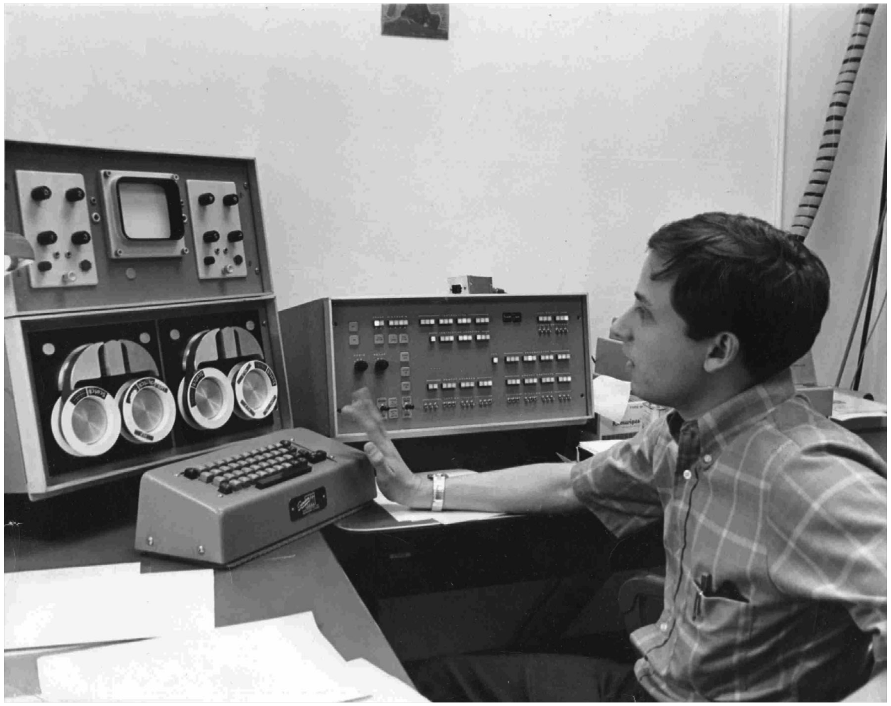
5. The TOY Machine II



Laboratory Instrument Computer (LINC)

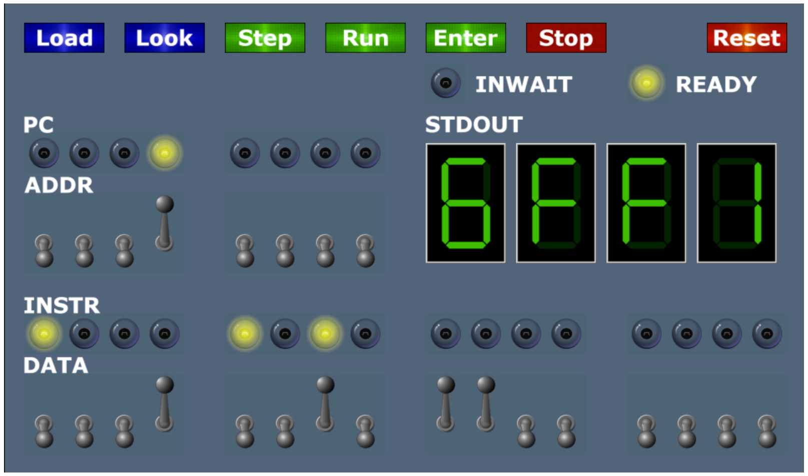
What We've Learned About TOY

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.



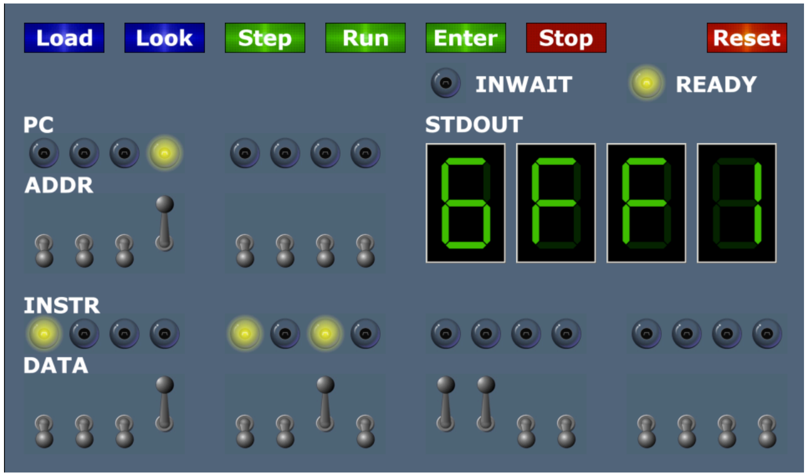
What We Do Today

Data representation. Negative numbers.

Input and output. Standard input, standard output.

Manipulate addresses. References (pointers) and arrays.

TOY simulator in Java.



Data Representation

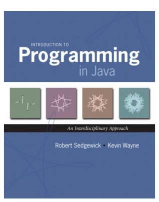
Digital World

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: 117th Unicode character = `'u'`.
- As music: 117/256 position of speaker.
- As grayscale value: 45.7% black.




```java
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
```

flip bits and add 1

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

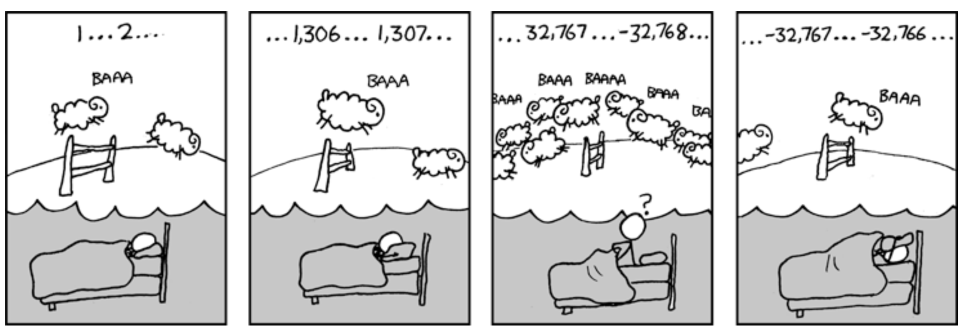
Properties of Two's Complement Integers

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 -32768 but not 32768.

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 Unicode (16 bits per char).
- Use one 16-bit TOY word per 16-bit Java **`double`**.

	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

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

Standard Input and 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`.

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

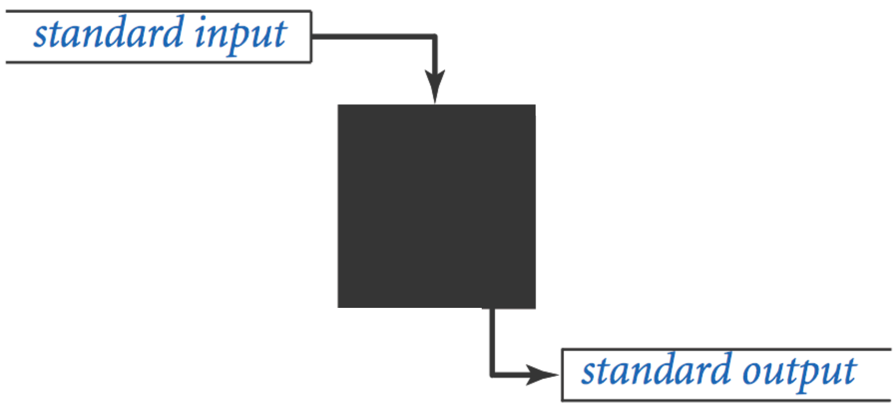
```
00: 0000   0

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
```

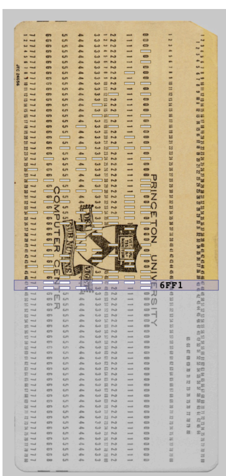
```
00AE
0046
0003
0000
00F7
```

Standard Input and Output: Implications

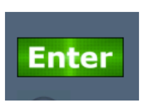
Standard input and output enable you to:

- 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.



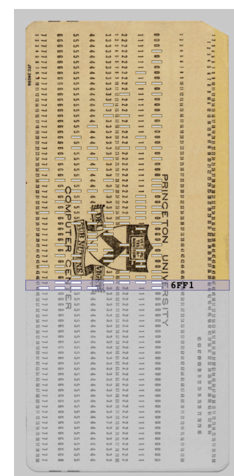


redirected from punchcard



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, …
- 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?

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.

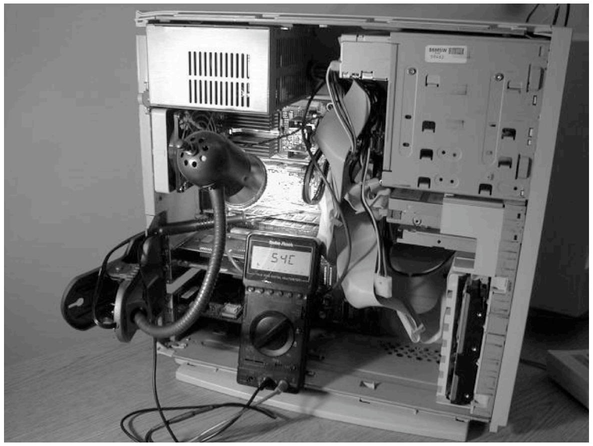
```
#include <stdio.h>
int main(void) {
   char buffer[100];
   scanf("%s", buffer);
   printf("%s\n", buffer);
   return 0;
}
```

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 Example: JPEG of Death

Stuxnet worm. [July 2010]

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

Buffer overflow attacks. Morris worm, Code Red, SQL Slammer, iPhone unlocking, Xbox softmod, GDI+ library for JPEG, …

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 IN .toy FILE

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

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

standard input: A012, 002B
standard output: A03D

TOY Simulator: Fetch

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]; 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

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)
- Reuse software from old machines.

Ancient programs still running on modern computers.

- Ticketron.
- Lode Runner on Apple IIe.