 0 0 0 0 0 0 0

    x       0 0 1 1 0 1 0 0
          + 1 1 0 0 1 0 1 1
+(-x)       1 1 1 1 1 1 1 1
          +               1
    0       0 0 0 0 0 0 0 0
```

"Two's Complement" Integers

Properties:

- Leading bit (bit 15) signifies sign.
- Negative integer -N represented by 2^{16} - N.
- Trick to compute -N:

1. Start with N.

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

2. Flip bits.

	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1

3. Add 1.

-4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0

Two's Complement Integers

		15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Dec	Hex	Binary															
+32767	7FFF	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
								•••									
+4	0004	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
+3	0003	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
+2	0002	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
+1	0001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
+0	0000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-1	FFFF	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
-2	FFFE	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
-3	FFFD	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1
-4	FFFC	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
								•••									
-32768	8000	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Properties of Two's Complement Integers

Nice properties:

- 0000000000000000 represents 0.
- -0 and +0 are the same.
- Addition is easy (see next slide).
- Checking for arithmetic overflow is easy.

- N = ~N + 1

Not-so-nice properties.

- Can represent one more negative integer than positive integer. (-32,768 = -2^{15} but not 32,768 = 2^{15}).

Two's Complement Arithmetic

Addition is carried out as if all integers were positive.

- It usually works.

-3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1

+

4	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0

=

1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Two's Complement Arithmetic

Addition is carried out as if all integers were positive.

- It usually works.
- But overflow can occur:
  - carry into sign (left most) bit with no carry out

+32,767	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

+

2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0

=

-32,767	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Standard Output

Standard output.

- Writing to memory location `FF` sends one word to TOY stdout.
- `9AFF` writes the integer in register `A` to stdout.

```
00: 0000   0
01: 0001   1

10: 8A00   RA <- mem[00]            a = 0
11: 8B01   RB <- mem[01]            b = 1
                                    while(a > 0) {
12: 9AFF   print RA                    print a
13: 1AAB   RA <- RA + RB               a = a + b
14: 2BAB   RB <- RA - RB               b = a - b
15: DA12   if (RA > 0) goto 12      }
16: 0000   halt
```

Standard Output

Standard output.

- Writing to memory location `FF` sends one word to TOY stdout.
- `9AFF` writes the integer in register `A` to stdout.

```
00: 0000   0
01: 0001   1

10: 8A00   RA <- mem[00]            a = 0
11: 8B01   RB <- mem[01]            b = 1
                                    while(a > 0) {
12: 9AFF   print RA                    print a
13: 1AAB   RA <- RA + RB               a = a + b
14: 2BAB   RB <- RA - RB               b = a - b
15: DA12   if (RA > 0) goto 12      }
16: 0000   halt
```

```
0000
0001
0001
0002
0003
0005
0008
000D
0015
0022
0037
0059
0090
00E9
0179
0262
03DB
063D
0A18
1055
1A6D
2AC2
452F
6FF1
```

Standard Input

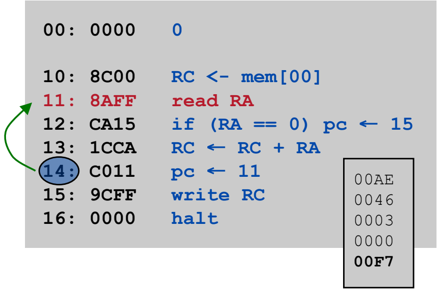
Standard input.

- Loading from memory address `FF` loads one word from TOY stdin.
- `8AFF` reads in an integer from stdin and stores it in register `A`.

Ex: read in a sequence of integers and print their sum.

- In Java, stop reading when EOF.
- In TOY, stop reading when user enters `0000`.

```
while(!StdIn.isEmpty()) {
   a = StdIn.readInt();
   sum = sum + a;
}
System.out.println(sum);
```



```
00: 0000   0

10: 8C00   RC <- mem[00]
11: 8AFF   read RA
12: CA15   if (RA == 0) pc ← 15
13: 1CCA   RC ← RC + RA
14: C011   pc ← 11
15: 9CFF   write RC
16: 0000   halt
```

```
00AE
0046
0003
0000
00F7
```

Standard Input and Output: Implications

Standard input and output enable you to:

- Put information from real world into machine.
- Get information out of machine.
- Process more information than fits in memory.
- Interact with the computer while it is running.

Information can be instructions!

- Booting a computer.

Load Address (a.k.a. Load Constant)

Load address. (opcode 7)

- Loads an 8-bit integer into a register.
- `7A30` means load the value `30` into register `A`.

Applications.

- Load a small constant into a register.
- Load a 8-bit memory address into a register.
  - register stores "pointer" to a memory cell

```
a = 30;
```

Java code

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

Arrays in TOY

TOY main memory is a giant array.

- Can access memory cell `30` using load and store.
- `8C30` means load `mem[30]` into register `C`.
- Goal: access memory cell `i` where `i` is a variable.

Load indirect. (opcode B)

a variable index

- `BC06` means load `mem[R6]` into register `C`.

Store indirect. (opcode A)

a variable index

- `AC06` means store contents of register `C` into `mem[R6]`.

```
for (int i = 0; i < N; i++)
   a[i] = StdIn.readInt();

for (int i = 0; i < N; i++)
   System.out.println(a[N-i-1]);
```

Reverse.java

TOY Implementation of Reverse

TOY implementation of reverse.

- Read in a sequence of integers and store in memory `30`, `31`, `32`, …
  - stop reading if `0000`
- Print sequence in reverse order.

```
10: 7101   R1 ← 0001                    constant 1
11: 7A30   RA ← 0030                    a[]
12: 7B00   RB ← 0000                    n

                                        while(true) {
13: 8CFF   read RC                         c = StdIn.readInt();
14: CC19   if (RC == 0) goto 19            if (c == 0) break;
15: 16AB   R6 ← RA + RB                    address of a[n]
16: BC06   mem[R6] ← RC                    a[n] = c;
17: 1BB1   RB ← RB + R1                    n++;
18: C013   goto 13                      }
```

read in the data

TOY Implementation of Reverse

TOY implementation of reverse.

- Read in a sequence of integers and store in memory `30`, `31`, `32`, …
  - stop reading if `0000`
- Print sequence in reverse order.

```
19: CB20   if (RB == 0) goto 20      while (n > 0) {
1A: 16AB   R6 ← RA + RB                 address of a[n]
1B: 2661   R6 ← R6 – R1                 address of a[n-1]
1C: AC06   RC ← mem[R6]                 c = a[n-1];
1D: 9CFF   write RC                     System.out.println(c);
1E: 2BB1   RB ← RB – R1                 n--;
1F: C019   goto 19                   }
20: 0000   halt
```

Unsafe Code at any Speed

What happens if we make array start at `00` instead of `30`?

- Self modifying program.
- Exploit buffer overflow and run arbitrary code!

```
10: 7101   R1 ← 0001                    constant 1
11: 7A00   RA ← 0000                    a[]
12: 7B00   RB ← 0000                    n

                                        while(true) {
13: 8CFF   read RC                         c = StdIn.readInt();
14: CC19   if (RC == 0) goto 19            if (c == 0) break;
15: 16AB   R6 ← RA + RB                    address of a[n]
16: BC06   mem[R6] ← RC                    a[n] = c;
17: 1BB1   RB ← RB + R1                    n++;
18: C013   goto 13                      }
```

Crazy 8s Input

```
1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1
8888 8810
98FF C011
```

Dumping

Dumping.

- Work all day to develop operating system.
- How do you save it for tomorrow?
  - leave computer on?
  - write short program `dump.toy`
  - run `dump.toy` to dump contents of memory onto tape

```
00: 7001   R1 ← 0001
01: 7210   R2 ← 0010                 i = 10
02: 73FF   R3 ← 00FF
                                     do {
03: AA02   RA ← mem[R2]                 a = mem[i]
04: 9AFF   write RA                     print a
05: 1221   R2 ← R2 + R1                 i++
06: 2432   R4 ← R3 - R2
07: D403   if (R4 > 0) goto 03       } while (i < 255)
08: 0000   halt
```

dump.toy

Booting

Booting.

- How do you get it back?
  - turn on computer, old memory values gone
  - write short program `boot.toy`
  - read contents of memory from tape by running `boot.toy`
  - use original program

```
00: 7001   R1 ← 0001
01: 7210   R2 ← 0010               i = 10
02: 73FF   R3 ← 00FF
                                   do {
03: 8AFF   read RA                    read a
04: BA02   mem[R2] ← RA               mem[i] = a
05: 1221   R2 ← R2 + R1               i++
06: 2432   R4 ← R3 - R2
07: D403   if (R4 > 0) goto 03     } while (i < 255)
08: 0000   halt
```

boot.toy

TOY Simulator

Write a program to "simulate" the behavior of the TOY machine.

- ➡ TOY simulator in Java.
- TOY simulator in TOY!

```
public class TOY {
   public static void main(String[] args) {
      int pc     = 0x10;            // program counter
      int[] R    = new int[16];     // registers
      int[] mem  = new int[256];    // main memory

      // READ IN .toy FILE

      while(true) {
         // FETCH INSTRUCTION and DECODE
         ...
         // EXECUTE
         ...
      }
   }
}
```

```
% java TOY add-stdin.toy
A012
002B
A03D
```

TOY Simulator: Fetch

Extract destination register of `1CAB` by shifting and masking.

0	0	0	1	1	1	0	0	1	0	1	0	1	0	1	1	inst
1_{16}				C_{16}				A_{16}				B_{16}				

0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	inst >> 8
0_{16}				0_{16}				1				C_{16}				

0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	15
0_{16}				0_{16}				0_{16}				F_{16}				

0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	(inst >> 8) & 15
0_{16}				0_{16}				0				C_{16}				

```
int inst = mem[pc++];             // fetch and increment
int op   = (inst >> 12) &  15;    // opcode     (bits 12-15)
int d    = (inst >>  8) &  15;    // dest d     (bits 08-11)
int s    = (inst >>  4) &  15;    // source s   (bits 04-07)
int t    = (inst >>  0) &  15;    // source t   (bits 00-03)
int addr = (inst >>  0) & 255;    // addr       (bits 00-07)
```

TOY Simulator: Execute

```
if (op == 0) break;        // halt

switch (op) {
   case  1: R[d] = R[s] +  R[t];          break;
   case  2: R[d] = R[s] -  R[t];          break;
   case  3: R[d] = R[s] &  R[t];          break;
   case  4: R[d] = R[s] ^  R[t];          break;
   case  5: R[d] = R[s] << R[t];          break;
 † case  6: R[d] = R[s] >> R[t];          break;
   case  7: R[d] = addr;                  break;
   case  8: R[d] = mem[addr];             break;
   case  9: mem[addr] = R[d];             break;
   case 10: R[d] = mem[R[t]];             break;
   case 11: mem[R[t]] = R[d];             break;
   case 12: if (R[d] == 0) pc = addr;     break;
 † case 13: if (R[d] >  0) pc = addr;     break;
   case 14: pc = R[d];                    break;
   case 15: R[d] = pc; pc = addr;         break;
}
```

TOY Simulator: Missing Details

Omitted details.

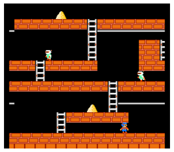
- Register 0 is always 0.
  - reset to `0000` after each fetch-execute step
- Standard input and output.
  - if `addr` is `FF` and opcode is load (indirect) then read in data
  - if `addr` is `FF` and opcode is store (indirect) then write out data
- TOY registers are 16-bit integers; program counter is 8-bit.
  - Java `int` is 32 bits

See `TOY.java` for full details.

Simulation

Consequences of simulation.

- Test out new machine or microprocessor using simulator.
  - cheaper and faster than building actual machine
- Easy to add new functionality to simulator.
  - trace, single-step, breakpoint debugging
  - simulator more useful than TOY itself
- Reuse software from old machines.



Ancient programs still running on modern computers.

- Ticketron.
- Lode Runner on Apple IIe.

Announcments

Not-exactly Midterm Exam

- Not, repeat not next week!
- Wed March 23, 7:30 PM, right here
- Closed book, but
- You can bring one *cheatsheet*
  - one side of one (8.5 by 11) sheet, handwritten by you
- P.S. No calculators, laptops, Palm Pilots, talking watches, etc.

Helpful review session

- Tuesday March 22, 7:30 PM, COS 105
- Not a canned presentation
- Driven by your questions