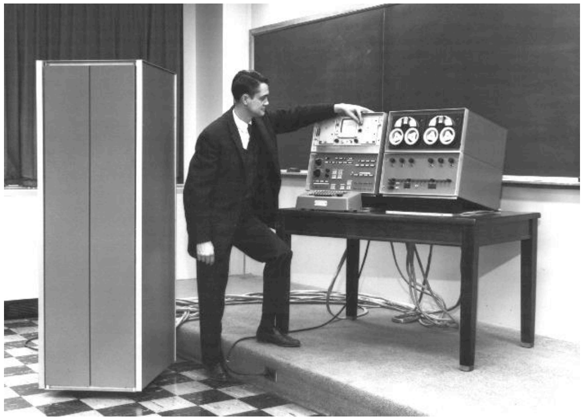
TOY II



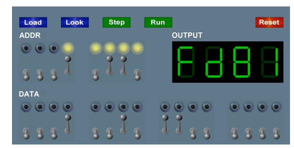
LINC

What We've Learned About TOY

Data representation. Binary and hex.

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

TOY instruction set architecture. 16 instruction types.
TOY machine language programs. Variables, arithmetic, loops.



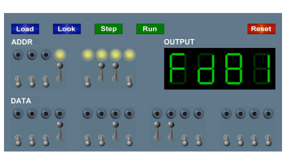
What We Do Today

Data representation. Negative numbers.

Input and output. Standard input, standard output.

Manipulate addresses. References (pointers) and arrays.

TOY simulator in Java and implications.



Data Representation

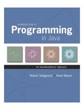
Digital World

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 (base ten).
- 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
 +(-x)        1 1 1 1 1 1 1 1
            +               1
    0         0 0 0 0 0 0 0 0
```

-x: flip bits and add 1

Two's Complement Integers

To compute -x from x:

- Start with x.

leading bit determines sign

+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.
- `0000000000000000` represents zero.
- Negative integer -x represented by $2^{16} - x$.
- Addition is easy.
- Checking for arithmetic overflow is easy.

Not-so-nice property. Can represent one more negative integer than positive integer.

$-32,768 = -2^{15}$

$32,767 = 2^{15}-1$

Remark. Java `int` data type is 32-bit two's complement integer.

Representing Other Primitive Data Types in TOY

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

Real numbers.

- Use "floating point" (like scientific notation).
- Use four 16-bit words per **`double`**.

Characters.

- Use ASCII code (8 bits / character).
- Pack two characters per 16-bit word.

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
                                   while(a > 0) {
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     }
16: 0000   halt
```

fibonacci.toy

standard output

```
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.

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

a variable index

Store indirect. [opcode B]
- `BC06` means store contents of register `C` into `mem[R6]`.

a variable index

```
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`, …
- 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                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`, …
- 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                    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?

```
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
```

A. With enough data, becomes a self-modifying program
- can overflow buffer
- and run arbitrary code!

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

Buffer overrun.
- 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.

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

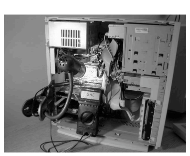
Buffer overrun.
- Array `buffer[]` has size 100.
- User might enter 200 characters.
- Might lose control of machine behavior.

```
#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 Overrun 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. 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 memory 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

TOY Simulator

TOY Simulator

Goal. 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 .toy FILE into mem[10..]

      while (true)
      {
         int inst = mem[pc++];   // fetch and increment
         // DECODE
         // EXECUTE
      }
   }
}
```

```
% more add-stdin.toy
8C00    ← TOY program to load at 10
8AFF
CA15
1CCA
C011
9CFF
0000

% java TOY add-stdin.toy
00AE    ← standard input
0046
0003
0000
00F7    ← standard output
```

TOY Simulator: Decode

Ex. 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]; pc; pc = addr; break;
    case 15: R[d] = pc; pc = addr;     break;
}
```


TOY Simulator: Omitted Details

Omitted details.

- Register 0 is always 0.
  - reset `R[0]=0` 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-bit; Java `short` is 16-bit
  - use casts and bit-whacking

Complete implementation. See `TOY.java` on booksite.

Simulation

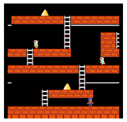
Profound ideas stemming from simulation.

- Backwards compatiblity
- Virtual machines
- Layers of abstraction

Backwards Compatibility

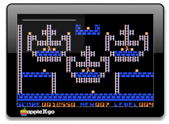
Building a new computer? Need a plan for old software.

Two possible approaches
- Rewrite software (costly, error-prone, boring, and time-consuming).
- Simulate old computer on new computer.



Lode Runner

Apple IIe



Mac OS X Apple IIe emulator widget running Lode Runner

Ancient programs still running on modern computers.
- Payroll
- Power plants
- Air traffic control
- Ticketron.
- Games.

Backwards Compatibility

Q. Why is standard US rail gauge 4 feet, 8.5 inches?

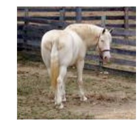
A. Same spacing as wheel ruts on old English roads.

Q. Why is wheel rut spacing 4 feet, 8.5 inches?

A. For Roman war chariots.

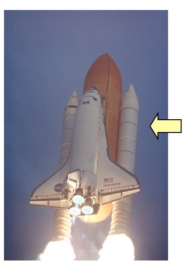
Q. Why is war chariot rut spacing 4 feet, 8.5 inches?

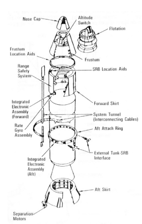
A. Fits "back ends" of two war horses!



Effects of Backwards Compatibility: example 1

Q. Why is Space Shuttle SRB long and narrow?

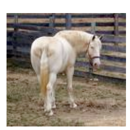




A. Fits on standard US rail guage.

. . .

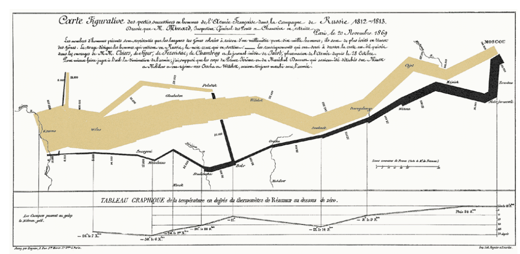
A. Fits "back ends" of two war horses!



Effects of Backwards Compatibility: Example 2

Napoleon's march on Russia.

- Progress slower than expected.
- Eastern European ruts didn't match Roman gauge.
- Stuck in the field during Russian winter instead of Moscow.
- Lost war.



Lessons.
- Maintaining backwards compatibility can lead to inelegance and inefficiency.
- Maintaining backwards compatibility is Not Always A Good Thing.
- May need fresh ideas to conquer civilized world.

Virtual machines

Building a new airplane? Simulate it to test it.

- Issue 1: Simulation may not reflect reality.
- Issue 2: May not be able to afford simulation.

Building a new computer? Simulate it to test it.

- Advantage 1: Simulation is reality (it defines the new machine).
- Advantage 2: Can develop software without having machine.
- Advantage 3: Can simulate machines you wouldn't build.

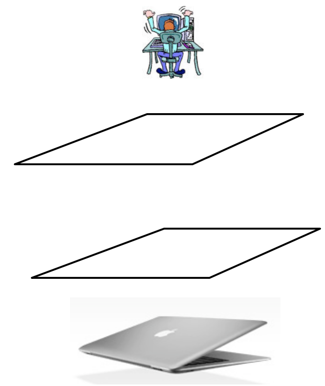
Example 1: An operating system can implement a Virtual Memory that is much larger than a real memory by simulating programs and going to disk or the web to reference "memory"

Example 2: An operating system can implement multiple Virtual Machines on the same real machine by keeping track of multiple PCs and rotating control to the different machines

Layers of Abstraction

Is TOY real?

Is Java real?



Approaching a new problem?

- build an (abstract) language for expressing solutions — Examples: MATLAB, BLAST, AMP ....
- design an (abstract) machine to execute the language
- food for thought: Why build the machine?

simulate it instead