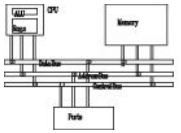
Computer Organization and Assembly Languages

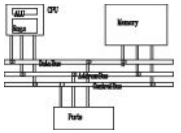
with slides by Kip Irvine

Prerequisites



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

Books



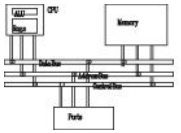
Textbook

Assembly Language for Intel-Based Computers, 4th, 5th, 6th Edition, Kip Irvine

Reference

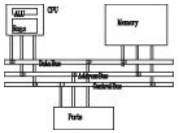
The Art of Assembly Language, Randy Hyde

Grading (subject to change)



- Assignments/Quizzes (20%)
- Class participation (10%)
- Midterm exam (30%)
- Final Exam (40%)

Why learning assembly?

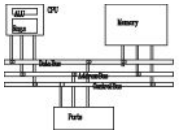


- It is required.
- It is foundation for computer architecture and compilers.
- At times, you do need to write assembly code.

"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

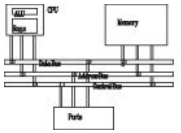
Why programming in assembly?



- It is all about lack of smart compilers

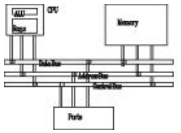
- Faster code, compiler is not good enough
- Smaller code , compiler is not good enough, e.g. mobile devices, embedded devices, also Smaller code → better cache performance → faster code
- Unusual architecture , there isn't even a compiler or compiler quality is bad, eg GPU, DSP chips, even MMX.

Syllabus (topics we might cover)



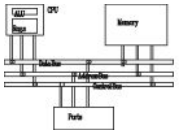
- IA-32 Processor Architecture
- Assembly Language Fundamentals
- Data Transfers, Addressing, and Arithmetic
- Procedures
- Conditional Processing
- Integer Arithmetic
- Advanced Procedures
- Strings and Arrays
- Structures and Macros

What you will learn



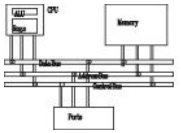
- Basic principle of computer architecture
- IA-32 modes and memory management
- Assembly basics
- How high-level language is translated to assembly
- How to communicate with OS

Chapter.1 Overview

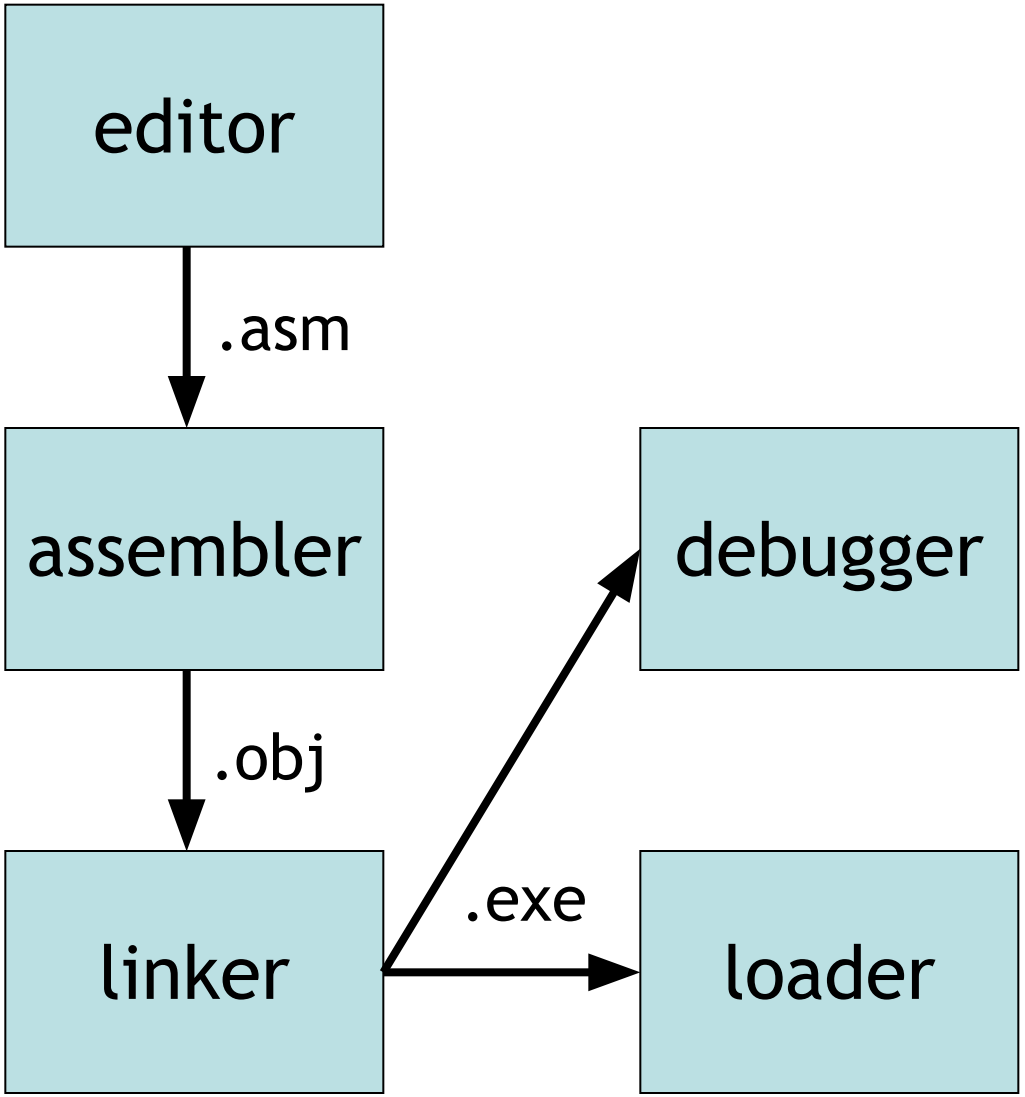


- Virtual Machine Concept
- Data Representation
- Boolean Operations

Assembly programming

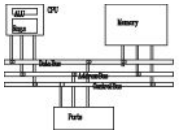


```
mov eax, Y
add eax, 4
mov ebx, 3
imul ebx
mov X, eax
```



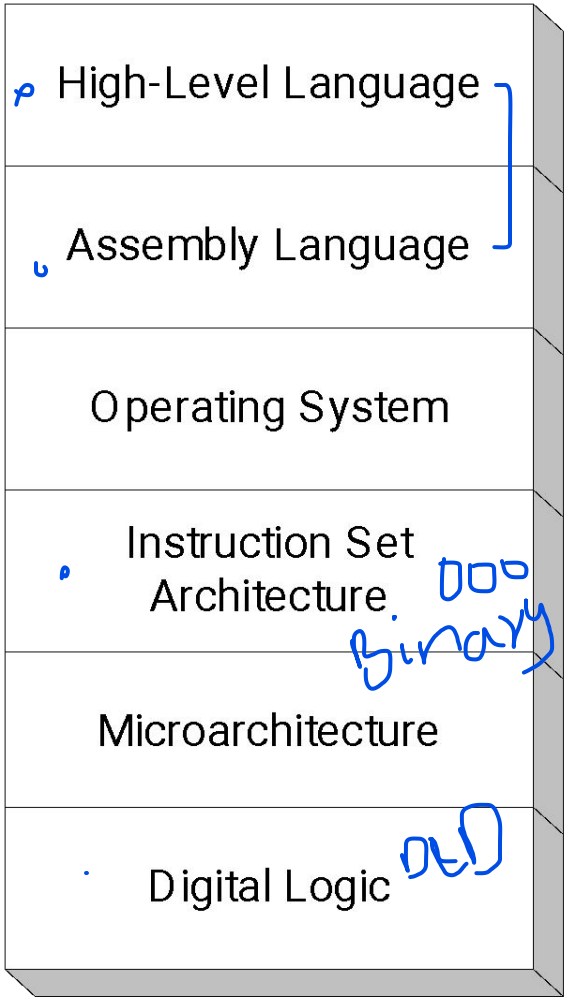
Virtual machines

how a computer's hardware and software are related is called the virtual machine concept.



Abstractions for computers

At Level 4 are high-level programming languages such as C, C++, and Java.
Programs in these languages contain powerful statements that translate into multiple assembly language instructions. The assembly language code is automatically assembled by the compiler into machine language.
program -> Assem-> Machine



Level 5

Level 4

Assembly language, which appears at Level 3, uses short mnemonics (catchwords.) such as ADD, SUB, and MOV, which are easily translated to the ISA level. Assembly language programs are translated (assembled) in their entirety into machine language before they begin to execute.
program->Machine lang

Level 3

Level 2

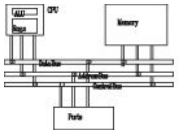
Above this is Level 2, called the instruction set architecture (ISA). This is the first level at which users can typically write programs, although the programs consist of binary values called machine language.

Level 1

Level 0

A computer's digital logic hardware represents machine Level 1

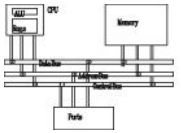
High-Level Language



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

```
X:=(Y+4)*3
```

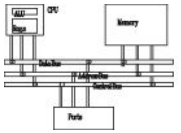
Assembly Language



- 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)

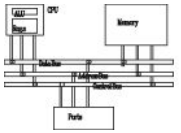
```
mov eax, Y
add eax, 4
mov ebx, 3
imul ebx
mov X, eax
```

Operating System



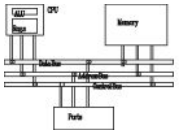
- Level 3
- Provides services
- Programs translated and run at the instruction set architecture level (Level 2)

Instruction Set Architecture



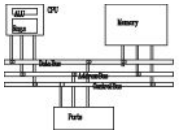
- Level 2
- Also known as conventional machine language
- Executed by Level 1 program (microarchitecture, Level 1)

Microarchitecture



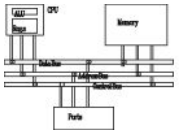
- Level 1
- Interprets conventional machine instructions (Level 2)
- Executed by digital hardware (Level 0)

Digital Logic



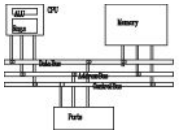
- Level 0
- CPU, constructed from digital logic gates
- System bus
- Memory

Data representation



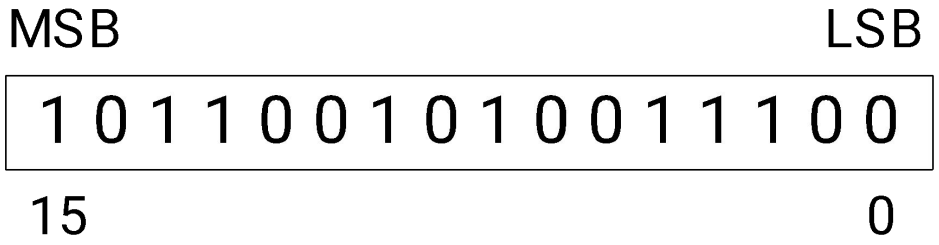
- Computer is a construction of digital circuits with two states: *on* and *off*
- You need to have the ability to translate between different representations to examine the content of the machine
- Common number systems: binary, octal, decimal and hexadecimal

Binary numbers



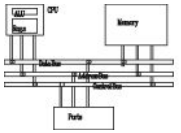
- Digits are 1 and 0
  (a binary digit is called a bit)
  1 = true
  0 = false
- MSB –most significant bit
- LSB –least significant bit

- Bit numbering:

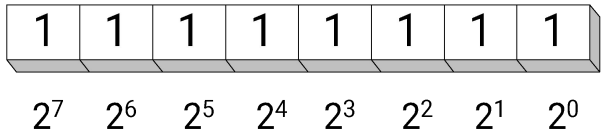


- A bit string could have different interpretations

Unsigned binary integers



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

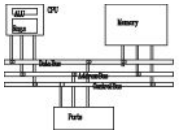


Every binary number is a sum of powers of 2

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:

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

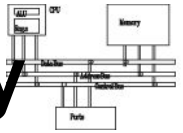
D = binary digit

8421
1001
answer: 8 + 1 = 9

binary 00001001 = decimal 9:

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

Translating Unsigned Decimal to Binary



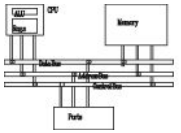
- Repeatedly divide the decimal integer by 2. Each remainder is a binary digit in the translated value:

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

$$37 = 100101$$

9
solution:
8421
1001

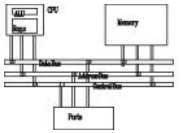
Binary addition



- 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:

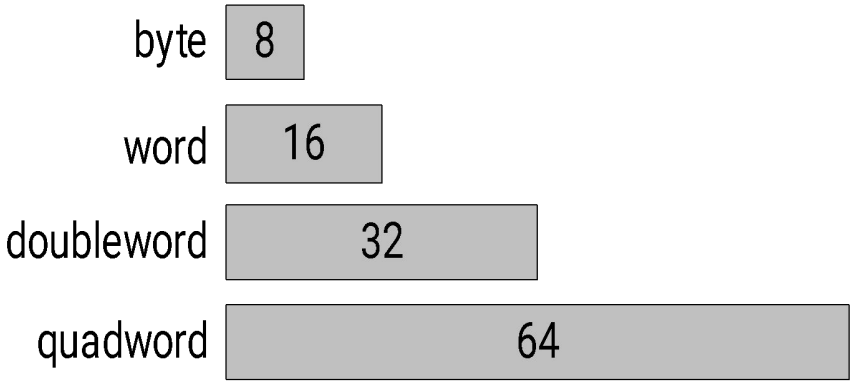


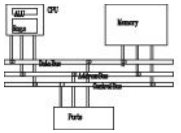
Table 1-4 Ranges of Unsigned Integers.

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?

2^20 - 1

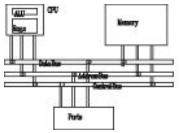
Large measurements



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

One petabyte is equal to 2^50, or 1,125,899,906,842,624 bytes.
- One exabyte is equal to 2^60, or 1,152,921,504,606,846,976 bytes.
- One zettabyte is equal to 2^70 bytes.
- One yottabyte is equal to 2^80 bytes

Hexadecimal integers

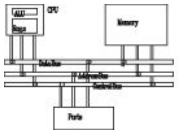


All values in memory are stored in binary. Because long binary numbers are hard to read, we use hexadecimal representation.

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

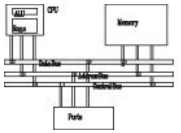


- Each hexadecimal digit corresponds to 4 binary bits.
- Example: Translate the binary integer 00010110101001111100010100 to hexadecimal:

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

Hexa-decimal to binary = E699DA2C? 1110 0110 1001 1001 1101 1010 0010 1100

Converting hexadecimal to decimal



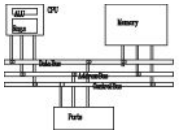
- Multiply each digit by its corresponding power of 16:

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

- 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.

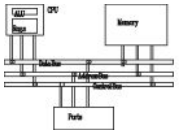
Powers of 16



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

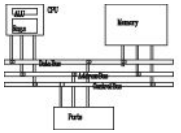
Converting decimal to hexadecimal



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

decimal 422 = 1A6 hexadecimal

Hexadecimal addition



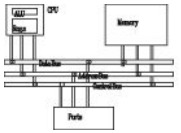
Divide the sum of two digits by the number base (16). The quotient becomes the carry value, and the remainder is the sum digit.

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

max limit 15

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:

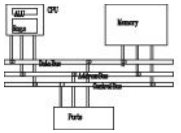
```
      -1
  C675
  A247
------
  242E
```

Borrow = 16

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

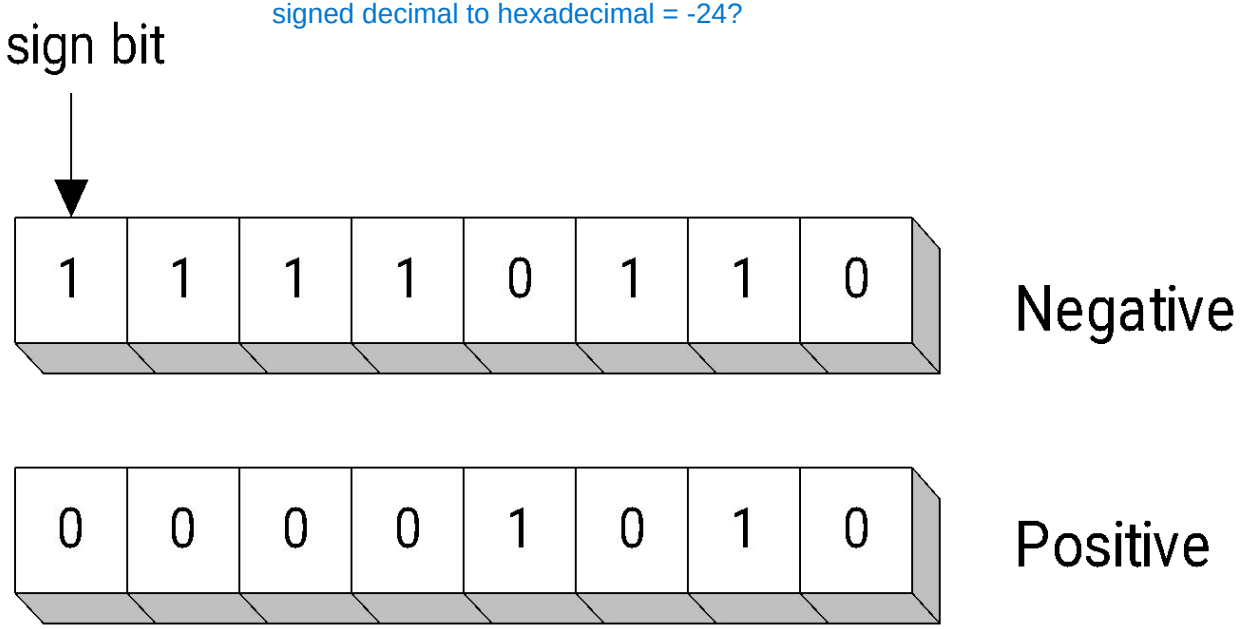
4 Bytes

Signed integers



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

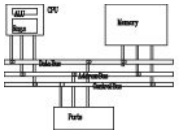
signed decimal to hexadecimal = -24?



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

You can tell whether a hexadecimal integer is positive or negative by inspecting its most significant (highest) digit. If the digit is greater than or equal to 8, the number is negative; if the digit is less than or equal to7, the number is positive. For example, hexadecimal 8A20 is negative and 7FD9 is positive.

Two's complement notation



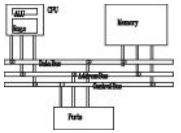
Steps:

- 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



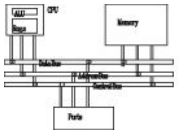
- When subtracting A – B, convert B to its two's complement
- Add A to (–B)

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

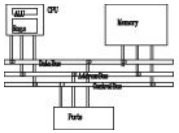
Ranges of signed integers



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



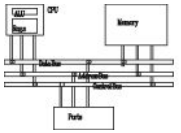
- Character sets
  - Standard ASCII(0 – 127)
  - Extended ASCII (0 – 255)
  - ANSI (0 – 255)
  - Unicode (0 – 65,535)
- Null-terminated String
  - Array of characters followed by a *null byte*
- Using the ASCII table
  - back inside cover of book

ASCII is an acronym for American Standard Code for Information Interchange. In ASCII, a unique 7-bit integer is assigned to each character. Because ASCII codes use only the lower 7 bits of every byte, the extra bit is used on various computers to create a proprietary (Owner:title) character set.

American National Standards Institute (ANSI) defines an 8-bit character set that represents up to 256 characters. The first 128 characters correspond to the letters and symbols on a standard U.S. keyboard. The second 128 characters represent special characters such as letters in international alphabets, accents, currency symbols, and fractions.

There has been a need for some time to represent a wide variety of international languages in computer software. As a result, the Unicode standard was created as a universal way of defining characters and symbols.

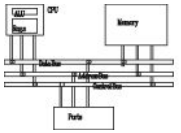
Boolean algebra



- 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)

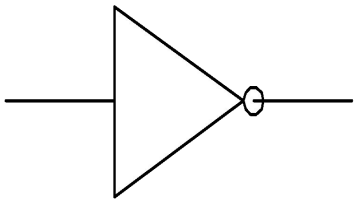
NOT



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

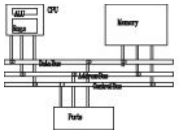
X	¬X
F	T
T	F

Digital gate diagram for NOT:



NOT

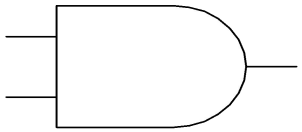
AND



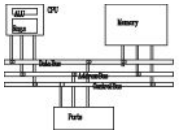
- Truth if both are true
- Truth table for Boolean AND operator:

X	Y	X ∧ Y
F	F	F
F	T	F
T	F	F
T	T	T

Digital gate diagram for AND:



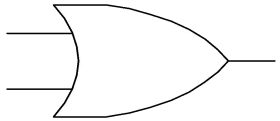
OR



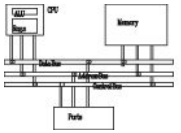
- True if either is true
- Truth table for Boolean OR operator:

X	Y	X ∨ Y
F	F	F
F	T	T
T	F	T
T	T	T

Digital gate diagram for OR:



Operator precedence

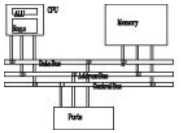


- NOT > AND > OR
- Examples showing the order of operations:

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

Truth Tables (1 of 3)

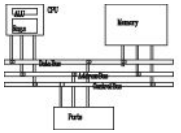


- A Boolean function has one or more Boolean inputs, and returns a single Boolean output.
- A truth table shows all the inputs and outputs of a Boolean function

Example: ¬X ∨ Y

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

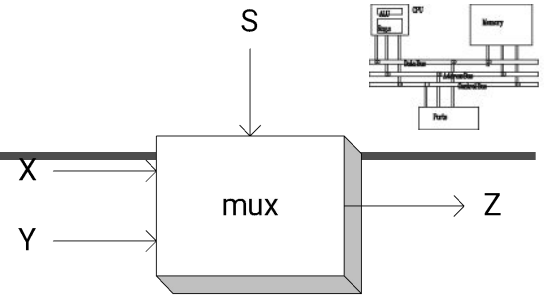
Truth Tables (2 of 3)



- Example: X ∧ ¬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 ∧ S) ∨ (X ∧ ¬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