Course overview

Computer Organization and Assembly Languages

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with slides by Kip Irvine

Logistics

- **Meeting time**: 9:10am-12:10pm, Monday
- **Classroom**: CSIE Room 102
- **Instructor**: Yung-Yu Chuang
- **Teaching assistants**: 謝毓庭/黃子桓
- **Webpage**:

  http://www.csie.ntu.edu.tw/~cyy/assembly

  id / password
- **Forum**:

  http://www.cmlab.csie.ntu.edu.tw/~cyy/forum/viewforum.php?f=7
- **Mailing list**: assembly@cmlab.csie.ntu.edu.tw

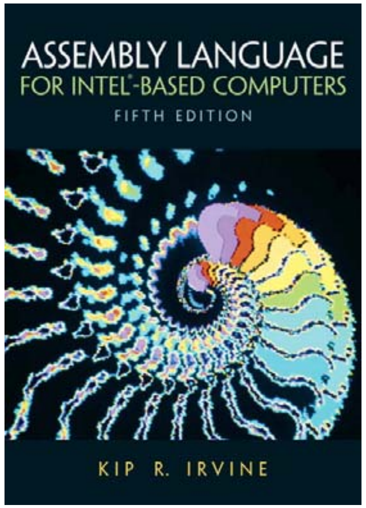
  Please subscribe via

  https://cmlmail.csie.ntu.edu.tw/mailman/listinfo/assembly/

Prerequisites

- Programming experience with some high-level language such C, C ++,Java …

Textbook



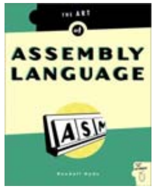
Assembly Language for Intel-Based Computers,

5th Edition,

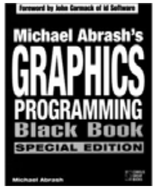
Kip Irvine

References

Computer Systems: A Programmer's Perspective, Randal E. Bryant and David R. O'Hallaron



The Art of Assembly Language, Randy Hyde



Michael Abrash' s Graphics Programming Black Book

Grading (subject to change)

- Assignments (50%)
- Class participation (5%)
- Midterm exam (20%)
- Final project (25%)

Computer Organization and Assembly language

- It is not only about assembly.
- I hope to cover
  - Basic concept of computer systems and architecture
  - x86 assembly language

Why taking this course?

- It is required.
- It is foundation for computer architecture and compilers.
- At times, you do need to write assembly code.

"I really don't think that you can write a book for serious computer programmers unless you are able to discuss low-level details."

Donald Knuth

Reasons for not using assembly

- Development time: it takes much longer to develop in assembly. Harder to debug, no type checking, side effects…
- Maintainability: unstructured, dirty tricks
- Portability: platform-dependent

Reasons for using assembly

- Educational reasons: to understand how CPUs and compilers work. Better understanding to efficiency issues of various constructs.
- Making compilers, debuggers and other development tools.
- Hardware drivers and system code
- Embedded systems
- Making libraries.
- Accessing instructions that are not available through high-level languages.
- Optimizing for speed or space

To sum up

- It is all about lack of smart compilers

- Faster code, compiler is not good enough
- Smaller code , compiler is not good enough, e.g. mobile devices, embedded devices, also Smaller code → better cache performance → faster code
- Unusual architecture , there isn't even a compiler or compiler quality is bad, eg GPU, DSP chips, even MMX.

Syllabus (topics we might cover)

- IA-32 Processor Architecture
- Assembly Language Fundamentals
- Data Transfers, Addressing, and Arithmetic
- Procedures
- Conditional Processing
- Integer Arithmetic
- Advanced Procedures
- Strings and Arrays
- Structures and Macros
- High-Level Language Interface
- Real Arithmetic (FPU)
- SIMD
- Code Optimization

What you will learn

- Basic principle of computer architecture
- IA-32 modes and memory management
- Assembly basics
- How high-level language is translated to assembly
- How to communicate with OS
- Specific components, FPU/MMX
- Code optimization
- Interface between assembly to high-level language

Chapter.1 Overview

- Virtual Machine Concept
- Data Representation
- Boolean Operations

Translating Languages

English: Display the sum of A times B plus C.

C++:

```
cout << (A * B + C);
```

Assembly Language:

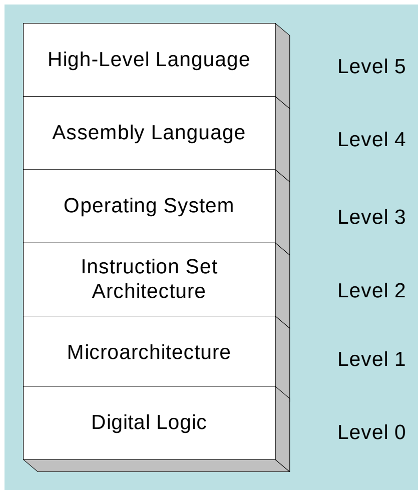
```
mov eax,A
mul B
add eax,C
call WriteInt
```

Intel Machine Language:

```
A1 00000000
F7 25 00000004
03 05 00000008
E8 00500000
```

Virtual machines

Abstractions for computers



High-Level Language

- Level 5
- Application-oriented languages
- Programs compile into assembly language (Level 4)

```
cout << (A * B + C);
```

Assembly Language

- Level 4
- Instruction mnemonics that have a one-to-one correspondence to machine language
- Calls functions written at the operating system level (Level 3)
- Programs are translated into machine language (Level 2)

```
mov  eax, A
mul  B
add  eax, C
call WriteInt
```

Operating System

- Level 3
- Provides services
- Programs translated and run at the instruction set architecture level (Level 2)

Instruction Set Architecture

- Level 2
- Also known as conventional machine language
- Executed by Level 1 program (microarchitecture, Level 1)

```
A1 00000000
F7 25 00000004
03 05 00000008
E8 00500000
```

Microarchitecture

- Level 1
- Interprets conventional machine instructions (Level 2)
- Executed by digital hardware (Level 0)

Digital Logic

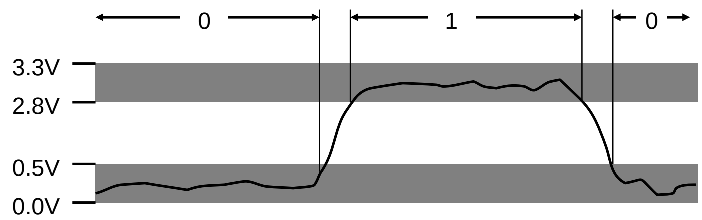
- Level 0
- CPU, constructed from digital logic gates
- System bus
- Memory

Data representation

- Computer is a construction of digital circuits with two states: *on* and *off*
- You need to have the ability to translate between different representations to examine the content of the machine
- Common number systems: binary, octal, decimal and hexadecimal

Binary Representations

- Electronic Implementation
  - Easy to store with bistable elements
  - Reliably transmitted on noisy and inaccurate wires



Binary numbers

- Digits are 1 and 0
  (a binary digit is called a bit)
  1 = true
  0 = false
- MSB –most significant bit
- LSB –least significant bit
- Bit numbering:

MSB	LSB
1 0 1 1 0 0 1 0 1 0 0 1 1 1 0 0	
15	0

- A bit string could have different interpretations

Unsigned binary integers

- Each digit (bit) is either 1 or 0
- Each bit represents a power of 2:

1	1	1	1	1	1	1	1
2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0

Every binary number is a sum of powers of 2

Table 1-3 Binary Bit Position Values.

2^n	Decimal Value	2^n	Decimal Value
2^0	1	2^8	256
2^1	2	2^9	512
2^2	4	2^{10}	1024
2^3	8	2^{11}	2048
2^4	16	2^{12}	4096
2^5	32	2^{13}	8192
2^6	64	2^{14}	16384
2^7	128	2^{15}	32768

Translating Binary to Decimal

Weighted positional notation shows how to calculate the decimal value of each binary bit:

$$dec = (D_{n-1} \times 2^{n-1}) + (D_{n-2} \times 2^{n-2}) + ... + (D_1 \times 2^1) + (D_0 \times 2^0)$$

D = binary digit

binary 00001001 = decimal 9:

$(1 \times 2^3) + (1 \times 2^0) = 9$

Translating Unsigned Decimal to Binary

- Repeatedly divide the decimal integer by 2. Each remainder is a binary digit in the translated value:

Division	Quotient	Remainder
37 / 2	18	1
18 / 2	9	0
9 / 2	4	1
4 / 2	2	0
2 / 2	1	0
1 / 2	0	1

37 = 100101

Binary addition

- Starting with the LSB, add each pair of digits, include the carry if present.

carry: 1

	0	0	0	0	0	1	0	0	(4)
+	0	0	0	0	0	1	1	1	(7)
	0	0	0	0	1	0	1	1	(11)
bit position:	7	6	5	4	3	2	1	0	

Integer storage sizes

Standard sizes:

byte	8
word	16
doubleword	32
quadword	64

Table 1-4 Ranges of Unsigned Integers.

Storage Type	Range (low–high)	Powers of 2
Unsigned byte	0 to 255	0 to $(2^8 - 1)$
Unsigned word	0 to 65,535	0 to $(2^{16} - 1)$
Unsigned doubleword	0 to 4,294,967,295	0 to $(2^{32} - 1)$
Unsigned quadword	0 to 18,446,744,073,709,551,615	0 to $(2^{64} - 1)$

Practice: What is the largest unsigned integer that may be stored in 20 bits?

Large measurements

- Kilobyte (KB), 2^{10} bytes
- Megabyte (MB), 2^{20} bytes
- Gigabyte (GB), 2^{30} bytes
- Terabyte (TB), 2^{40} bytes
- Petabyte
- Exabyte
- Zettabyte
- Yottabyte

Hexadecimal integers

All values in memory are stored in binary. Because long binary numbers are hard to read, we use hexadecimal representation.

Table 1-5 Binary, Decimal, and Hexadecimal Equivalents.

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

Translating binary to hexadecimal

- Each hexadecimal digit corresponds to 4 binary bits.
- Example: Translate the binary integer 000101101010011110010100 to hexadecimal:

1	6	A	7	9	4
0001	0110	1010	0111	1001	0100

Converting hexadecimal to decimal

- Multiply each digit by its corresponding power of 16:

  $\text{dec} = (D_3 \times 16^3) + (D_2 \times 16^2) + (D_1 \times 16^1) + (D_0 \times 16^0)$

- Hex 1234 equals $(1 \times 16^3) + (2 \times 16^2) + (3 \times 16^1) + (4 \times 16^0)$, or decimal 4,660.
- Hex 3BA4 equals $(3 \times 16^3) + (11 * 16^2) + (10 \times 16^1) + (4 \times 16^0)$, or decimal 15,268.

Powers of 16

Used when calculating hexadecimal values up to 8 digits long:

16^n	Decimal Value	16^n	Decimal Value
16^0	1	16^4	65,536
16^1	16	16^5	1,048,576
16^2	256	16^6	16,777,216
16^3	4096	16^7	268,435,456

Converting decimal to hexadecimal

Division	Quotient	Remainder
422 / 16	26	6
26 / 16	1	A
1 / 16	0	1

decimal 422 = 1A6 hexadecimal

Hexadecimal addition

Divide the sum of two digits by the number base (16). The quotient becomes the carry value, and the remainder is the sum digit.

		1	**1**
36	28	28	6A
42	45	58	4B
78	6D	80	B5

Important skill: Programmers frequently add and subtract the addresses of variables and instructions.

Hexadecimal subtraction

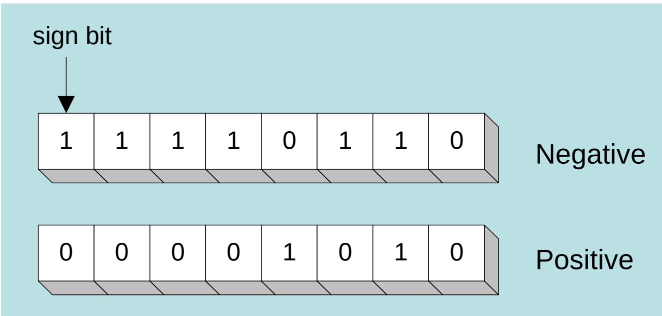
When a borrow is required from the digit to the left, add 10h to the current digit's value:

	–1
C6	75
A2	47
24	2E

Practice: The address of **var1** is 00400020. The address of the next variable after var1 is 0040006A. How many bytes are used by var1?

Signed integers

The highest bit indicates the sign. 1 = negative, 0 = positive



If the highest digit of a hexadecmal integer is > 7, the value is negative. Examples: 8A, C5, A2, 9D

Two's complement notation

Steps:

- Complement (reverse) each bit
- Add 1

Starting value	00000001
Step 1: reverse the bits	11111110
Step 2: add 1 to the value from Step 1	11111110 +00000001
Sum: two's complement representation	11111111

Note that 00000001 + 11111111 = 00000000

Binary subtraction

- When subtracting A – B, convert B to its two's complement
- Add A to (–B)

```
  1 1 0 0   ------>   1 1 0 0
– 0 0 1 1             1 1 0 1
---------            --------
                      1 0 0 1
```

Advantages for 2's complement:

- No two 0's
- Sign bit
- Remove the need for separate circuits for add and sub

Ranges of signed integers

The highest bit is reserved for the sign. This limits the range:

Storage Type	Range (low–high)	Powers of 2
Signed byte	−128 to +127	-2^7 to $(2^7 - 1)$
Signed word	−32,768 to +32,767	-2^{15} to $(2^{15} - 1)$
Signed doubleword	−2,147,483,648 to 2,147,483,647	-2^{31} to $(2^{31} - 1)$
Signed quadword	−9,223,372,036,854,775,808 to +9,223,372,036,854,775,807	-2^{63} to $(2^{63} - 1)$

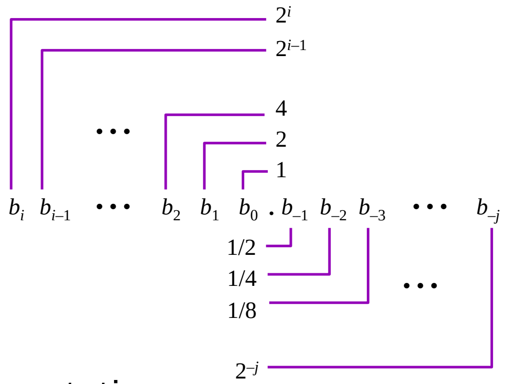
Character

- Character sets
  - Standard ASCII(0 – 127)
  - Extended ASCII (0 – 255)
  - ANSI (0 – 255)
  - Unicode (0 – 65,535)
- Null-terminated String
  - Array of characters followed by a *null byte*
- Using the ASCII table
  - back inside cover of book

IEEE Floating Point

- IEEE Standard 754
  - Established in 1985 as uniform standard for floating point arithmetic
    - Before that, many idiosyncratic formats
  - Supported by all major CPUs
- Driven by Numerical Concerns
  - Nice standards for rounding, overflow, underflow
  - Hard to make go fast
    - Numerical analysts predominated over hardware types in defining standard

Fractional Binary Numbers



- Representation
  - Bits to right of "binary point" represent fractional powers of 2
  - Represents rational number: $\sum_{k=-j}^{i} b_k \cdot 2^k$

Binary real numbers

- Binary real to decimal real

$$110.011_2 = 4 + 2 + 0.25 + 0.125 = 6.375$$

- Decimal real to binary real

$$\begin{array}{rcl}0.5625 \times 2 & = & 1.125 \\ 0.125 \times 2 & = & 0.25 \\ 0.25 \times 2 & = & 0.5 \\ 0.5 \times 2 & = & 1.0\end{array} \qquad \begin{array}{rcl}\text{first bit} & = & 1 \\ \text{second bit} & = & 0 \\ \text{third bit} & = & 0 \\ \text{fourth bit} & = & 1\end{array}$$

$$4.5625 = 100.1001_2$$

Frac. Binary Number Examples

Value	Representation
5-3/4	101.11_2
2-7/8	10.111_2
63/64	0.111111_2

Value	Representation
1/3	$0.0101010101[01]\ldots_2$
1/5	$0.001100110011[0011]\ldots_2$
1/10	$0.0001100110011[0011]\ldots_2$

IEEE floating point format

- IEEE defines two formats with different precisions: single and double

31	30 … 23	22 … 0
s	e	f

s sign bit - 0 = positive, 1 = negative
e biased exponent (8-bits) = true exponent + 7F (127 decimal). The values 00 and FF have special meaning (see text).
f fraction - the first 23-bits after the 1. in the significand.

$23.85 = 10111.11\overline{0110}_2 = 1.011111\overline{0110} \text{x} 2^4$

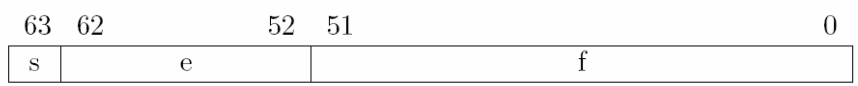
e = 127+4=83h

0 100 0001 1 011 1110 1100 1100 1100 1100

IEEE floating point format

$e = 0$	and $f = 0$	denotes the number zero (which can not be normalized) Note that there is a +0 and -0.
$e = 0$	and $f \neq 0$	denotes a *denormalized number*. These are discussed in the next section.
$e = \mathrm{FF}$	and $f = 0$	denotes infinity (∞). There are both positive and negative infinities.
$e = \mathrm{FF}$	and $f \neq 0$	denotes an undefined result, known as *NaN* (Not a Number).

special values



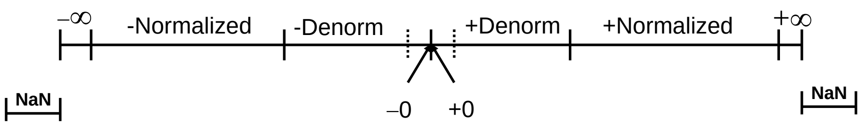
IEEE double precision

Denormalized numbers

- Number smaller than 1.0×2^{-126} can't be presented by a single with normalized form. However, we can represent it with denormalized format.
- $1.0000..00 \times 2^{-126}$ the least "normalized" number
- $0.1111..11 \times 2^{-126}$ the largest "denormalized" numbr
- $1.001 \times 2^{-129} = 0.001001 \times 2^{-126}$

0 000 0000 0 001 0010 0000 0000 0000 0000

Summary of Real Number Encodings



(3.14+1e20)-1e20=0
3.14+(1e20-1e20)=3.14

Representing Instructions

```
int sum(int x, int y)
{
   return x+y;
}
```

- For this example, Alpha & Sun use two 4-byte instructions
  - Use differing numbers of instructions in other cases
- PC uses 7 instructions with lengths 1, 2, and 3 bytes
  - Same for NT and for Linux
  - NT / Linux not fully binary compatible

Alpha sum	Sun sum	PC sum
00	81	55
00	C3	89
30	E0	E5
42	08	8B
01	90	45
80	02	0C
FA	00	03
6B	09	45
		08
		89
		EC
		5D
		C3

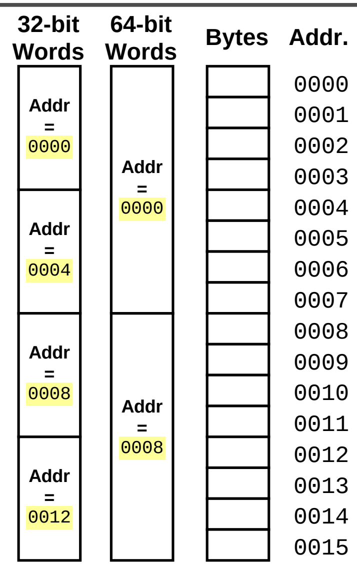
Different machines use totally different instructions and encodings

Machine Words

- Machine Has "Word Size"
  - Nominal size of integer-valued data
    - Including addresses
  - Most current machines use 32 bits (4 bytes) words
    - Limits addresses to 4GB
    - Becoming too small for memory-intensive applications
  - High-end systems use 64 bits (8 bytes) words
    - Potential address space ≈ 1.8 X 10^{19} bytes
  - Machines support multiple data formats
    - Fractions or multiples of word size
    - Always integral number of bytes

Word-Oriented Memory Organization

- Addresses Specify Byte Locations
  - Address of first byte in word
  - Addresses of successive words differ by 4 (32-bit) or 8 (64-bit)



Data Representations

- Sizes of C Objects (in Bytes)

C Data Type	Alpha (RIP)	Typical 32-bit	Intel IA32
unsigned	4	4	4
int	4	4	4
long int	8	4	4
char	1	1	1
short	2	2	2
float	4	4	4
double	8	8	8
long double	8/16†	8	10/12
char *	8	4	4

– Or any other pointer

(†: Depends on compiler&OS, 128bit FP is done in software)

Byte Ordering

- How should bytes within multi-byte word be ordered in memory?
- Conventions
  - Sun's, Mac's are "Big Endian" machines
    - Least significant byte has highest address
  - Alphas, PC's are "Little Endian" machines
    - Least significant byte has lowest address

Byte Ordering Example

- Big Endian
  - Least significant byte has highest address
- Little Endian
  - Least significant byte has lowest address
- Example
  - Variable `x` has 4-byte representation `0x01234567`
  - Address given by `&x` is `0x100`

Big Endian

		0x100	0x101	0x102	0x103		
		01	23	45	67		

Little Endian

		0x100	0x101	0x102	0x103		
		67	45	23	01		

Boolean algebra

- Boolean expressions created from:
  - NOT, AND, OR

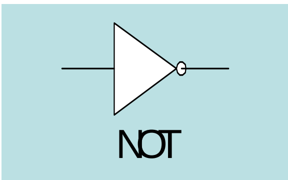
Expression	Description
$\neg X$	NOT X
$X \wedge Y$	X AND Y
$X \vee Y$	X OR Y
$\neg X \vee Y$	(NOT X) OR Y
$\neg(X \wedge Y)$	NOT (X AND Y)
$X \wedge \neg Y$	X AND (NOT Y)

NOT

- Inverts (reverses) a boolean value
- Truth table for Boolean NOT operator:

X	$\neg$X
F	T
T	F

Digital gate diagram for NOT:

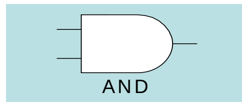


AND

- Truth if both are true
- Truth table for Boolean AND operator:

X	Y	$X \wedge Y$
F	F	F
F	T	F
T	F	F
T	T	T

Digital gate diagram for AND:

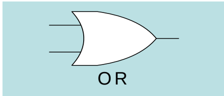


OR

- True if either is true
- Truth table for Boolean OR operator:

X	Y	X ∨ Y
F	F	F
F	T	T
T	F	T
T	T	T

Digital gate diagram for OR:



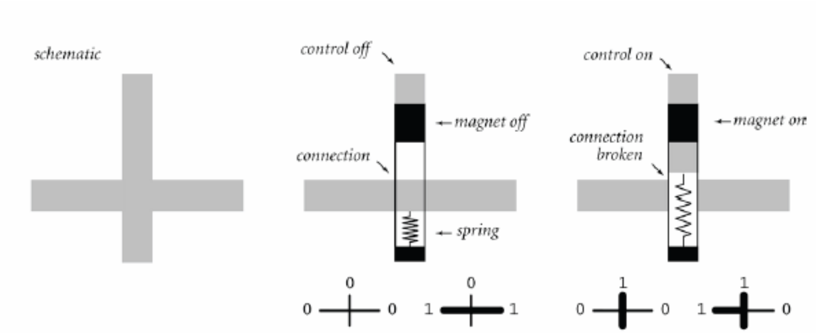
Operator precedence

- NOT > AND > OR
- Examples showing the order of operations:

Expression	Order of Operations
$\neg X \vee Y$	NOT, then OR
$\neg(X \vee Y)$	OR, then NOT
$X \vee (Y \wedge Z)$	AND, then OR

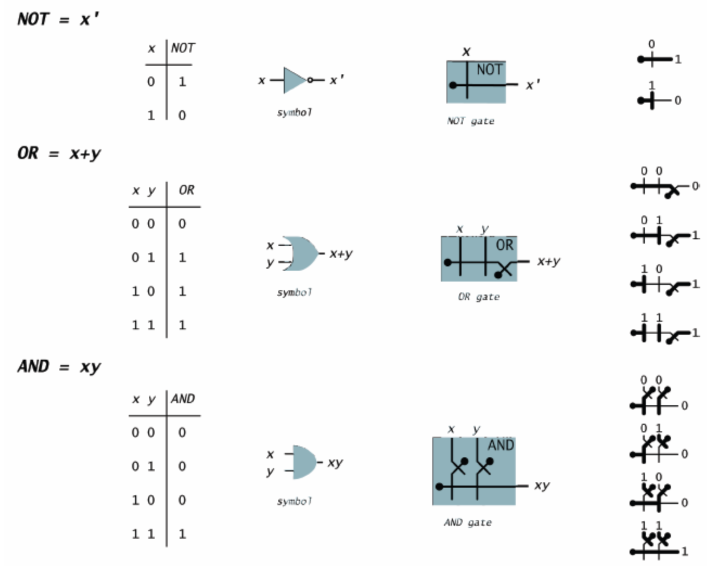
- Use parentheses to avoid ambiguity

Implementation of gates



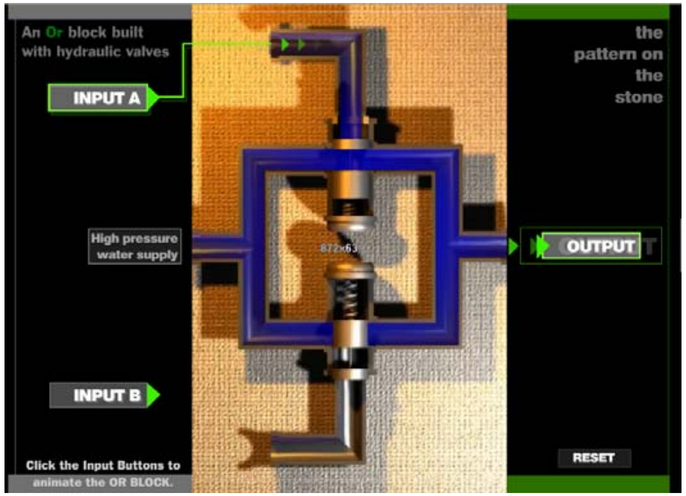
Anatomy of a relay (controlled switch)

Implementation of gates



Implementation of gates

- Fluid switch (http://www.cs.princeton.edu/introcs/lectures/fluid-computer.swf)



Truth Tables (1 of 3)

- A Boolean function has one or more Boolean inputs, and returns a single Boolean output.
- A truth table shows all the inputs and outputs of a Boolean function

Example: $\neg X \vee Y$

X	¬X	Y	¬X ∨ Y
F	T	F	T
F	T	T	T
T	F	F	F
T	F	T	T

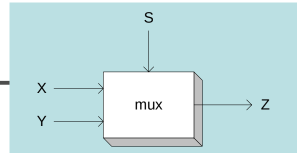
Truth Tables (2 of 3)

- Example: $X \wedge \neg Y$

X	Y	¬Y	X ∧ ¬Y
F	F	T	F
F	T	F	F
T	F	T	T
T	T	F	F

Truth Tables (3 of 3)

- Example: $(Y \wedge S) \vee (X \wedge \neg S)$



Two-input multiplexer

X	Y	S	Y ∧ S	¬S	X ∧ ¬S	(Y ∧ S) ∨ (X ∧ ¬S)
F	F	F	F	T	F	F
F	T	F	F	T	F	F
T	F	F	F	T	T	T
T	T	F	F	T	T	T
F	F	T	F	F	F	F
F	T	T	T	F	F	T
T	F	T	F	F	F	F
T	T	T	T	F	F	T