5. The TOY Machine II

Laboratory Instrument Computer (LINC)

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What We've Learned About TOY

TOY machine.

- Box with switches and lights.
- 16-bit memory locations, 16-bit registers, 8-bit pc.
- 4,328 bits $= (255 \times 16) + (15 \times 16) + (8) =$ 541 bytes!
- von Neumann architecture.

TOY programming.

- TOY instruction set architecture: 16 instruction types.
- Variables, arithmetic, loops.

What We Do Today

Data representation. Negative numbers.

Input and output. Standard input, standard output.

Manipulate addresses. References (pointers) and arrays.

TOY simulator in Java.

Data Representation

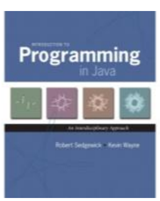
Digital World

Data is a sequence of bits. (interpreted in different ways)

- Integers, real numbers, characters, strings, …
- Documents, pictures, sounds, movies, Java programs, …

Ex. `01110101`

- As binary integer: $1 + 4 + 16 + 32 + 64 = 117_{10}$.
- As character: 117^{th} Unicode character = `'u'`.
- As music: 117/256 position of speaker.
- As grayscale value: 45.7% black.




```
public class HelloWorld {

    public static void main(String[] args) {
        System.out.println("Hello, World");
    }

}
```

Adding and Subtracting Binary Numbers

Decimal and binary addition.

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
```

Subtraction. Add a negative integer.

e.g., 6 - 4 = 6 + (-4))

Q. How to represent negative integers?

Representing Negative Integers

TOY words are 16 bits each.

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

Highly desirable property. If x is an integer, then the representation of -x, when added to x, is 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
                                   -----------------
flip bits and add 1   +(-x)          1 1 1 1 1 1 1 1
                                   +               1
                      -----        -----------------
                          0          0 0 0 0 0 0 0 0
```

Two's Complement Integers

To compute -x from x:

- Start with x.

leading bit

+4	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0

- Flip bits.

-5	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1

- Add one.

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

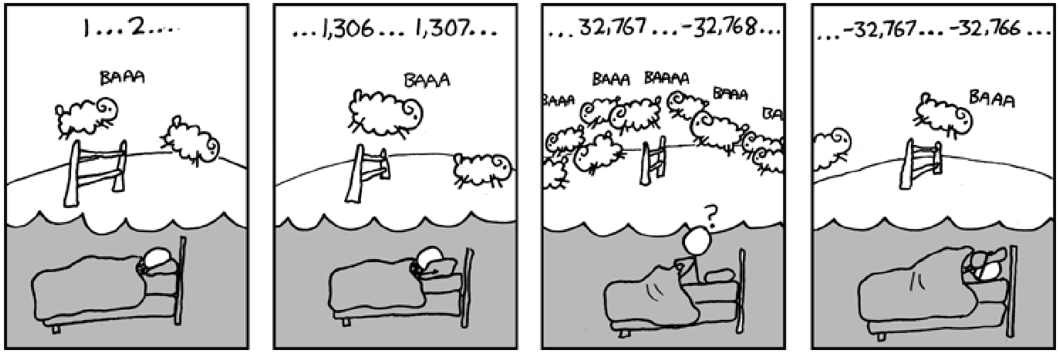
Two's Complement Integers

		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

Properties.
- Leading bit (bit 15) signifies sign.
- Addition and subtraction are easy.
- `0000000000000000` represents zero.
- Checking for arithmetic overflow is easy.
- Negative integer -x represented by 2^{16} - x.
- Not symmetric: can represent -32,768 but not 32,768.

Java. Java's `int` data type is a 32-bit two's complement integer.
Ex. `2147483647 + 1` equals `-2147483648`.



`http://xkcd.com/571`

Representing Other Primitive Data Types in TOY

Bigger integers. Use two 16-bit TOY words per 32-bit Java **`int`**.

Real numbers.
- Use IEEE floating point (like scientific notation).
- Use four 16-bit TOY words per 64-bit Java **`double`**.

Characters. Use one 16-bit TOY word per 16-bit Java Unicode **`char`**.

	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0	NUL	SOH	STX	ETX	EOT	ENQ	ACK	BEL	BS	HT	LF	VT	FF	CR	SO	SI
1	DLE	DC1	DC2	DC3	DC4	NAK	SYN	ETB	CAN	EM	SUB	ESC	FS	GS	RS	US
2	SP	!	"	#	$	%	&	'	(	)	*	+	,	-	.	/
3	0	1	2	3	4	5	6	7	8	9	:	;	<	=	>	?
4	@	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
5	P	Q	R	S	T	U	V	W	X	Y	Z	[	\	]	^	_
6	`	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o
7	p	q	r	s	t	u	v	w	x	y	z	{	|	}	~	DEL

Hexadecimal-to-ASCII conversion table

$\texttt{M} = 01001101_2 = \texttt{4D}_{16}$
$\texttt{O} = 01001111_2 = \texttt{4F}_{16}$
$\texttt{M} = 01001101_2 = \texttt{4D}_{16}$

Note. Real microprocessors add hardware support for **`int`** and **`double`**.

Standard Input and Output

Standard Output

Standard output.

- Writing to memory location **FF** sends one word to TOY stdout.
- Ex. **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
                                     do {
12: 9AFF   write RA to stdout           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       } while (a > 0)
16: 0000   halt
```

fibonacci.toy

```
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.
- Ex. **8AFF** reads an integer from stdin and store 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;
}
StdOut.println(sum);
```

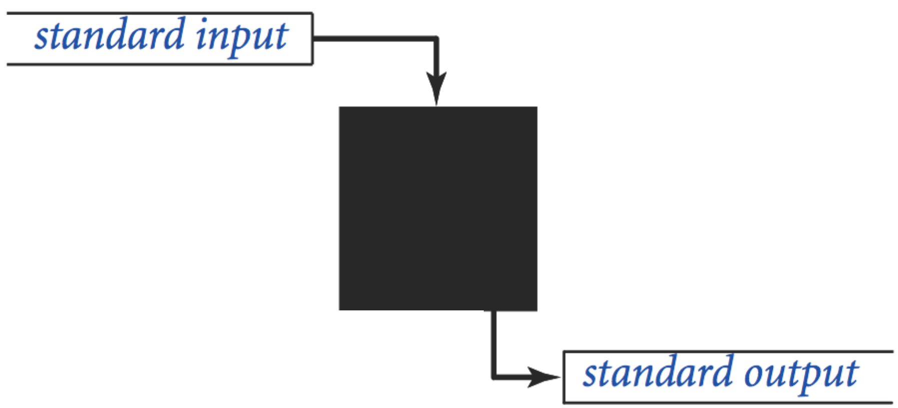
```
00: 0000   0

10: 8C00   RC <- mem[00]
11: 8AFF   read RA from stdin
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:

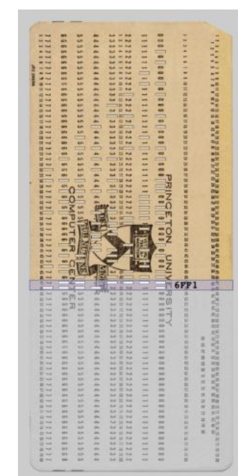
- Get information out of machine.
- Put information from real world into machine.
- Process more information than fits in memory.
- Interact with the computer while it is running.



redirected from punchcard

by default: flip switch, press button

by default: LED



redirected to punchcard

Pointers

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 = 0x30;
```

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.

…	…
30	0000
31	0001
32	0001
33	0002
34	0003
35	0005
36	0008
37	000D
…	…

TOY memory

Load indirect. [opcode A]

a variable index

- **AC06** means load **mem[R6]** into register C.

Store indirect. [opcode B]

a variable index

- **BC06** 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++)
   StdOut.println(a[N-i-1]);
```

TOY Implementation of Reverse

TOY implementation of reverse.

- Read in a sequence of integers and store in memory 30, 31, 32, … until reading 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                    memory 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, …
  until reading 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                         StdOut.println(c);
1E: 2BB1   RB ← RB - R1                     n--;
1F: C019   goto 19                       }
20: 0000   halt
```

print in reverse order

Unsafe Code at any Speed

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

A. Self modifying program; can overflow buffer 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                     }
```

```
% more crazy8.txt
1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1
8888 8810
98FF C011
```

What Can Happen When We Lose Control (in C or C++)?

Buffer overflow.

- Array `buffer[]` has size 100.
- User might enter 200 characters.
- Might lose control of machine behavior.

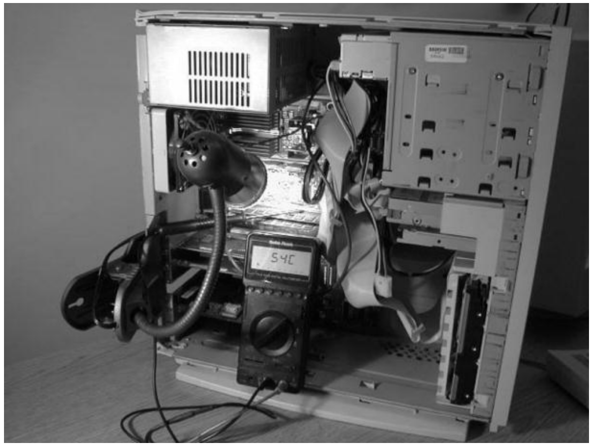
```
#include <stdio.h>
int main(void) {
   char buffer[100];
   scanf("%s", buffer);
   printf("%s\n", buffer);
   return 0;
}
```

unsafe C program

Consequences. Viruses and worms.

Java enforces security.

- Type safety.
- Array bounds checking.
- Not foolproof.



shine 50W bulb at DRAM
[Appel-Govindavajhala '03]

Buffer Overflow Attacks

Stuxnet worm. [July 2010]

- Step 1. Natanz centrifuge fuel-refining plant employee plugs in USB flash drive.
- Step 2. Data becomes code by exploiting Window buffer overflow; machine is Owned.
- Step 3. Uranium enrichment in Iran stalled.

More buffer overflow attacks: Morris worm, Code Red, SQL Slammer, iPhone unlocking, Xbox softmod, JPEG of death, …

Lesson.

- Not easy to write error-free software.
- Embrace Java security features.
- Keep your OS patched.

Buffer Overflow Example: JPEG of Death

Microsoft Windows JPEG bug. [September, 2004]

- Step 1. User views malicious JPEG in IE or Outlook.
- Step 2. Machine is Owned.
- Data becomes code by exploiting buffer overrun in GDI+ library.

Fix. Update old library with patched one.

but many applications install independent copies of GDI library

Moral.

- Not easy to write error-free software.
- Embrace Java security features.
- Don't try to maintain several copies of the same file.
- Keep your OS patched.

Dumping

Q. Work all day to develop operating system in **`mem[10]`** to **`mem[FF]`**. How to save it?

A. Write short program **`dump.toy`** and run it 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

Q. How do you get it back?

A. Write short program `boot.toy` and run it to read contents of `mem[10]` to `mem[FF]` from tape.

```
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`

Extra Slides

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
or carry out out of sign bit with no carry in

+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

Java and TOY

Correspondence between Java constructs and TOY mechanisms.

Java	TOY
assignment	load, store
arithmetic expressions	add, subtract
logical expressions	xor, and, shifts
loops (for, while)	jump absolute, branch
branches (if-else, switch)	branch if zero, positive
arrays, linked lists	indirect addressing
function call	jump and link, jump indirect
recursion	implement stack with arrays
whitespace	no-op 1000
. . .	. . .