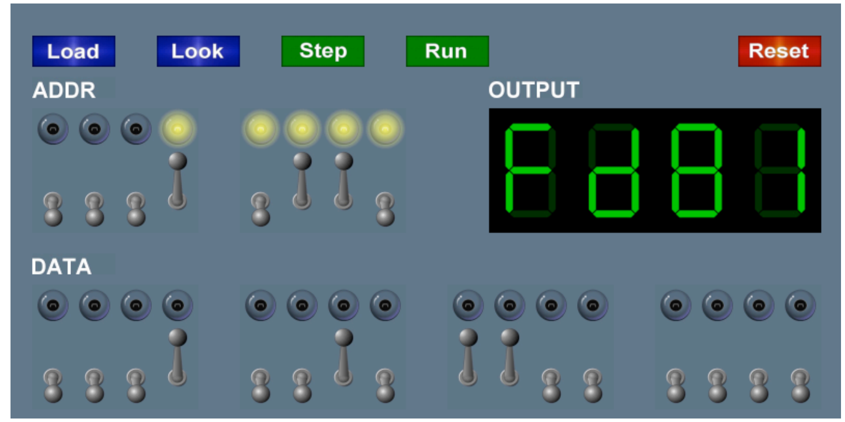
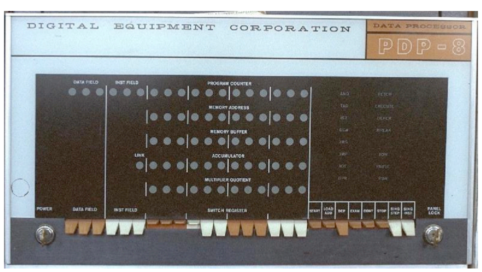
5. The TOY Machine



What is TOY?

An imaginary machine similar to:

- Ancient computers.
- Today's microprocessors.



Why Study TOY?

Machine language programming.

- How do Java programs relate to computer?
- Key to understanding Java references.
- Still situations today where it is really necessary.

multimedia, computer games, embedded devices, scientific computing, MMX, Altivec

Computer architecture.

- How does it work?
- How is a computer put together?

TOY machine. Optimized for simplicity, not cost or performance.

Inside the Box

Switches. Input data and programs.

Lights. View data.

Memory.
- Stores data and programs.
- 256 16-bit "words."
- Special word for stdin / stdout.

Program counter (PC).
- An extra 8-bit register.
- Keeps track of next instruction to be executed.

Registers.
- Fastest form of storage.
- Scratch space during computation.
- 16 16-bit registers.
- Register 0 is always 0.

Arithmetic-logic unit (ALU). Manipulate data stored in registers.

Standard input, standard output. Interact with outside world.

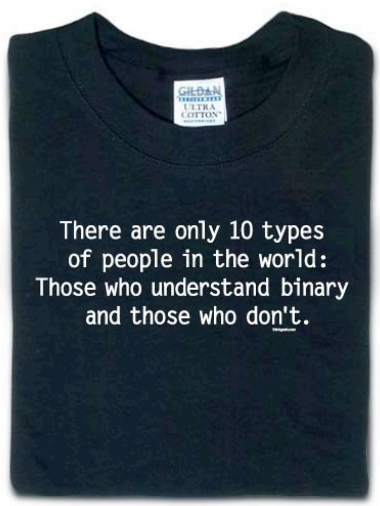
Data and Programs Are Encoded in Binary

Each bit consists of two states:
- 1 or 0; true or false.
- Switch is on or off; wire has high voltage or low voltage.

Everything stored in a computer is a sequence of bits.
- Data and programs.
- Text, documents, pictures, sounds, movies, executables, ...

$M = 77_{10} = 01001101_2 = 4D_{16}$
$O = 79_{10} = 01001111_2 = 4F_{16}$
$M = 77_{10} = 01001101_2 = 4D_{16}$

Binary People



http://www.thinkgeek.com/tshirts/frustrations/5aa9/zoom/

Binary Encoding

How to represent integers?
- Use binary encoding.
- Ex: $6375_{10} = 0001100011100111_2$

Dec	Bin	Dec	Bin
0	0000	8	1000
1	0001	9	1001
2	0010	10	1010
3	0011	11	1011
4	0100	12	1100
5	0101	13	1101
6	0110	14	1110
7	0111	15	1111

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

$$6375_{10} = +2^{12} +2^{11} +2^{7} +2^{6} +2^{5} +2^{2} +2^{1} +2^{0}$$
$$= 4096 +2048 +128 +64 +32 +4 +2 +1$$

Hexadecimal Encoding

How to represent integers?

- Use hexadecimal encoding.
- Binary code, four bits at a time.
- Ex: 6375_{10} = 0001100011100111_2
  = $18E7_{16}$

Dec	Bin	Hex	Dec	Bin	Hex
0	0000	0	8	1000	8
1	0001	1	9	1001	9
2	0010	2	10	1010	A
3	0011	3	11	1011	B
4	0100	4	12	1100	C
5	0101	5	13	1101	D
6	0110	6	14	1110	E
7	0111	7	15	1111	F

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
1				8				E				7			

$$6375_{10} = 1 \times 16^3 + 8 \times 16^2 + 14 \times 16^1 + 7 \times 16^0$$
$$= 4096 + 2048 + 224 + 7$$

Machine "Core" Dump

Machine contents at a particular place and time.

- Record of what program has done.
- Completely determines what machine will do.

Registers

R0	R1	R2	R3
0000	0000	0000	0000
R4	**R5**	**R6**	**R7**
0000	0000	0000	0000
R8	**R9**	**RA**	**RB**
0000	0000	0000	0000
RC	**RD**	**RE**	**RF**
0000	0000	0000	0000

pc: 10 — index of next instruction

Main Memory

00:	0008	0005	0000	0000	0000	0000	0000	0000
08:	0000	0000	0000	0000	0000	0000	0000	0000
10:	8A00	8B01	1CAB	9C02	0000	0000	0000	0000
18:	0000	0000	0000	0000	0000	0000	0000	0000
20:	0000	0000	0000	0000	0000	0000	0000	0000
28:	0000	0000	0000	0000	0000	0000	0000	0000
.								
.								
E8:	0000	0000	0000	0000	0000	0000	0000	0000
F0:	0000	0000	0000	0000	0000	0000	0000	0000
F8:	0000	0000	0000	0000	0000	0000	0000	0000

data

program

variables

A Sample Program

A sample program. Adds 0008 + 0005 = 000D.

RA	RB	RC
0000	0000	0000

Registers

pc
10

Program counter

TOY memory (program and data)

comments

```
00: 0008    8
01: 0005    5
02: 0000    0

10: 8A00    RA ← mem[00]
11: 8B01    RB ← mem[01]
12: 1CAB    RC ← RA + RB
13: 9C02    mem[02] ← RC
14: 0000    halt
```

add.toy

A Sample Program

Program counter. The pc is initially 10, so the machine interprets 8A00 as an instruction.

RA	RB	RC
0000	0000	0000

Registers

pc
10

Program counter

index of next instruction to execute

```
00: 0008    8
01: 0005    5
02: 0000    0

10: 8A00    RA ← mem[00]
11: 8B01    RB ← mem[01]
12: 1CAB    RC ← RA + RB
13: 9C02    mem[02] ← RC
14: 0000    halt
```

add.toy

Load

Load. [opcode 8]

- Loads the contents of some memory location into a register.
- 8A00 means load the contents of memory cell 00 into register A.

RA	RB	RC
0000	0000	0000

Registers

pc
10

Program counter

```
00: 0008    8
01: 0005    5
02: 0000    0

10: 8A00    RA ← mem[00]
11: 8B01    RB ← mem[01]
12: 1CAB    RC ← RA + RB
13: 9C02    mem[02] ← RC
14: 0000    halt
```

add.toy

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
8_{16}				A_{16}				00_{16}							
opcode				dest d				addr							

Load

Load. [opcode 8]

- Loads the contents of some memory location into a register.
- 8B01 means load the contents of memory cell 01 into register B.

RA	RB	RC
0008	0000	0000

Registers

pc
11

Program counter

```
00: 0008    8
01: 0005    5
02: 0000    0

10: 8A00    RA ← mem[00]
11: 8B01    RB ← mem[01]
12: 1CAB    RC ← RA + RB
13: 9C02    mem[02] ← RC
14: 0000    halt
```

add.toy

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	0	1	0	1	1	0	0	0	0	0	0	0	1
8_{16}				B_{16}				01_{16}							
opcode				dest d				addr							

Add

Add. [opcode 1]

- Add contents of two registers and store sum in a third.
- 1CAB means add the contents of registers A and B and put the result into register C.

RA	RB	RC
0008	0005	0000

Registers

pc
12

Program counter

```
00: 0008    8
01: 0005    5
02: 0000    0

10: 8A00    RA ← mem[00]
11: 8B01    RB ← mem[01]
12: 1CAB    RC ← RA + RB
13: 9C02    mem[02] ← RC
14: 0000    halt
```

add.toy

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

Store

Store. [opcode 9]

- Stores the contents of some register into a memory cell.
- 9C02 means store the contents of register C into memory cell 02.

RA	RB	RC
0008	0005	000D

Registers

pc
13

Program counter

```
00: 0008    8
01: 0005    5
02: 0000    0

10: 8A00    RA ← mem[00]
11: 8B01    RB ← mem[01]
12: 1CAB    RC ← RA + RB
13: 9C02    mem[02] ← RC
14: 0000    halt
```

add.toy

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	1	1	1	0	0	0	0	0	0	0	0	1	0
9_{16}				C_{16}				02_{16}							
opcode				dest d				addr							

Halt

Halt. [opcode 0]

- Stop the machine.

RA	RB	RC
0008	0005	000D

Registers

pc
14

Program counter

```
00: 0008   8
01: 0005   5
02: 000D   D

10: 8A00   RA ← mem[00]
11: 8B01   RB ← mem[01]
12: 1CAB   RC ← RA + RB
13: 9C02   mem[02] ← RC
14: 0000   halt
```

add.toy

Program and Data

Program. Sequence of 16-bit integers, interpreted one way.

Data. Sequence of 16-bit integers, interpreted other way.

Program counter (pc). Holds memory address of the "next instruction" and determines which integers get interpreted as instructions.

16 instruction types. Changes contents of registers, memory, and pc in specified, well-defined ways.

	Instructions
→ 0:	halt
→ 1:	add
2:	subtract
3:	and
4:	xor
5:	shift left
6:	shift right
7:	load address
→ 8:	load
→ 9:	store
A:	load indirect
B:	store indirect
C:	branch zero
D:	branch positive
E:	jump register
F:	jump and link

TOY Instruction Set Architecture

TOY instruction set architecture (ISA).

- Interface that specifies behavior of machine.
- 16 register, 256 words of main memory, 16-bit words.
- 16 instructions.

Each instruction consists of 16 bits.

- Bits 12-15 encode one of 16 instruction types or opcodes.
- Bits 8-11 encode destination register d.
- Bits 0-7 encode:
  - [Format 1] source registers s and t
  - [Format 2] 8-bit memory address or constant

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
	1	0	1	1	1	0	1	0	0	0	0	0	0	1	0	0
Format 1	opcode				dest d				source s				source t			
Format 2	opcode				dest d				addr							

TOY Reference Card

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Format 1	opcode				dest d				source s				source t			
Format 2	opcode				dest d				addr							

#	Operation	Fmt	Pseudocode
0:	halt	1	exit(0)
1:	add	1	R[d] ← R[s] + R[t]
2:	subtract	1	R[d] ← R[s] - R[t]
3:	and	1	R[d] ← R[s] & R[t]
4:	xor	1	R[d] ← R[s] ^ R[t]
5:	shift left	1	R[d] ← R[s] << R[t]
6:	shift right	1	R[d] ← R[s] >> R[t]
7:	load addr	2	R[d] ← addr
8:	load	2	R[d] ← mem[addr]
9:	store	2	mem[addr] ← R[d]
A:	load indirect	1	R[d] ← mem[R[t]]
B:	store indirect	1	mem[R[t]] ← R[d]
C:	branch zero	2	if (R[d] == 0) pc ← addr
D:	branch positive	2	if (R[d] > 0) pc ← addr
E:	jump register	2	pc ← R[d]
F:	jump and link	2	R[d] ← pc; pc ← addr

Register 0 always 0.
Loads from mem[FF] from stdin.
Stores to mem[FF] to stdout.

TEQ on TOY 1

What is the interpretation of **1A75**

A. as a TOY instruction?

B. as an integer value?

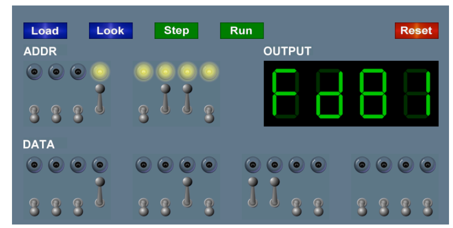
Interfacing with the TOY Machine

To enter a program or data:

- Set 8 memory address switches.
- Set 16 data switches.
- Press `Load`: data written into addressed word of memory.

To view the results of a program:

- Set 8 memory address switches.
- Press `Look`: contents of addressed word appears in lights.



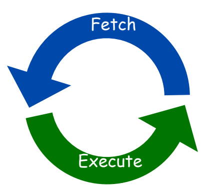
Using the TOY Machine: Run

To run the program:

- Set 8 memory address switches to address of first instruction.
- Press `Look` to set `pc` to first instruction.
- Press `Run` button to repeat fetch-execute cycle until halt opcode.

Fetch-execute cycle.

- Fetch: get instruction from memory.
- Execute: update `pc` move data to or from memory and registers, perform calculations.



Flow Control

Flow control.

- To harness the power of TOY, need loops and conditionals.
- Manipulate `pc` to control program flow.

Branch if zero. [opcode C]

- Changes `pc` depending on whether value of some register is zero.
- Used to implement: `for`, `while`, `if-else`.

Branch if positive. [opcode D]

- Changes `pc` depending on whether value of some register is positive.
- Used to implement: `for`, `while`, `if-else`.

An Example: Multiplication

Multiply. Given integers `a` and `b`, compute `c = a × b`.

TOY multiplication. No direct support in TOY hardware.

Brute-force multiplication algorithm:

- Initialize `c` to `0`.
- Add `b` to `c`, `a` times.

```
int a = 3;
int b = 9;
int c = 0;

while (a != 0) {
   c = c + b;
   a = a - 1;
}
```

brute force multiply in Java

Issues ignored. Slow, overflow, negative numbers.

Multiply

```
0A: 0003    3    ← inputs
0B: 0009    9
0C: 0000    0    ← output

0D: 0000    0    ← constants
0E: 0001    1

10: 8A0A    RA ← mem[0A]                a
11: 8B0B    RB ← mem[0B]                b
12: 8C0D    RC ← mem[0D]                c = 0

13: 810E    R1 ← mem[0E]                always 1

14: CA18    if (RA == 0) pc ← 18        while (a != 0) {
15: 1CCB    RC ← RC + RB                   c = c + b
16: 2AA1    RA ← RA - R1                   a = a - 1
17: C014    pc ← 14                     }

18: 9C0C    mem[0C] ← RC
19: 0000    halt
```

loop

multiply.toy

Step-By-Step Trace

Instruction		R1	RA	RB	RC
10: 8A0A	RA ← mem[0A]		0003		
11: 8B0B	RB ← mem[0B]			0009	
12: 8C0D	RC ← mem[0D]				0000
13: 810E	R1 ← mem[0E]	0001			
14: CA18	if (RA == 0) pc ← 18				
15: 1CCB	RC ← RC + RB				0009
16: 2AA1	RA ← RA – R1		0002		
17: C014	pc ← 14				
14: CA18	if (RA == 0) pc ← 18				
15: 1CCB	RC ← RC + RB				0012
16: 2AA1	RA ← RA – R1		0001		
17: C014	pc ← 14				
14: CA18	if (RA == 0) pc ← 18				
15: 1CCB	RC ← RC + RB				001B
16: 2AA1	RA ← RA – R1		0000		
17: C014	pc ← 14				
14: CA18	if (RA == 0) pc ← 18				
18: 9C0C	mem[0C] ← RC				
19: 0000	halt				

multiply.toy

TEQ on TOY 2

What does the following TOY program leave in R2?

```
10: 7C0A
11: 7101
12: 7201
13: 5221
14: 2CC1
15: DC13
16: 0000
```

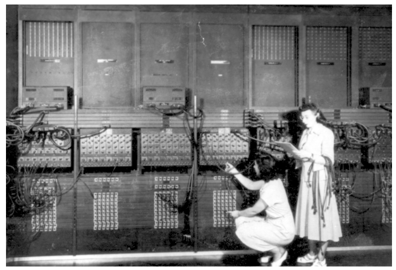
A Little History

Electronic Numerical Integrator and Calculator (ENIAC).

- First widely known general purpose electronic computer.
- Conditional jumps, programmable.
- Programming: change switches and cable connections.
- Data: enter numbers using punch cards.

30 tons
30 x 50 x 8.5 ft
17,468 vacuum tubes
300 multiply/sec

John Mauchly (left) and J. Presper Eckert (right)
http://cs.swau.edu/~durkin/articles/history_computing.html



ENIAC, Ester Gerston (left), Gloria Gordon (right)
US Army photo: http://ftp.arl.mil/ftp/historic-computers

Basic Characteristics of TOY Machine

TOY is a general-purpose computer.

- Sufficient power to perform ANY computation.
- Limited only by amount of memory and time.

Stored-program computer. [von Neumann memo, 1944]

- Data and program encoded in binary.
- Data and program stored in SAME memory.
- Can change program without rewiring.

Outgrowth of Alan Turing's work. (stay tuned)

All modern computers are general-purpose computers and have same (von Neumann) architecture.

John von Neumann

Maurice Wilkes (left)
EDSAC (right)

Harvard vs. Princeton

Harvard architecture.

- Separate program and data memories.
- Can't load game from disk (data) and execute (program).
- Used in some microcontrollers.

Von Neumann architecture.

- Program and data stored in same memory.
- Used in almost all computers.

Q. What's the difference between Harvard and Princeton?
A. At Princeton, data and programs are the same.