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Digital Logic Design

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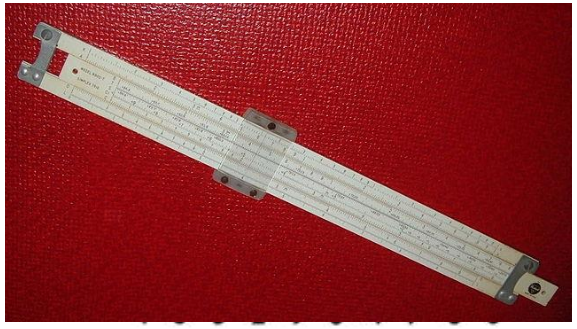
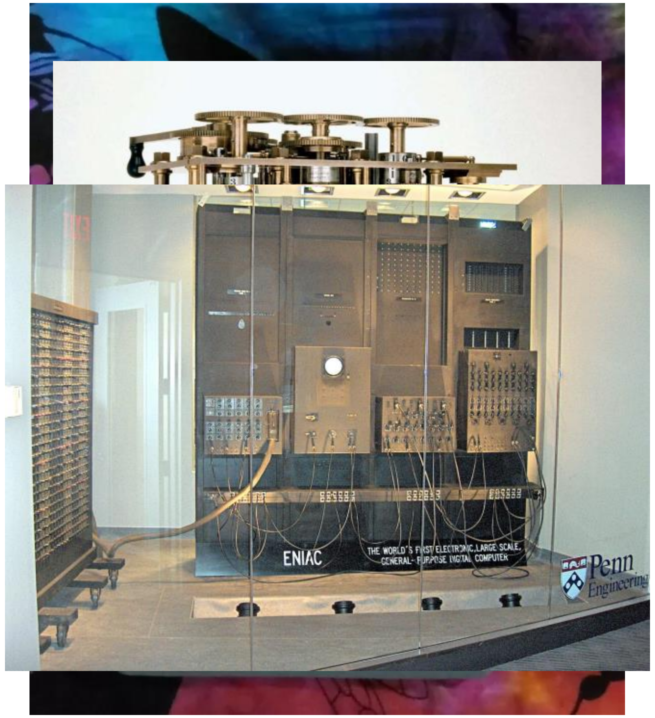
History of Computing - Early Computers



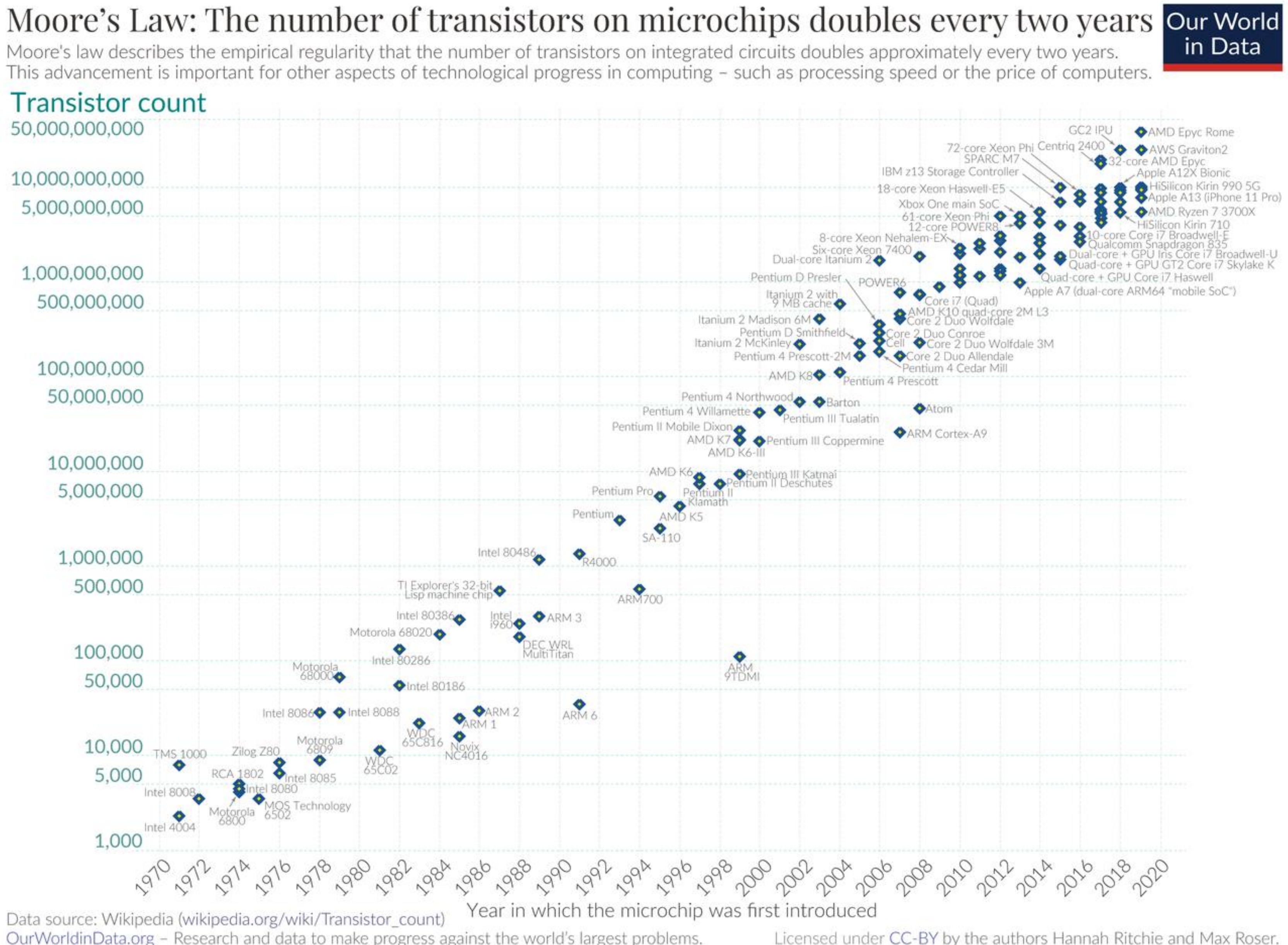
- Abacus (ancient orient, still in use)
- Slide rule (17C, John Napier)
- Adding machine with geared wheels (17C, B. Pascal)
- Difference Engine (19C, C. Babbage): First device using the principles of modern computer.
- ENIAC (1945, John Mauchly and J. Presper Eckert, Jr.)
    - Vacuum tube computer (18,000 electron tubes)
- Three important inventions 20C
    - Stored program concept (John von Neumann)
    - Transistor (J. Bardeen, W.H. Brattain, W. Shockley)
    - Magnetic core memory (J.W. Forrester and colleagues in MIT)



History of Computing - First Four Generations

- First generation: Vacuum tube computers (1940s - 1950s)
- Second generation (1950s): Transistors
- Third generation (1960s and 1970s): Integrated circuits
- Fourth generation (late 1970s through present): LSI and VLSI
  - Personal computers, computer networks, WWW, etc.
- Actual generation:
  - New user interfaces (voice activation, etc.)
  - New computational paradigm (parallel processing, neural network, etc.)
  - Parallel processing, artificial intelligence, optical processing, visual programming, gigabit networks, etc.

History of Computing - Evolution of processors



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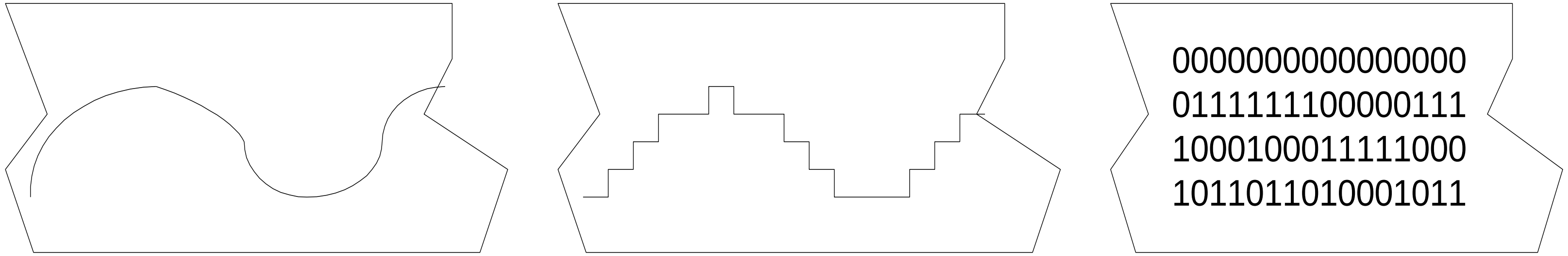
Digital Systems - Analog vs. Digital

- Analog vs. Digital: Continuous vs. discrete.



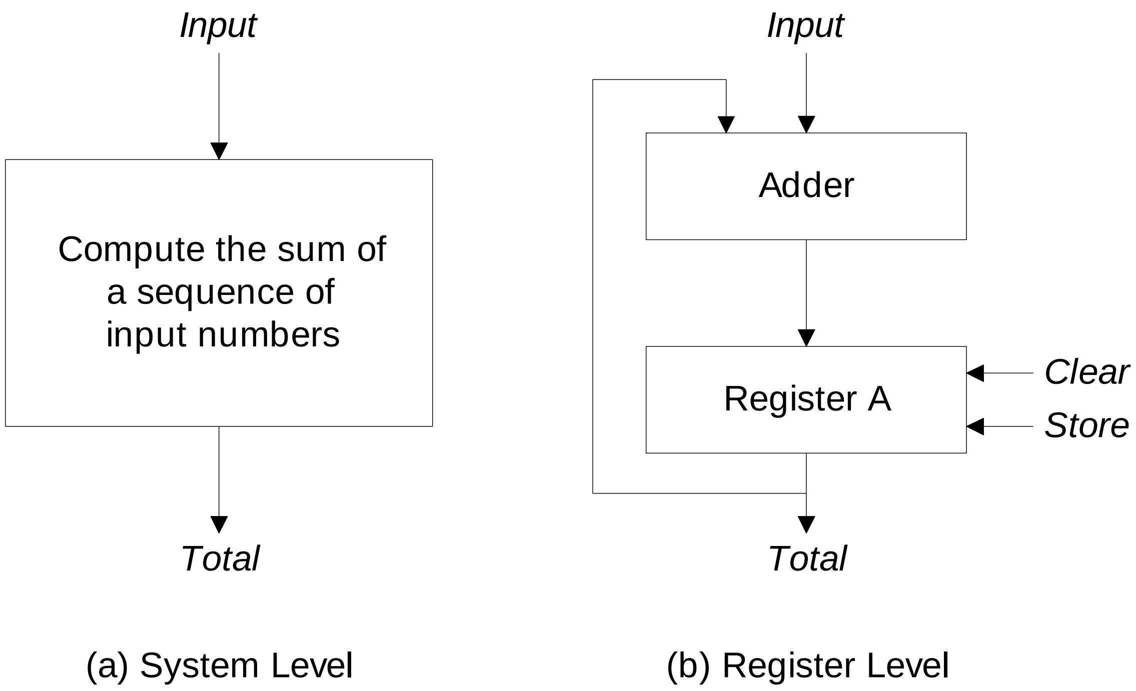
(a) Analog form (b) Sampled analog form (c) Digital form

Magnetic tape contaning analog and digital forms of a signal.

- Digital computers replaced analog computers:
  - More flexible (easy to program), faster, more precise.
  - Storage devices are easier to implement.
  - Built-in error detection and correction.
  - Easier to minimize.

Digital Systems - Design Hierarchy (1)

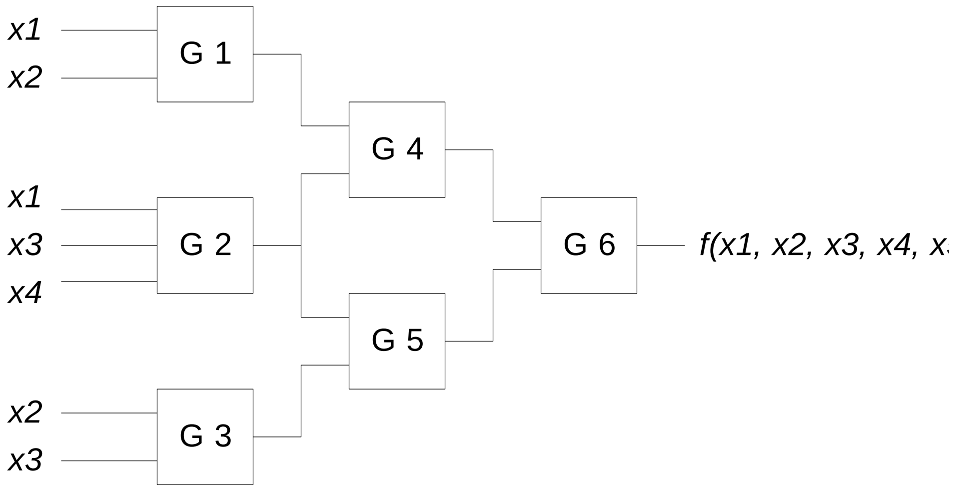
- System level: Black box specification.
- Register level: Collection of registers.



Models of a digital system that adds lists of numbers.

Digital Systems - Design Hierarchy (2)

- Gate level: Collection of logic gates.



A combinational logic circuit with six gates.

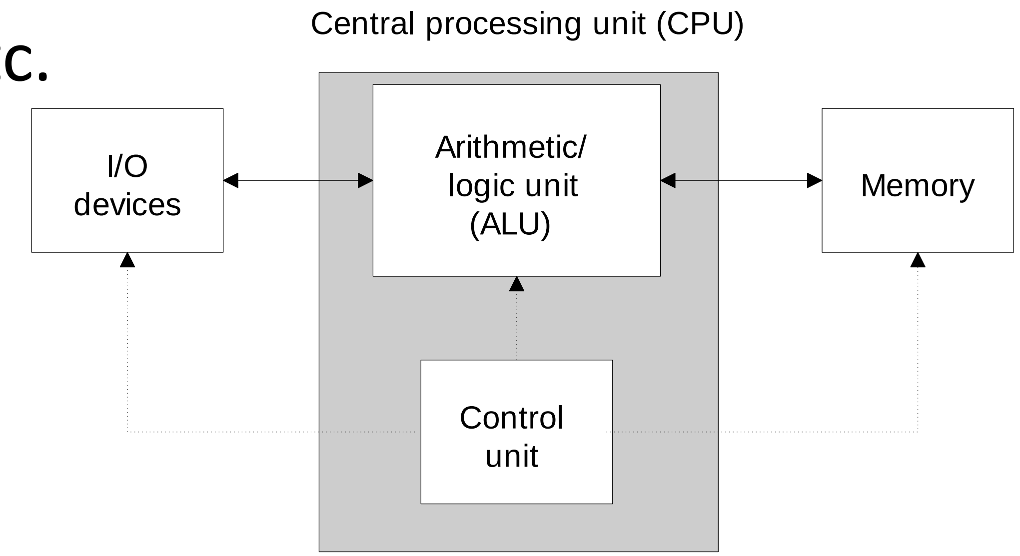
Digital Systems - Design Hierarchy (3)

- Transistor and physical design level: Each logic gate is implemented by a lower-level transistor circuit.
- Electronic Technologies:

Technology (Device Type)	Power Consumption	Speed	Packaging
RTL (Bipolar junction)	High	Low	Discrete
DTL (Bipolar junction)	High	Low	Discrete, SSI
TTL (Bipolar junction)	Medium	Medium	SSI, MSI
ECL (Bipolar junction)	High	High	SSI, MSI, LSI
pMOS (MOSFET)	Medium	Low	MSI, LSI
nMOS (MOSFET)	Medium	Medium	MSI, LSI, VLSI
CMOS (MOSFET)	Low	Medium	SSI, MSI, LSI, VLSI
GaAs (MOSFET)	High	High	SSI, MSI, LSI

Organization of a Digital Computer - Four Major Components

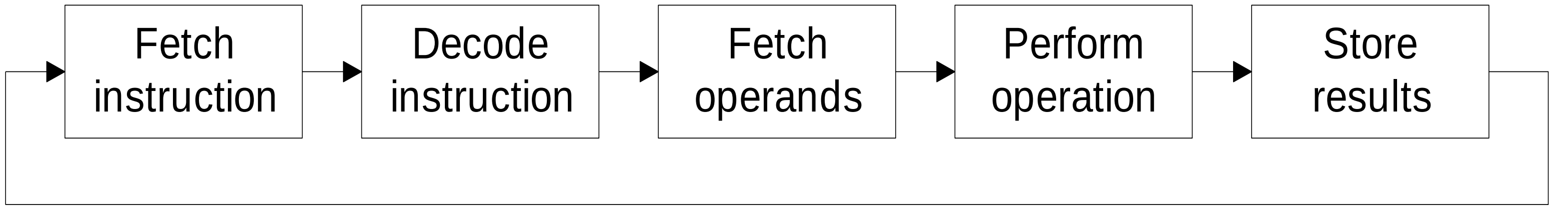
- Control unit: Follows the stored list of instructions and supervises the flow of information among other components.
- Arithmetic/logic unit (ALU): Performs various operations.
- Memory unit: Stores programs, input, output, and intermediate data.
- I/O devices: Printers, monitors, keyboard, etc.



High-level organization of a digital computer.

Organization of a Digital Computer - Instruction Cycle

- Fetch the next instruction into the control unit.
- Decode the instruction.
- Fetch the operands from memory or input devices.
- Perform the operation.
- Store the results in the memory (or send the results to an output device).



Instruction cycle of a stored program computer.

Organization of a Digital Computer - Computer Instructions

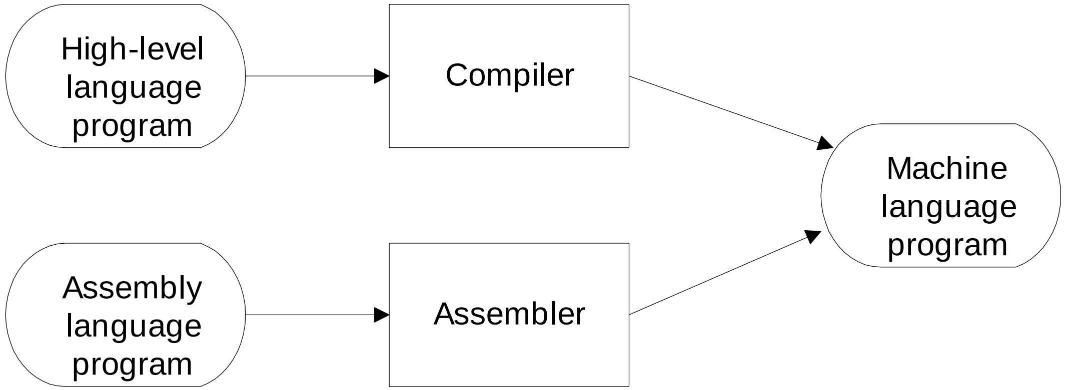
- Arithmetic instructions.
- Test and compare instructions.
- Branch or skip instructions.
- Input and output commands.
- Logical and shift operations.

Organization of a Digital Computer - Information Representation

- Numeric data: Binary number system.
- Numeric (Input/Output) codes: ASCII.
- Instruction codes: Operation code and memory addresses of operands and result.

Organization of a Digital Computer - Software

- Programming: The process of designing a list of instructions.
- Application programs: Word processor, spreadsheet, drawing programs, inventory management programs, accounting programs, etc.
- System programs: Operating systems, language translation programs, utility programs, performance monitoring programs, etc.



Translation of computer programs into machine language

Number systems and codes

Number Systems (1)

- ***Positional Notation***

  $N = (a_{n-1}a_{n-2} \ldots a_1a_0 \,.\, a_{-1}a_{-2} \ldots a_{-m})_r$ (1.1)

  where . = radix point (decimal point)

  r = radix or base

  n = number of integer digits to the left of the radix point

  m = number of fractional digits to the right of the radix point

  a_{n-1} = most significant digit (MSD)

  a_{-m} = least significant digit (LSD)

- ***Polynomial Notation*** (Series Representation)

  $N = a_{n-1} \times r^{n-1} + a_{n-2} \times r^{n-2} + \ldots + a_0 \times r^0 + a_{-1} \times r^{-1} \ldots + a_{-m} \times r^{-m}$

  $= \sum_{i=-m}^{n-1} a_i r^i$ (1.2)

- $N = (251.41)_{10} = 2 \times 10^2 + 5 \times 10^1 + 1 \times 10^0 + 4 \times 10^{-1} + 1 \times 10^{-2}$

Number Systems (2)

- ***Binary*** numbers
  - Digits = {0, 1}
  - $(11010.11)_2 = 1 \times 2^4 + 1 \times 2^3 + 0 \times 2^2 + 1 \times 2^1 + 0 \times 2^0 + 1 \times 2^{-1} + 1 \times 2^{-2}$
    $= (26.75)_{10}$

- ***Octal*** numbers
  - Digits = {0, 1, 2, 3, 4, 5, 6, 7}
  - $(127.4)_8 = 1 \times 8^2 + 2 \times 8^1 + 7 \times 8^0 + 4 \times 8^{-1} = (87.5)_{10}$

- ***Hexadecimal*** numbers
  - Digits = {0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, F}
  - $(B65F)_{16} = 11 \times 16^3 + 6 \times 16^2 + 5 \times 16^1 + 15 \times 16^0 = (46{,}687)_{10}$

Number Systems (2)

- ***Special power of 2***

  1 K (kilo) $= 2^{10} = 1{,}024$,

  1M (mega) $= 2^{20} = 1{,}048{,}576$,

  1G (giga) $= 2^{30} = 1{,}073{,}741{,}824$

  1T (tera) $= 2^{40} = 1{,}099{,}511{,}627{,}776$

Number Systems (3)

- ***Important Number Systems***

Decimal	Binary	Octal	Hexadecimal
0	0	0	0
1	1	1	1
2	10	2	2
3	11	3	3
4	100	4	4
5	101	5	5
6	110	6	6
7	111	7	7
8	1000	10	8
9	1001	11	9
10	1010	12	A
11	1011	13	B
12	1100	14	C
13	1101	15	D
14	1110	16	E
15	1111	1	F
16	10000	20	10

Arithmetic - *Binary Arithmetic*

- ***Addition***

```
 111011   Carries
  101011   Augend
+  11001   Addend
 -------
 1000100
```

- ***Subtraction***

```
 0   1  10   0  10       Borrows
 1   0   0   1   0   1   Minuend
-        1   1   0   1   1   Subtrahend
 ------------------------
             1   0   1   0
```

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Arithmetic - *Binary Arithmetic*

- ***Multiplication***

```
        1 1 0 1 0    Multiplicand
      x   1 0 1 0    Multiplier
      -----------
        0 0 0 0 0
      1 1 0 1 0
    0 0 0 0 0
  1 1 0 1 0
-----------------------
1 0 0 0 0 0 1 0 0    Product
```

Division

```
                    1 1 0     Quotient
                ___________
Divider  1 0 0 1 ) 1 1 1 1 0 1   Dividend
                   1 0 0 1
                   ---------
                     1 1 0 0
                     1 0 0 1
                     -------
                       1 1 1   Remainder
```

Arithmetic - *Octal Arithmetic*

- ***Addition***

```
  1 1 1       Carries
    5 4 7 1   Augend
  + 3 7 5 4   Addend
  ---------
  1 1 4 4 5   Sum
```

- ***Subtraction***

```
 6 10   4 10   Borrows
 7   4   5   1   Minuend
- 5   6   4   3   Subtrahend
 ---------------
 1   6   0   6   Difference
```

OCTAL ADDITION TABLE

+	0	1	2	3	4	5	6	7
0	0	1	2	3	4	5	6	7
1	1	2	3	4	5	6	7	10
2	2	3	4	5	6	7	10	11
3	3	4	5	6	7	10	11	12
4	4	5	6	7	10	11	12	13
5	5	6	7	10	11	12	13	14
6	6	7	10	11	12	13	14	15
7	7	10	11	12	13	14	15	16

Arithmetic - *Octal Arithmetic*

OCTAL MULTIPLICATION TABLE

X	0	1	2	3	4	5	6	7
0	0	0	0	0	0	0	0	0
1	0	1	2	3	4	5	6	7
2	0	2	4	6	10	12	14	16
3	0	3	6	11	14	17	22	25
4	0	4	10	14	20	24	30	34
5	0	5	12	17	24	31	36	43
6	0	6	14	22	30	36	44	52
7	0	7	16	25	34	43	52	61

- ***Multiplication***

```
     326   Multiplicand
x     67   Multiplier
--------
    2732   Partial products
   2404
   -----
   26772   Product
```

Division

```
              114      Quotient
Divider  63 ) 7514     Dividend
              63
              ----
              114
               63
              ----
               364
               314
              ----
                50     Remainder
```

Arithmetic - *Hexadecimal Arithmetic*

- ***Addition***

```
 1 0 1 1     Carries
   5 B A 9   Augend
+  D 0 5 8   Addend
 ----------
 1 2 C 0 1   Sum
```

- ***Subtraction***

```
   9 10  A 10   Borrows
   A  5  B  9   Minuend
+  5  8  0  D   Subtrahend
 ----------------
   4  D  A  C   Difference
```

+	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
1	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F	10
2	2	3	4	5	6	7	8	9	A	B	C	D	E	F	10	11
3	3	4	5	6	7	8	9	A	B	C	D	E	F	10	11	12
4	4	5	6	7	8	9	A	B	C	D	E	F	10	11	12	13
5	5	6	7	8	9	A	B	C	D	E	F	10	11	12	13	14
6	6	7	8	9	A	B	C	D	E	F	10	11	12	13	14	15
7	7	8	9	A	B	C	D	E	F	10	11	12	13	14	15	16
8	8	9	A	B	C	D	E	F	10	11	12	13	14	15	16	17
9	9	A	B	C	D	E	F	10	11	12	13	14	15	16	17	18
A	A	B	C	D	E	F	10	11	12	13	14	15	16	17	18	19
B	B	C	D	E	F	10	11	12	13	14	15	16	17	18	19	1A
C	C	D	E	F	10	11	12	13	14	15	16	17	18	19	1A	1B
D	D	E	F	10	11	12	13	14	15	16	17	18	19	1A	1B	1C
E	E	F	10	11	12	13	14	15	16	17	18	19	1A	1B	1C	1D
F	F	10	11	12	13	14	15	16	17	18	19	1A	1B	1C	1D	1E

Arithmetic – *Hexadecimal Arithmetic*

×	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
2	0	2	4	6	8	A	C	E	10	12	14	16	18	1A	1C	1E
3	0	3	6	9	C	F	12	15	18	1B	1E	21	24	27	2A	2D
4	0	4	8	C	10	14	18	1C	20	24	28	2C	30	34	38	3C
5	0	5	A	F	14	19	1E	23	28	2D	32	37	3C	41	46	4B
6	0	6	C	12	18	1E	24	2A	30	36	3C	42	48	4E	54	5A
7	0	7	E	15	1C	23	2A	31	38	3F	46	4D	54	5B	62	69
8	0	8	10	18	20	28	30	38	40	48	50	58	60	68	70	78
9	0	9	12	1B	24	2D	36	3F	48	51	5A	63	6C	75	7E	87
A	0	A	14	1E	28	32	3C	46	50	5A	64	6E	78	82	8C	96
B	0	B	16	21	2C	37	42	4D	58	63	6E	79	84	8F	9A	A5
C	0	C	18	24	30	3C	48	54	60	6C	78	84	90	9C	A8	B4
D	0	D	1A	27	34	41	4E	5B	68	75	82	8F	9C	A9	B6	C3
E	0	E	1C	2A	38	46	54	62	70	7E	8C	9A	A8	B6	C4	D2
F	0	F	1E	2D	3C	4B	5A	69	78	87	96	A5	B4	C3	D2	E1

- ***Multiplication***

```
   B9A5   Multiplicand
 x  D50   Multiplier
 ------
 3A0390   Partial products
96D61
-------
9A76490   Product
```

- ***Division***

```
            79B     Quotient
          -------
Divider B9) 57F6D   Dividend
            50F
            ----
             706
             681
             ----
              85D
              7F3
             ----
               6A   Remainder
```

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Base Conversion (1)

- ***Series Substitution Method***
  - Expanded form of polynomial representation:
    $N = a_{n-1}r^{n-1} + \dots + a_0r^0 + a_{-1}r^{-1} + \dots + a_{-m}r^{-m}$ (1.3)
  - Conversation Procedure (base *A* to base *B*)
    - Represent the number in base *A* in the format of Eq. 1.3.
    - Evaluate the series using base *B* arithmetic.
  - ***Examples***:
    - $(11010)_2 \rightarrow (\ ?\ )_{10}$
      $N = 1\times2^4 + 1\times2^3 + 0\times2^2 + 1\times2^1 + 0\times2^0$
      $= (16)_{10} + (8)_{10} + 0 + (2)_{10} + 0$
      $= (26)_{10}$
    - $(627)_8 \rightarrow (\ ?\ )_{10}$
      $N = 6\times8^2 + 2\times8^1 + 7\times8^0$
      $= (384)_{10} + (16)_{10} + (7)_{10}$
      $= (407)_{10}$

Base Conversion (2)

- ***Radix Divide Method***
  - Used to convert the integer in base *A* to the equivalent base *B* integer.
  - Underlying theory:
    - $(N_I)_A = b_{n-1}B^{n-1} + \ldots + b_0B^0$ (1.4)

      Here, b_i's represents the digits of $(N_I)_B$ in base *A*.
    - $N_I / B = (b_{n-1}B^{n-1} + \ldots + b_1B^1 + b_0B^0) / B$

      $= (\text{Quotient } Q_1: b_{n-1}B^{n-2} + \ldots + b_1B^0) + (\text{Remainder } R_0: b_0)$
    - In general, $(b_i)_A$ is the remainder R_i when Q_i is divided by $(B)_A$.

  - ***Conversion Procedure***

    1. Divide $(N_I)_B$ by $(B)_A$, producing Q_1 *and* R_0. R_0 is the least significant digit, d_0, of the result.
    2. Compute d_i, for $i = 1 \ldots n - 1$, by dividing Q_i by $(B)_A$, producing Q_{i+1} and R_i, which represents d_i.
    3. Stop when $Q_{i+1} = 0$.

Base Conversion (3)

- ***Examples***
  - $(315)_{10} = (473)_8$

$(123)_{10} = (111\ 1011)_2$

  - $(315)_{10} = (13B)_{16}$

Base Conversion (4)

- ***Radix Multiply Method***
  - Used to convert fractions.
  - Underlying theory:
    - $(N_F)_A = b_{-1}B^{-1} + b_{-2}B^{-2} + \ldots + b_{-m}B^{-m}$ (1.5)
      Here, $(N_F)_A$ is a fraction in base A and b_i's are the digits of $(N_F)_B$ in base A.
    - $B \times N_F = B \times (b_{-1}B^{-1} + b_{-2}B^{-2} + \ldots + b_{-m}B^{-m})$
      $= (\text{Integer } I_{-1}\text{: } b_{-1}) + (\text{Fraction } F_{-2}\text{: } b_{-2}B^{-1} + \ldots + b_{-m}B^{-(m-1)})$
    - In general, $(b_i)_A$ is the integer part I_{-i}, of the product of $F_{-(i+1)} \times (B_A)$.
  - ***Conversion Procedure***
    1. Let $F_{-1} = (N_F)_A$.
    2. Compute digits $(b_{-i})_A$, for $i = 1 \ldots m$, by multiplying F_i by $(B)_A$, producing integer I_{-i}, which represents $(b_{-i})_A$, and fraction $F_{-(i+1)}$.
    3. Convert each digits $(b_{-i})_A$ to base B.

Base Conversion (5)

- ***Examples***
  - $(0.479)_{10} = (0.3651\ldots)_8$

    MSD $3.832 \leftarrow 0.479 \times 8$

    $6.656 \leftarrow 0.832 \times 8$

    $5.248 \leftarrow 0.656 \times 8$

    LSD $1.984 \leftarrow 0.248 \times 8$

    …

  - $(0.479)_{10} = (0.0111\ldots)_2$

    MSD $0.9580 \leftarrow 0.479 \times 2$

    $1.9160 \leftarrow 0.9580 \times 2$

    $1.8320 \leftarrow 0.9160 \times 2$

    LSD $1.6640 \leftarrow 0.8320 \times 2$

    …

Base Conversion (6)

- ***General Conversion Algorithm***
- ***Algorithm 1.1***

  To convert a number *N* from base *A* to base *B*, use

  (a) the series substitution method with base *B* arithmetic, or

  (b) the radix divide or multiply method with base *A* arithmetic.

- ***Algorithm 1.2***

  To convert a number *N* from base *A* to base *B*, use

  (a) the series substitution method with base 10 arithmetic to convert *N* from base *A* to base 10, and

  (b) the radix divide or multiply method with decimal arithmetic to convert *N* from base 10 to base *B*.

- Algorithm 1.2 is longer, but easier and less error prone.

Base Conversion (7)

- ***Example***

  $(18.6)_9 = (\ ?\ )_{11}$

  (a) Convert to base 10 using series substitution method:

  $$\begin{aligned} N_{10} &= 1 \times 9^1 + 8 \times 9^0 + 6 \times 9^{-1} \\ &= 9 + 8 + 0.666\ldots \\ &= (17.666\ldots)_{10} \end{aligned}$$

  (b) Convert from base 10 to base 11 using radix divide and multiply method:

  17 | 11
  (6) 1 | 11
  (1) 0

  $$\begin{aligned} 7.326 &\leftarrow 0.666 \times 11 \\ 3.586 &\leftarrow 0.326 \times 11 \\ 6.446 &\leftarrow 0.586 \times 11 \end{aligned}$$

  $N_{11} = (16.736\ \ldots)_{11}$

Base Conversion (8)

- When $B = A^k$
- ***Algorithm 1.3***

  (a) To convert a number N from base A to base B when $B = A^k$ and k is a positive integer, group the digits of N in groups of k digits in both directions from the radix point and then replace each group with the equivalent digit in base B

  (b) To convert a number N from base B to base A when $B = A^k$ and k is a positive integer, replace each base B digit in N with the equivalent k digits in base A.

- ***Examples***
  - $(001\ 010\ 111.\ 100)_2 = (127.4)_8$ (group bits by 3)
  - $(1011\ 0110\ 0101\ 1111)_2 = (\mathrm{B65F})_{16}$ (group bits by 4)

Signed Number Representation

- ***Signed Magnitude Method***
  - $N = \pm(a_{n-1} \ldots a_0.a_{-1} \ldots a_{-m})_r$ is represented as
    $N = (sa_{n-1} \ldots a_0.a_{-1} \ldots a_{-m})_{rsm}$, (1.6)
    where $s = 0$ if N is positive and $s = r - 1$ otherwise.
  - $N = -(15)_{10}$
  - In binary: $N = -(15)_{10} = -(1111)_2 = (1, 1111)_{2sm}$
  - In decimal: $N = -(15)_{10} = (9, 15)_{10sm}$

- ***Complementary Number Systems***
  - ***Radix complements*** (r's complements)
    $[N]_r = r^n - (N)_r$ (1.7)
    where n is the number of digits in $(N)_r$.
  - *Positive full scale*: $r^{n-1} - 1$
  - *Negative full scale*: $-r^{n-1}$
  - ***Diminished radix complements*** (r-1's complements)

    $[N]_{r-1} = r_n - (N)_r - 1$

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Radix Complement Number Systems (1)

- Two's complement of $(N)_2 = (101001)_2$
  $[N]_2 = 2^6 - (101001)_2 = (1000000)_2 - (101001)_2 = (010111)_2$

- $(N)_2 + [N]_2 = (101001)_2 + (010111)_2 = (1000000)_2$
  If we discard the carry, $(N)_2 + [N]_2 = 0$.
  Hence, $[N]_2$ can be used to represent $-(N)_2$.
- $[\,[N]_2\,]_2 = [(010111)_2]_2 = (1000000)_2 - (010111)_2 = (101001)_2 = (N)_2$.

- Two's complement of $(N)_2 = (1010)_2$ for $n = 6$
  $[N]_2 = (1000000)_2 - (1010)_2 = (110110)_2$.

- Ten's complement of $(N)_{10} = (72092)_{10}$
  $[N]_{10} = (100000)_{10} - (72092)_{10} = (27908)_{10}$.

Radix Complement Number Systems (2)

- ***Algorithm 1.4* Find $[N]_r$ given $(N)_r$.**
  - Copy the digits of N, beginning with the LSD and proceeding toward the MSD until the first nonzero digit, a_i, has been reached
  - Replace a_i with r - a_i .
  - Replace each remaining digit a_j , of N by $(r - 1) - a_j$ until the MSD has been replaced.

- ***Example***: 10's complement of $(56700)_{10}$ is $(43300)_{10}$
- ***Example***: 2's complement of $(10100)_2$ is $(01100)_2$.
- ***Example***: 2's complement of $N = (10110)_2$ for $n = 8$.
  - Put three zeros in the MSB position and apply algorithm 1.4
  - N = 00010110
  - $[N]_2 = (11101010)_2$

- The same rule applies to the case when N contains a radix point.

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Radix Complement Number Systems (3)

- ***Algorithm 1.5*** **Find $[N]_r$ given $(N)_r$.**
  - First replace each digit, a_k , of $(N)_r$ by $(r - 1) - a_k$ and then add 1 to the resultant.
- For binary numbers ($r = 2$), complement each digit and add 1 to the result.

- ***Example***: Find 2's complement of $N = (01100101)_2$.

  $N =$ 01100101
  10011010 Complement the bits
  +1 Add 1
  $[N]_2 = (10011011)_{10}$

- ***Example***: Find 10's complement of $N = (40960)_{10}$

  $N = 40960$
  59039 Complement the bits
  +1 Add 1
  $[N]_2 = (59040)_{10}$

Radix Complement Number Systems (4)

- ***Two's complement number***:
  - Positive number :
    - $N = +(a_{n-2}, \ldots, a_0)_2 = (0, a_{n-2}, \ldots, a_0)_{2cns}$,
      where $0 \le N \le 2^{n-1} - 1$.
  - Negative number:
    - $N = (a_{n-1}, a_{n-2}, \ldots, a_0)_2$
    - $-N = [a_{n-1}, a_{n-2}, \ldots, a_0]_2$ (two's complement of N),
      where $-1 \ge N \ge -2^{n-1}$.
  - ***Example***: Two's complement number system representation of $\pm (N)_2$

    when $(N)_2 = (1011001)_2$ for $n = 8$:
    - $+(N)_2 = (0, 1011001)_{2cns}$
    - $-(N)_2 = [+(N)_2]_2 = [0, 1011001]_2 = (1, 0100111)_{2cns}$

Signed Decimal	Sign Magnitude Binary	Two's Complement System	One's Complement System
+15	0,1111	0,1111	0,1111
+14	0,1110	0,1110	0,1110
+13	0,1101	0,1101	0,1101
+12	0,1100	0,1100	0,1100
+11	0,1011	0,1011	0,1011
+10	0,1010	0,1010	0,1010
+9	0,1001	0,1001	0,1001
+8	0,1000	0,1000	0,1000
+7	0,0111	0,0111	0,0111
+6	0,0110	0,0110	0,0110
+5	0,0101	0,0101	0,0101
+4	0,0100	0,0100	0,0100
+3	0,0011	0,0011	0,0011
+2	0,0010	0,0010	0,0010
+1	0,0001	0,0001	0,0001
0	0,0000	0,0000	0,0000
	(1,0000)		(1,1111)
-1	1,0001	1,1111	1,1110
-2	1,0010	1,1110	1,1101
-3	1,0011	1,1101	1,1100
-4	1,0100	1,1100	1,1011
-5	1,0101	1,1011	1,1010
-6	1,0110	1,1010	1,1001
-7	1,0111	1,1001	1,1000
-8	1,1000	1,1000	1,0111
-9	1,1001	1,0111	1,0110
-10	1,1010	1,0110	1,0101
-11	1,1011	1,0101	1,0100
-12	1,1100	1,0100	1,0011
-13	1,1101	1,0011	1,0010
-14	1,1110	1,0010	1,0001
-15	1,1111	1,0001	1,0000
-16	—	1,0000	—

Radix Complement Number Systems (5)

- ***Example***: Two's complement number system representation of $-(18)_{10}$, $n = 8$:
  - $+(18)_{10} = (0, 0010010)_{2cns}$
  - $-(18)_{10} = [0, 0010010]_2 = (1, 1101110)_{2cns}$

- ***Example***: Decimal representation of $N = (1, 1101000)_{2cns}$
  - $N = (1, 1101000)_{2cns} = -[1, 1101000]_2 = -(0, 0011000)_{2cns} = -(24)_2$.

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Radix Complement Arithmetic (1)

- Radix complement number systems are used to convert subtraction to addition, which reduces hardware requirements (only adders are needed).
- *A* - *B* = *A* + (-*B*) (add *r*'s complement of *B* to *A*)

- Range of numbers in two's complement number system:

$-2^{n-1} \leq N \leq 2^{n-1} - 1$, where *n* is the number of bits.

- $2^{n-1} - 1 = (0, 11 \ldots 1)_{2cns}$ and $-2^{n-1} = (1, 00 \ldots 0)_{2cns}$
- If the result of an operation falls outside the range, an ***overflow condition*** is said to occur and the result is not valid.

- Consider three cases:
  - $A = B + C$,
  - $A = B - C$,
  - $A = -B - C$,

    (where $B \geq 0$ and $C \geq 0$.)

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Radix Complement Arithmetic (2)

- ***Case 1***: $A = B + C$
  - $(A)_2 = (B)_2 + (C)_2$
  - If $A > 2^{n-1} - 1$ (***overflow***), it is detected by the n^{th} bit, which is set to 1.

  - ***Example***: $(7)_{10} + (4)_{10}$ = ? using 5-bit two's complement arithmetic.
    - $+(7)_{10} = +(0111)_2 = (0, 0111)_{2cns}$
    - $+(4)_{10} = +(0100)_2 = (0, 0100)_{2cns}$
    - $(0, 0111)_{2cns} + (0, 0100)_{2cns} = (0, 1011)_{2cns} = +(1011)_2 = +(11)_{10}$
    - No overflow.
  - ***Example***: $(9)_{10} + (8)_{10}$ = ?
    - $+(9)_{10} = +(1001)_2 = (0, 1001)_{2cns}$
    - $+(8)_{10} = +(1000)_2 = (0, 1000)_{2cns}$
    - $(0, 1001)_{2cns} + (0, 1000)_{2cns} = (\boldsymbol{1}, 0001)_{2cns}$ (***overflow***)

Radix Complement Arithmetic (3)

- ***Case 2***: $A = B - C$
  - $A = (B)_2 + (-(C)_2) = (B)_2 + [C]_2 = (B)_2 + 2^n - (C)_2 = 2^n + (B - C)_2$
  - If $B \geq C$, then $A \geq 2^n$ and the carry is discarded.
    So, $(A)_2 = (B)_2 + [C]|_{\text{carry discarded}}$
  - If $B < C$, then $A = 2^n - (C - B)_2 = [C - B]_2$ or $A = -(C - B)_2$ (no carry in this case).
    No overflow for Case 2.

  - ***Example***: $(14)_{10} - (9)_{10} = ?$
    - Perform $(14)_{10} + (-(9)_{10})$

$$(14)_{10} = +(1110)_2 = (0, 1110)_{2cns}$$
$$-(9)_{10} = -(1001)_2 = (1, 0111)_{2cns}$$
$$(14)_{10} - (9)_{10} = (0, 1110)_{2cns} + (1, 0111)_{2cns} = (0, 0101)_{2cns} + carry$$
$$= +(0101)_2 = +(5)_{10}$$

Radix Complement Arithmetic (4)

- ***Example***: $(9)_{10}$ - $(14)_{10}$ = ?
  - Perform $(9)_{10} + (-(14)_{10})$

    $(9)_{10} = +(1001)_2 = (0, 1001)_{2cns}$

    $-(14)_{10} = -(1110)_2 = (1, 0010)_{2cns}$

    $(9)_{10} - (14)_{10} = (0, 1001)_{2cns} + (1, 0010)_{2cns} = (1, 1011)_{2cns}$

    $= -(0101)_2 = -(5)_{10}$

- ***Example***: $(0, 0100)_{2cns}$ - $(1, 0110)_{2cns}$ = ?
  - Perform $(0, 0100)_{2cns} + (- (1, 0110)_{2cns})$

    $- (1, 0110)_{2cns}$ = two's complement of $(1,0110)_{2cns}$

    $= (0, 1010)_{2cns}$

    $(0, 0100)_{2cns} - (1, 0110)_{2cns} = (0, 0100)_{2cns} + (0, 1010)_{2cns}$

    $= (0, 1110)_{2cns} = +(1110)_2 = +(14)_{10}$

    $+(4)_{10} - (-(10)_{10}) = +(14)_{10}$

Radix Complement Arithmetic (5)

- ***Case 3***: $A = -B - C$
  - $A = [B]_2 + [C]_2 = 2^n - (B)_2 + 2^n - (C)_2 = 2^n + 2^n - (B + C)_2 = 2^n + [B + C]_2$
  - The carry bit (2^n) is discarded.
  - An overflow can occur, in which case the sign bit is 0.

  - ***Example***: $-(7)_{10} - (8)_{10} = ?$
    - Perform $(-(7)_{10}) + (-(8)_{10})$

      $-(7)_{10} = -(0111)_2 = (1, 1001)_{2cns}$, $-(8)_{10} = -(1000)_2 = (1, 1000)_{2cns}$

      $-(7)_{10} - (8)_{10} = (1, 1001)_{2cns} + (1, 1000)_{2cns} = (1, 0001)_{2cns} + carry$

      $= -(1111)_2 = -(15)_{10}$
  - ***Example***: $-(12)_{10} - (5)_{10} = ?$
    - Perform $(-(12)_{10}) + (-(5)_{10})$

      $-(12)_{10} = -(1100)_2 = (1, 0100)_{2cns}$, $-(5)_{10} = -(0101)_2 = (1, 1011)_{2cns}$

      $-(7)_{10} - (8)_{10} = (1, 0100)_{2cns} + (1, 1011)_{2cns} = (0, 1111)_{2cns} + carry$

      Overflow, because the sign bit is 0.

Radix Complement Arithmetic (6)

- ***Example***: $A = (25)_{10}$ and $B = -(46)_{10}$
  - $A = +(25)_{10} = (0, 0011001)_{2cns}$, $-A = (1, 1100111)_{2cns}$
  - $B = -(46)_{10} = -(0, 0101110)_2 = (1, 1010010)_{2cns}$, $-B = (0, 0101110)_{2cns}$

  - $A + B = (0, 0011001)_{2cns} + (1, 1010010)_{2cns} = (1, 1101011)_{2cns} = -(21)_{10}$
  - $A - B = A + (-B) = (0, 0011001)_{2cns} + (0, 0101110)_{2cns}$
    $= (0, 1000111)_{2cns} = +(71)_{10}$
  - $B - A = B + (-A) = (1, 1010010)_{2cns} + (1, 1100111)_{2cns}$
    $= (1, 0111001)_{2cns} + carry = -(0, 1000111)_{2cns} = -(71)_{10}$
  - $-A - B = (-A) + (-B) = (1, 1100111)_{2cns} + (0, 0101110)_{2cns}$
    $= (0, 0010101)_{2cns} + carry = +(21)_{10}$
  - Note: Carry bit is discarded.

Radix Complement Arithmetic (7)

- Summary

Case	Carry	Sign Bit	Condition	Overflow ?
B + C	0 0	0 1	$B + C \le 2^{n-1} - 1$ $B + C > 2^{n-1} - 1$	No Yes
B - C	1 0	0 1	$B \le C$ $B > C$	No No
-B - C	1 1	1 0	$-(B + C) \ge -2^{n-1}$ $-(B + C) < -2^{n-1}$	No Yes

- When numbers are represented using two's complement number system:
  - Addition: Add two numbers.
  - Subtraction: Add two's complement of the subtrahend to the minuend.
  - Carry bit is discarded, and overflow is detected as shown above.

  - Radix complement arithmetic can be used for any radix.

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Diminished Radix Complement Number systems (1)

- ***Diminished radix complement*** $[N]_{r-1}$ of a number $(N)_r$ is:

  $[N]_{r-1} = r^n - (N)_r - 1$ (1.10)

- ***One's complement*** (r = 2):

  $[N]_{2-1} = 2^n - (N)_2 - 1$ (1.11)

- ***Example***: One's complement of $(01100101)_2$

  $$\begin{aligned}[N]_{2-1} &= 2^8 - (01100101)_2 - 1 \\ &= (100000000)_2 - (01100101)_2 - (00000001)_2 \\ &= (10011011)_2 - (00000001)_2 \\ &= (10011010)_2\end{aligned}$$

Diminished Radix Complement Number systems (2)

- ***Example***: Nine's complement of (40960)

$$[N]_{2\text{-}1} = 10^5 - (40960)_{10} - 1$$
$$= (100000)_{10} - (40960)_{10} - (00001)_{10}$$
$$= (59040)_{10} - (00001)_{10}$$
$$= (59039)_{10}$$

- ***Algorithm 1.6*** **Find $[N]_{r-1}$ given $(N)_r$.**

  Replace each digit a_i of $(N)_r$ by r - 1 - a. Note that when r = 2, this simplifies to complementing each individual bit of $(N)_r$.

- Radix complement and diminished radix complement of a number (N):

$$[N]_r = [N]_{r-1} + 1 \qquad (1.12)$$

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Diminished Radix Complement Arithmetic (1)

- Operands are represented using diminished radix complement number system.
- The carry, if any, is added to the result (***end-around carry***).

- ***Example***: Add $+(1001)_2$ and $-(0100)_2$.
  One's complement of +(1001) = 01001
  One's complement of -(0100) = 11011
  01001 + 11011 = 100100 (carry)
  Add the carry to the result: correct result is 00101.

- ***Example***: Add $+(1001)_2$ and $-(1111)_2$.
  One's complement of +(1001) = 01001
  One's complement of -(1111) = 10000
  01001 + 10000 = 11001 (no carry, so this is the correct result).

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Diminished Radix Complement Arithmetic (2)

- ***Example***: Add $-(1001)_2$ and $-(0011)_2$.
  One's complement of the operands are: 10110 and 11100
  10110 + 11100 = 110010 (carry)
  Correct result is 10010 + 1 = 10011.

- ***Example***: Add $+(75)_{10}$ and $-(21)_{10}$.
  Nine's complements of the operands are: 075 and 978
  075 + 978 = 1053 (carry)
  Correct result is 053 + 1 = 054

- ***Example***: Add $+(21)_{10}$ and $-(75)_{10}$.
  Nine's complements of the operands are: 021 and 924
  021 + 924 = 945 (no carry, so this is the correct result).

Exercise

Consider A=5, B=6. Use n=4 bits for representations of numbers

Calculate (using 2 complement number system and 1 complement number system):

A+B

A-B

B-A

-A-B

Computer Codes (1)

- ***Code*** is a systematic use of a given set of symbols for representing information.

  Example: Traffic light (Red: stop, Yellow: caution, Blue: go).

- ***Numeric Codes***
  - To represent numbers.
  - Fixed-point and floating-point number.

- ***Fixed-point Numbers***
  - Used for signed integers or integer fractions.
  - Sign magnitude, two's complement, or one's complement systems are used.
  - Integer: (Sign bit) + (Magnitude) + (Implied radix point)
  - Fraction: (Sign bit) + (Implied radix point) + (Magnitude)

Computer Codes (2)

- ***Excess or Biased Representation***
  - An excess -*K* representation of a code *C*: Add *K* to each code word *C*.
  - Frequently used for the exponents of floating-point numbers.
  - Excess-8 representation of 4-bit two's complement code

Decimal	Two's Complement	Excess-8
+7	0111	1111
+6	0110	1110
+5	0101	1101
+4	0100	1100
+3	0011	1011
+2	0010	1010
+1	0001	1001
0	0000	1000
-1	1111	0111
-2	1110	0110
-3	1101	0101
-4	1100	0100
-5	1011	0011
-6	1010	0010
-7	1001	0001
-8	1000	0000

Characters and Other Codes (1)

To represent information as strings of alpha-numeric characters.

- ***Binary Coded Decimal (BCD)***
  - Used to represent the decimal digits 0 - 9.
  - 4 bits are used.

  Used
    - to encode numbers for output to numerical displays
    - Used in processors that perform decimal arithmetic.

<u>Example</u>: $(9750)_{10} = (1001011101010000)_{BCD}$

Binary-Coded Decimal (BCD)

Decimal Symbol	BCD Digit
0	0000
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111
8	1000
9	1001

Characters and Other Codes (2)

- ***ASCII*** (American Standard Code for Information Interchange)
  - Most widely used character code.
  - The eighth bit is often used for error detection (parity bit)
  - ***Example***: ASCII code representation of the word ***Digital***

Character	Binary Code	Hexadecimal Code
D	1000100	44
i	1101001	69
g	1100111	67
i	1101001	69
t	1110100	74
a	1100001	61
l	1101100	6C

American Standard Code for Information Interchange (ASCII)

	$b_7b_6b_5$							
$b_4b_3b_2b_1$	**000**	**001**	**010**	**011**	**100**	**101**	**110**	**111**
0000	NUL	DLE	SP	0	@	P	`	p
0001	SOH	DC1	!	1	A	Q	a	q
0010	STX	DC2	"	2	B	R	b	r
0011	ETX	DC3	#	3	C	S	c	s
0100	EOT	DC4	$	4	D	T	d	t
0101	ENQ	NAK	%	5	E	U	e	u
0110	ACK	SYN	&	6	F	V	f	v
0111	BEL	ETB	'	7	G	W	g	w
1000	BS	CAN	(	8	H	X	h	x
1001	HT	EM	)	9	I	Y	i	y
1010	LF	SUB	*	:	J	Z	j	z
1011	VT	ESC	+	;	K	[	k	{
1100	FF	FS	,	<	L	\	l	|
1101	CR	GS	–	=	M	]	m	}
1110	SO	RS	.	>	N	∧	n	~
1111	SI	US	/	?	O	—	o	DEL

Characters and Other Codes (3)

- ***Gray Code***

  Two consecutive code words differ in only 1 bit

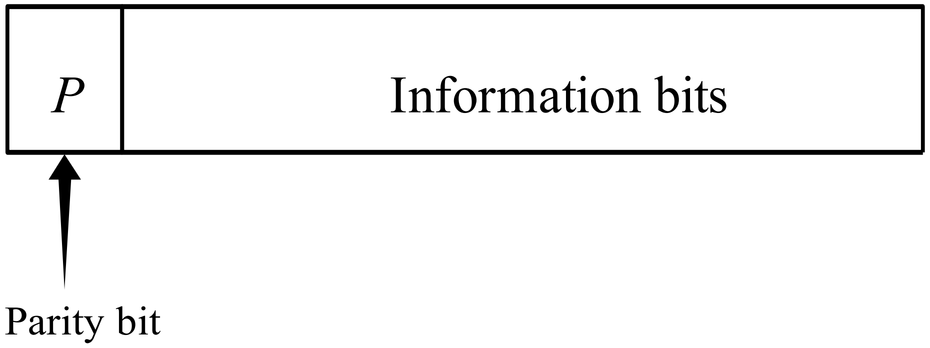
Gray Code

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

Error Detection Codes

- ***Simple Parity Code***
  - Concatenate (||) a *parity bit*, *P*, to each code word of *C*.

A parity bit is an extra bit included with a message to make the total number of 1's either even or odd



Error Detection Codes

Character	ASCII Code	Odd-parity Code
0	0110000	10110000
X	1011000	01011000
=	0111100	1111100
BEL	0000111	00000111

This method detects one, three, or any odd combination of errors in each character that is transmitted. An even combination of errors, however, goes undetected, and additional error detection codes may be needed to take care of that possibility.

Floating Point Numbers (1)

- $N = M \times r^E$, where
  - M (mantissa or significand) is a significant digits of N
  - E (exponent or characteristic) is an integer exponent.

- In general, $N = \pm (a_{n-1} \ldots a_0 . a_{-1} \ldots a_{-m})_r$ is represented by
  - $N = \pm (.a_{n-1} \ldots a_{-m})_r \times r^n$

- M is usually represented in sign magnitude:
  - $M = (S_M . a_{n-1} \ldots a_{-m})_{rsm}$, where (1.14)

    $(.a_{n-1} \ldots a_{-m})_r$ represents the magnitude

    $M = (-1)^{S_M} \times (.a_{n-1} \ldots a_{-m})_r$ (0: positive, 1: negative) (1.15)

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Floating Point Numbers (2) - IEEE 754 binary floating point

- *E* is coded in excess -*K*.
- *K* is called a bias and IEEE 754 selected to be 2^{e-1} -1 (*e* is the number of bits).
- So, biased *E* is:
  - $-2^{e-1} + 1 \leq \quad E \quad \leq 2^{e-1} - 1$

- The number 0 is represented by an all-zero word.

Floating Point Numbers (3)

- Multiple representations of a given number:

$$N = M \times r^{E} \quad (1.19)$$
$$= (M \div r) \times r^{E+1} \quad (1.20)$$
$$= (M \times r) \times r^{E-1} \quad (1.21)$$

- ***Example***: $M = +(1101.0101)_2$

$$M = +(1101.0101)_2$$
$$= (1.1010101)_2 \times 2^3 \quad (1.22)$$
$$= (0.011010101)_2 \times 2^5 \quad (1.23)$$
$$= (0.0011010101)_2 \times 2^6 \quad (1.24)$$

…

- ***Normalization*** is used for a unique representation: mantissa has a nonzero value in its MSD position.
- Eq. 1.22 gives the normalization representation of M.

Floating Point Numbers (4)

- ***Floating-point Number Formats***
  - Typical single-precision format

S_M	Exponent E	Mantissa M

Sign of mantissa

code + bias

  - Typical extended-precision format

S_M	Exponent E	Mantissa M (most significant part)

Mantissa M (least significant part)

Convert a base 10 decimal number to 32 bit single precision (IEEE 754 binary floating point)

1. If the number to be converted is negative, start with its the positive version.
2. Convert from base 10 to binary number.
3. Normalize the binary representation of the number, by shifting the decimal point "*n*" positions either to the left or to the right, so that only one non zero digit remains to the left of the decimal point.
4. Normalize mantissa, remove the leading (leftmost) bit, since it's always '1' (and the decimal sign if the case) and adjust its length to 23 bits, either by removing the excess bits from the right (losing precision...) or by adding extra '0' bits to the right.
5. Adjust the exponent in 8 bit excess/bias notation and then convert it from decimal (base 10) to 8 bit binary:

$$\textbf{Exponent (adjusted)} = \textbf{Exponent (unadjusted)} + [2^{(8-1)} - 1]$$

6. Sign (it takes 1 bit) is either 1 for a negative or 0 for a positive number.

Floating Point Numbers - IEEE 754 binary floating point

- ***Example***:

convert 325.25_{10} to IEEE 754 32bits floating point

$325_{10} = 1\ 0100\ 0101_2$

$0.25_{10} = 0.01_2$

$325.25_{10} = 1\ 0100\ 0101.01_2$

$325.25_{10} = \underset{\text{sign}}{+}1.\underbrace{0100\ 010101}_{\text{mantissa}}{}_2 \times 2^{\overset{\text{exponent}}{8}}$

Mantissa= 010 0010 1010 0000 0000 0000

Exponent = $8 + (2^8 - 1) = 135_{10} = 1000\ 0111$

Sign= 0

number: $0\ 1000\ 0111\ 010\ 0010\ 1010\ 0000\ 0000\ 0000_2$

$43a2a000_{16}$

Floating Point Numbers - IEEE 754 binary floating point

- ***Example***:

convert -325.25_{10} to IEEE 754 32bits floating point

$325_{10} = 1\ 0100\ 0101_2$

$0.25_{10} = 0.01_2$

$325.25_{10} = 1\ 0100\ 0101.01_2$

$325.25_{10} = +1.\underbrace{0100\ 010101}_{\text{mantissa}}{}_2 \times 2^{8}$

sign

exponent

Mantissa= 010 0010 1010 0000 0000 0000

Exponent = $8 + (2^8 - 1) = 135_{10}$ = 1000 0111

Sign= 1

number: $1\ 1000\ 0111\ 010\ 0010\ 1010\ 0000\ 0000\ 0000_2$

$c3a2a000_{16}$

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Floating Point Numbers - IEEE 754 binary floating point

- ***Example***:

convert 325.40_{10} to IEEE 754 32bits floating point

325_{10}= 1 0100 0101_2

0.4_{10} = $0.011001100110...._2$

Mantissa= 01000101011001100110011

Exponent = 8 + (2^8 -1) = 135_{10} = 1000 0111

Sign= 0

number: 0 1000 0111 010 0010 1011 0011 0011 0011 $_2$

$43a2b333_{16}$

325.25_{10} = 1 0100 0101.0110 0110 0110 0110_2

$325.25_{10} = +\underbrace{1.01000101011001100110011_2}_{\text{Mantissa -- 23 bits}} \times 2^{8}$ exponent

sign

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Convert a 32 bit single precision (IEEE 754 binary floating point) number to base 10

1. Sign (it takes 1 bit) is either 1 for a negative or 0 for a positive number.
2. Add the leading (leftmost) bit, since it's always '1'
3. Adjust the exponent in 8 bit excess/bias notation and then convert it from 8 bit binary to decimal (base 10):

   Exponent (unadjusted) = Exponent (adjusted) - [$2^{(8-1)}$ – 1]

4. Convert from binary number to base 10.
5. Add sign

Floating Point Numbers - IEEE 754 binary floating point

- ***Example***:

convert $c5aa9000_{16\ \text{floating point}}$ to decimal

1- 10001011-01010101001000000000000

Mantissa= 1.01010101001000000000000

Exponent (adjusted) = $10001011_2 = 139_{10}$
Exponent (unadjusted) = 139 – 127 = 12

Number: $1.01010101001000000000000_2 \times 2^{12}$
$= 1010101010010.00000000000_2$
$= 1010101010010_2 = 5458_{10}$

Convert to floating point

a) 4518712.375

b) -12.37505

c) 124.203125

d) -124203125

Convert from single precision floating point to decimal

a) $C4025000_{16}$

b) $4c026800_{16}$

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Boolean algebra fundamentals

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Fundamentals of Boolean Algebra

- Boolean algebra is defined with a set of ***elements***, a set of ***operators***, and a number of *axioms* and *postulates*.

- *A set of elements* is any collection of objects. If S is a set, and x and y are certain objects, then $x \in S$ means that x is a member of the set S and $y \notin S$ means that y is not an element of S.

Fundamentals of Boolean Algebra

- ***Basic Postulates***
- ***Postulate 1 (Definition)***: A Boolean algebra is a closed algebraic system containing a set *K* of two or more elements and the two operators · and +. For every pair of elements of K, the binary operator specifies a rule for obtaining a unique element of K.
- ***Postulate 2 (Existence of 1 and 0 element)***:

  (a) $a + 0 = a$ (identity for +), (b) $a \cdot 1 = a$ (identity for ·)
- ***Postulate 3 (Commutativity)***:

  (a) $a + b = b + a$, (b) $a \cdot b = b \cdot a$
- ***Postulate 4 (Associativity)***:

  (a) $a + (b + c) = (a + b) + c$ (b) $a \cdot (b \cdot c) = (a \cdot b) \cdot c$
- ***Postulate 5 (Distributivity)***:

  (a) $a + (b \cdot c) = (a + b) \cdot (a + c)$ (b) $a \cdot (b + c) = a \cdot b + a \cdot c$
- ***Postulate 6 (Existence of complement)***:

  (a) $a + \overline{a} = 1$ (b) $a \cdot \overline{a} = 0$

<u>Precedence</u>

()

‘

·

\+

Note: Normally · is omitted.

Fundamentals of Boolean Algebra

- ***Fundamental Theorems of Boolean Algebra***

- ***Theorem 1 (Idempotency)***:
  (a) $a + a = a$ (b) $aa = a$
- ***Theorem 2 (Null element)***:
  (a) $a + 1 = 1$ (b) $a0 = 0$
- ***Theorem 3 (Involution)***

$$\overline{\overline{a}} = a$$

- ***Properties of 0 and 1 elements***:

OR	AND	Complement
$a + 0 = a$	$a0 = 0$	$0' = 1$
$a + 1 = 1$	$a1 = a$	$1' = 0$

Fundamentals of Boolean Algebra

- ***Theorem 4 (Absorption)***

  (a) $a + ab = a$ (b) $a(a + b) = a$

- ***Examples***:
  - $(X + Y) + (X + Y)Z = X + Y$ [T4(a)]
  - $AB'(AB' + B'C) = AB'$ [T4(b)]

- ***Theorem 5***

  (a) $a + a'b = a + b$ (b) $a(a' + b) = ab$

- ***Examples***:
  - $B + AB'C'D = B + AC'D$ [T5(a)]
  - $(X + Y)((X + Y)' + Z) = (X + Y)Z$ [T5(b)]

Fundamentals of Boolean Algebra

- ***Theorem 6***

  (a) $ab + ab' = a$　　　(b) $(a + b)(a + b') = a$

- ***Examples***:
  - $ABC + AB'C = AC$　　　[T6(a)]
  - $(W' + X' + Y' + Z')(W' + X' + Y' + Z)(W' + X' + Y + Z')(W' + X' + Y + Z)$

    $= (W' + X' + Y')(W' + X' + Y + Z')(W' + X' + Y + Z)$　　　[T6(b)]

    $= (W' + X' + Y')(W' + X' + Y)$　　　[T6(b)]

    $= (W' + X')$　　　[T6(b)]

Fundamentals of Boolean Algebra

- ***Theorem 7***

  (a) $ab + ab'c = ab + ac$ (b) $(a + b)(a + b' + c) = (a + b)(a + c)$

- ***Examples***:
  - $wy' + wx'y + wxyz + wxz' = wy' + wx'y + wxy + wxz'$ [T7(a)]

    $= wy' + wy + wxz'$ [T7(a)]

    $= w + wxz'$ [T7(a)]

    $= w$ [T7(a)]
  - $(x'y' + z)(w + x'y' + z') = (x'y' + z)(w + x'y')$ [T7(b)]

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Fundamentals of Boolean Algebra

- ***Theorem 8 (DeMorgan's Theorem)***

  (a) $(a + b)' = a'b'$ (b) $(ab)' = a' + b'$

- Generalized DeMorgan's Theorem

  (a) $(a + b + \dots z)' = a'b' \dots z'$ (b) $(ab \dots z)' = a' + b' + \dots z'$

- ***Examples***:
  - $(a + bc)' = (a + (bc))'$
    $= a'(bc)'$ [T8(a)]
    $= a'(b' + c')$ [T8(b)]
    $= a'b' + a'c'$ [P5(b)]
  - Note: $(a + bc)' \neq a'b' + c'$

Fundamentals of Boolean Algebra

- ***More Examples for DeMorgan's Theorem***
  - $(a(b + z(x + a')))' = a' + (b + z(x + a'))'$ [T8(b)]
    $= a' + b'(z(x + a'))'$ [T8(a)]
    $= a' + b'(z' + (x + a')')$ [T8(b)]
    $= a' + b'(z' + x'(a')')$ [T8(a)]
    $= a' + b'(z' + x'a)$ [T3]
    $= a' + b'(z' + x')$ [T5(a)]

  - $(a(b + c) + a'b)' = (ab + ac + a'b)'$ [P5(b)]
    $= (b + ac)'$ [T6(a)]
    $= b'(ac)'$ [T8(a)]
    $= b'(a' + c')$ [T8(b)]

Fundamentals of Boolean Algebra

Apply DeMorgan's Theorem to these expressions

- (X+Y+Z)’
- (PQ+R)’
- (M+N)’Q’

Fundamentals of Boolean Algebra

- ***Theorem 9 (Consensus)***

  (a) $ab + a'c + bc = ab + a'c$ (b) $(a + b)(a' + c)(b + c) = (a + b)(a' + c)$

- ***Examples***:
  - $AB + A'CD + BCD = AB + A'CD$ [T9(a)]
  - $(a + b')(a' + c)(b' + c) = (a + b')(a' + c)$ [T9(b)]
  - $$\begin{aligned} ABC + A'D + B'D + CD &= ABC + (A' + B')D + CD && \text{[P5(b)]} \\ &= ABC + (AB)'D + CD && \text{[T8(b)]} \\ &= ABC + (AB)'D && \text{[T9(a)]} \\ &= ABC + (A' + B')D && \text{[T8(b)]} \\ &= ABC + A'D + B'D && \text{[P5(b)]} \end{aligned}$$

Switching Functions

- ***Switching algebra***: Boolean algebra with the set of elements $K = \{0, 1\}$

  If there are n variables, we can define 2^{2^n} switching functions.

- Sixteen functions of two variables:

AB	f_0	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	f_{12}	f_{13}	f_{14}	f_{15}
00	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
01	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1
10	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1
11	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1

- A switching function can be represented by a table as above, or by a switching expression as follows:

$$f_0(A,B)= 0,\ \ f_6(A,B) = AB' + A'B,\ \ f_{11}(A,B) = AB + A'B + A'B' = A' + B, \ldots$$

- Value of a function can be obtained by plugging in the values of all variables:

  The value of f_6 when A = 1 and B = 0 is: $1\cdot 0' + 1'\cdot 0 = 0 + 1 = 1.$

Truth Tables

- Shows the value of a function for all possible input combinations.
- Truth tables for OR, AND, and NOT:

ab	$f(a,b)=a+b$	ab	$f(a,b)=ab$	a	$f(a)=a'$
00	0	00	0	0	1
01	1	01	0	1	0
10	1	10	0		
11	1	11	1		

Truth Tables

- Truth tables for $f(A,B,C) = AB + A'C + AC'$

ABC	$f(A,B,C)$	ABC	$f(A,B,C)$
000	0	FFF	F
001	1	FFT	T
010	0	FTF	F
011	1	FTT	T
100	1	TFF	T
101	0	TFT	F
110	1	TTF	T
111	1	TTT	T

Algebraic Forms of Switching Functions

- ***Literal***: A variable, complemented or uncomplemented.
- ***Product term***: A literal or literals ANDed together.
- ***Sum term***: A literal or literals ORed together.

- ***SOP (Sum of Products)***:
- ORing product terms
- $f(A, B, C) = ABC + A'C + B'C$

- ***POS (Product of Sums)***
- ANDing sum terms
- $f(A, B, C) = (A' + B' + C')(A + C')(B + C')$

Algebraic Forms of Switching Functions

- A ***minterm*** is a product term in which all the variables appear exactly once either complemented or uncomplemented.
- ***Canonical Sum of Products*** (***canonical SOP***):
  - Represented as a sum of minterms only.
  - ***Example***: $f_1(A,B,C) = A'BC' + ABC' + A'BC + ABC$
- Minterms of three variables:

Minterm	Minterm Code	Minterm Number
$A'B'C'$	000	m_0
$A'B'C$	001	m_1
$A'BC'$	010	m_2
$A'BC$	011	m_3
$AB'C'$	100	m_4
$AB'C$	101	m_5
ABC'	110	m_6
ABC	111	m_7

Algebraic Forms of Switching Functions

- Compact form of canonical SOP form:

  $f_1(A,B,C) = m_2 + m_3 + m_6 + m_7$

- A further simplified form:

  $f_1(A,B,C) = \Sigma\, m\,(2,3,6,7)$ (minterm list form)

- The ***order of variables*** in the functional notation is important.
- Deriving truth table of $f_1(A,B,C)$ from minterm list:

Row No. (i)	**Inputs** ABC	**Outputs** $f_1(A,B,C)=\Sigma m(2,3,6,7)$	**Complement** $f_1'(A,B,C)=\Sigma m(0,1,4,5)$
0	000	0	1 $\leftarrow$ m_0
1	001	0	1 $\leftarrow$ m_1
2	010	1 $\leftarrow$ m_2	0
3	011	1 $\leftarrow$ m_3	0
4	100	0	1 $\leftarrow$ m_4
5	101	0	1 $\leftarrow$ m_5
6	110	1 $\leftarrow$ m_6	0
7	111	1 $\leftarrow$ m_7	0

Algebraic Forms of Switching Functions

- ***Example***: Given $f(A,B,Q,Z) = A'B'Q'Z' + A'B'Q'Z + A'BQZ' + A'BQZ$, express $f(A,B,Q,Z)$ and $f\,'(A,B,Q,Z)$ in minterm list form.

$$\begin{aligned} f(A,B,Q,Z) &= A'B'Q'Z' + A'B'Q'Z + A'BQZ' + A'BQZ \\ &= m_0 + m_1 + m_6 + m_7 \\ &= \Sigma\, m(0, 1, 6, 7) \end{aligned}$$

$$\begin{aligned} f\,'(A,B,Q,Z) &= m_2 + m_3 + m_4 + m_5 + m_8 + m_9 + m_{10} + m_{11} + m_{12} \\ &\quad + m_{13} + m_{14} + m_{15} \\ &= \Sigma\, m(2, 3, 4, 5, 8, 9, 10, 11, 12, 13, 14, 15) \end{aligned}$$

- $\sum_{i=0}^{2^n-1} m_i = 1$ (2.6)
- $AB + (AB)' = 1$ and $AB + A' + B' = 1$, but $AB + A'B' \neq 1$.

Algebraic Forms of Switching Functions

- A ***maxterm*** is a sum term in which all the variables appear exactly once either complemented or uncomplemented.
- ***Canonical Product of Sums*** (***canonical POS***):
  - Represented as a product of maxterms only.
  - ***Example***: $f_2(A,B,C) = (A+B+C)(A+B+C')(A'+B+C)(A'+B+C')$
- Maxterms of three variables:

Maxterm	Maxterm Code	Maxterm Number
$A+B+C$	000	M_0
$A+B+C'$	001	M_1
$A+B'+C$	010	M_2
$A+B'+C'$	011	M_3
$A'+B+C$	100	M_4
$A'+B+C'$	101	M_5
$A'+B'+C$	110	M_6
$A'+B'+C'$	111	M_7

Algebraic Forms of Switching Functions

- $f_2(A,B,C) = M_0 M_1 M_4 M_5$

  $= \Pi M(0,1,4,5)$ (maxterm list form)

- The truth table for $f_2(A,B,C)$:

Rwo No. (i)	**Inputs** ABC	M_0 $A+B+C$	M_1 $A+B+C'$	M_4 $A'+B+C$	M_5 $A'+B+C'$	**Outputs** $f_2(A,B,C)$
0	000	0	1	1	1	0
1	001	1	0	1	1	0
2	010	1	1	1	1	1
3	011	1	1	1	1	1
4	100	1	1	0	1	0
5	101	1	1	1	0	0
6	110	1	1	1	1	1
7	111	1	1	1	1	1

Algebraic Forms of Switching Functions

- Truth tables of $f_1(A,B,C)$ and $f_2(A,B,C)$ are identical.
- Hence, $f_1(A,B,C) = \Sigma\, m\,(2,3,6,7)$

$$= f_2(A,B,C)$$

$$= \Pi M(0,1,4,5)$$

- ***Example: Given*** $f(A,B,C) = (A+B+C')(A+B'+C')(A'+B+C')(A'+B'+C')$, construct the truth table and express in both maxterm and minterm form.
  - $f(A,B,C) = M_1M_3M_5M_7 = \Pi M(1,3,5,7) = \Sigma\, m\,(0,2,4,6)$

Row No. (i)	Inputs ABC	Outputs $f(A,B,C) = \Pi\, M(1,3,5,7) = \Sigma m(0,2,4,6)$
0	000	1 m_0
1	001	0 $\leftarrow M_1$
2	010	1 m_2
3	011	0 $\leftarrow M_3$
4	100	1 m_4
5	101	0 $\leftarrow M_5$
6	110	1 m_6
7	111	0 $\leftarrow M_7$

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Algebraic Forms of Switching Functions

- Relationship between minterm m_i and maxterm M_i:
  - For $f(A,B,C)$, $(m_1)' = (A'B'C)' = A + B + C' = M_1$
  - In general, $(m_i)' = M_i$

    $(Mi)' = ((m_i)')' = m_i$

Algebraic Forms of Switching Functions

- ***Example***: Relationship between the maxterms for a function and its complement.
  - For $f(A,B,C) = (A+B+C')(A+B'+C')(A'+B+C')(A'+B'+C')$
  - The truth table is:

Row No. (i)	**Inputs** ABC	**Outputs** $f(A,B,C)$	**Outputs** $f'(A,B,C) = \Pi\, M(0,2,4,6)$
0	000	1	0 $\leftarrow$ M_0
1	001	0	1
2	010	1	0 $\leftarrow$ M_2
3	011	0	1
4	100	1	0 $\leftarrow$ M_4
5	101	0	1
6	110	1	0 $\leftarrow$ M_6
7	111	0	1

Algebraic Forms of Switching Functions

- From the truth table

  $f'(A,B,C) = \Pi M(0,2,4,6)$ and $f(A,B,C) = \Pi M(1,3,5,7)$
- Since $f(A,B,C) \cdot f'(A,B,C) = 0$,

  $(M_0 M_2 M_4 M_6)(M_1 M_3 M_5 M_7) = 0$ or $\prod_{i=0}^{2^3-1} M_i = 0$
- In general, $\prod_{i=0}^{2^n-1} M_i = 0$

- Another observation from the truth table:

  $f(A,B,C) = \Sigma\, m\,(0,2,4,6) = \Pi M(1,3,5,7)$

  $f'(A,B,C) = \Sigma\, m\,(1,3,5,7) = \Pi M(0,2,4,6)$

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Derivation of Canonical Forms

- Derive canonical POS or SOP using switching algebra.
- ***Theorem 10. Shannon's expansion theorem***

  (a). $f(x_1, x_2, \ldots, x_n) = x_1 f(1, x_2, \ldots, x_n) + (x_1)' f(0, x_2, \ldots, x_n)$

  (b). $f(x_1, x_2, \ldots, x_n) = [x_1 + f(0, x_2, \ldots, x_n)]\,[(x_1)' + f(1, x_2, \ldots, x_n)]$

- ***Example***: $f(A,B,C) = AB + AC' + A'C$
  - $f(A,B,C) = AB + AC' + A'C = A\,f(1,B,C) + A'\,f(0,B,C)$
    $= A(1 \cdot B + 1 \cdot C' + 1' \cdot C) + A'(0 \cdot B + 0 \cdot C' + 0' \cdot C) = A(B + C') + A'C$
  - $f(A,B,C) = A(B + C') + A'C = B[A(1+C') + A'C] + B'[A(0 + C') + A'C]$
    $= B[A + A'C] + B'[AC' + A'C] = AB + A'BC + AB'C' + A'B'C$
  - $f(A,B,C) = AB + A'BC + AB'C' + A'B'C$
    $= C[AB + A'B \cdot 1 + AB' \cdot 1' + A'B' \cdot 1] + C'[AB + A'B \cdot 0 + AB' \cdot 0' + A'B' \cdot 0]$
    $= ABC + A'BC + A'B'C + ABC' + AB'C'$

Derivation of Canonical Forms

- ***Alternative:*** Use Theorem 6 to add missing literals.
- ***Example***: $f(A,B,C) = AB + AC' + A'C$ to canonical SOP form.
  - $AB = ABC' + ABC = m_6 + m_7$
  - $AC' = AB'C' + ABC' = m_4 + m_6$
  - $A'C = A'B'C + A'BC = m_1 + m_3$
  - Therefore,

    $f(A,B,C) = (m_6 + m_7) + (m_4 + m_6) + (m_1 + m_3) = \Sigma m(1, 3, 4, 6, 7)$

- ***Example***: $f(A,B,C) = A(A + C')$ to canonical POS form.
  - $A = (A+B')(A+B) = (A+B'+C')(A+B'+C)(A+B+C')(A+B+C)$

    $= M_3M_2M_1M_0$
  - $(A+C')= (A+B'+C')(A+B+C') = M_3M_1$
  - Therefore,

    $f(A,B,C) = (M_3M_2M_1M_0)(M_3M_1) = \Pi M(0, 1, 2, 3)$

Incompletely Specified Functions

- A switching function may be incompletely specified.
- Some minterms are omitted, which are called *don't-care minterms*.
- Don't cares arise in two ways:
  - Certain input combinations never occur.
  - Output is required to be 1 or 0 only for certain combinations.
- Don't care minterms: d_i Don't care maxterms: D_i

- ***Example***: $f(A,B,C)$ *has minterms* m_0, m_3, and m_7 and don't-cares d_4 and d_5.
  - Minterm list is: $f(A,B,C) = \Sigma m(0,3,7) + d(4,5)$
  - Maxterm list is: $f(A,B,C) = \Pi M(1,2,6) \cdot D(4,5)$
  - $f'(A,B,C) = \Sigma m(1,2,6) + d(4,5) = \Pi M(0,3,7) \cdot D(4,5)$
  - $f(A,B,C) = A'B'C' + A'BC + ABC + d(AB'C' + AB'C)$

    $= B'C' + BC$ (use d_4 and omit d_5)

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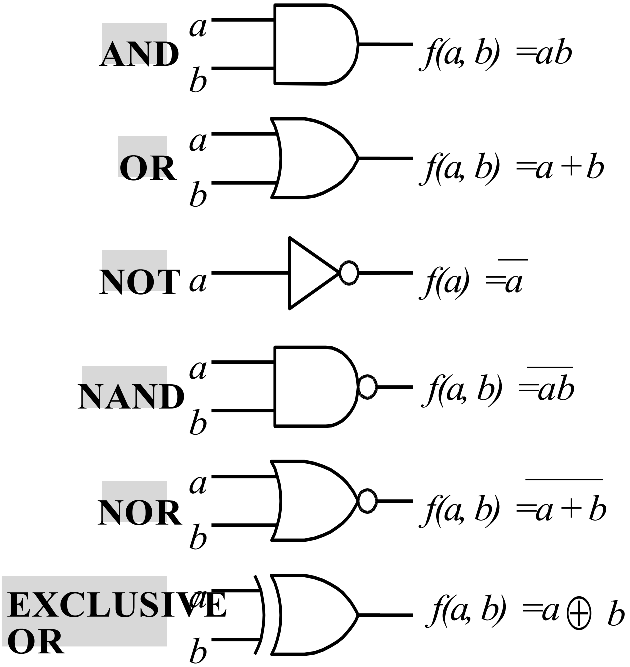
Electronic Logic Gates

- ***Electrical Signals and Logic Values***

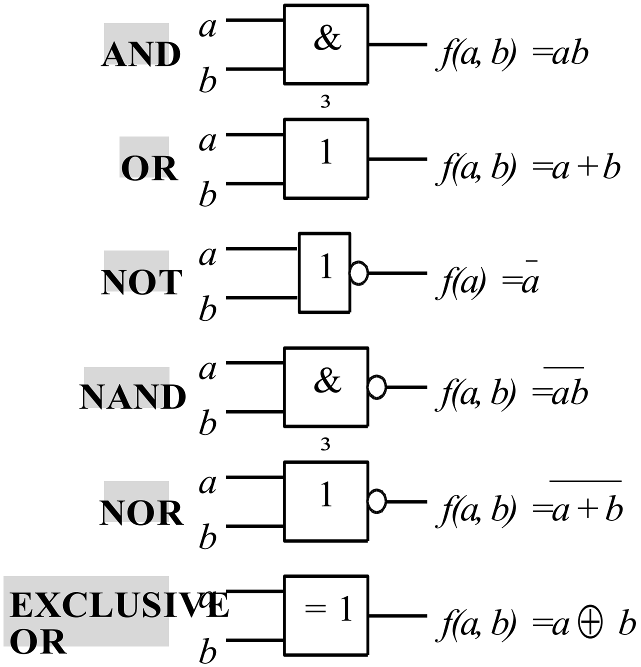
Electric Signal	Logic Value	
	Positive Logic	Negative Logic
High Voltage (H)	1	0
Low Voltage (L)	0	1

- A signal that is set to logic 1 is said to be *asserted*, *active*, or *true*.
- An *active-high* signal is asserted when it is high (positive logic).
- An *active-low* signal is asserted when it is low (negative logic).

Electronic Logic Gates

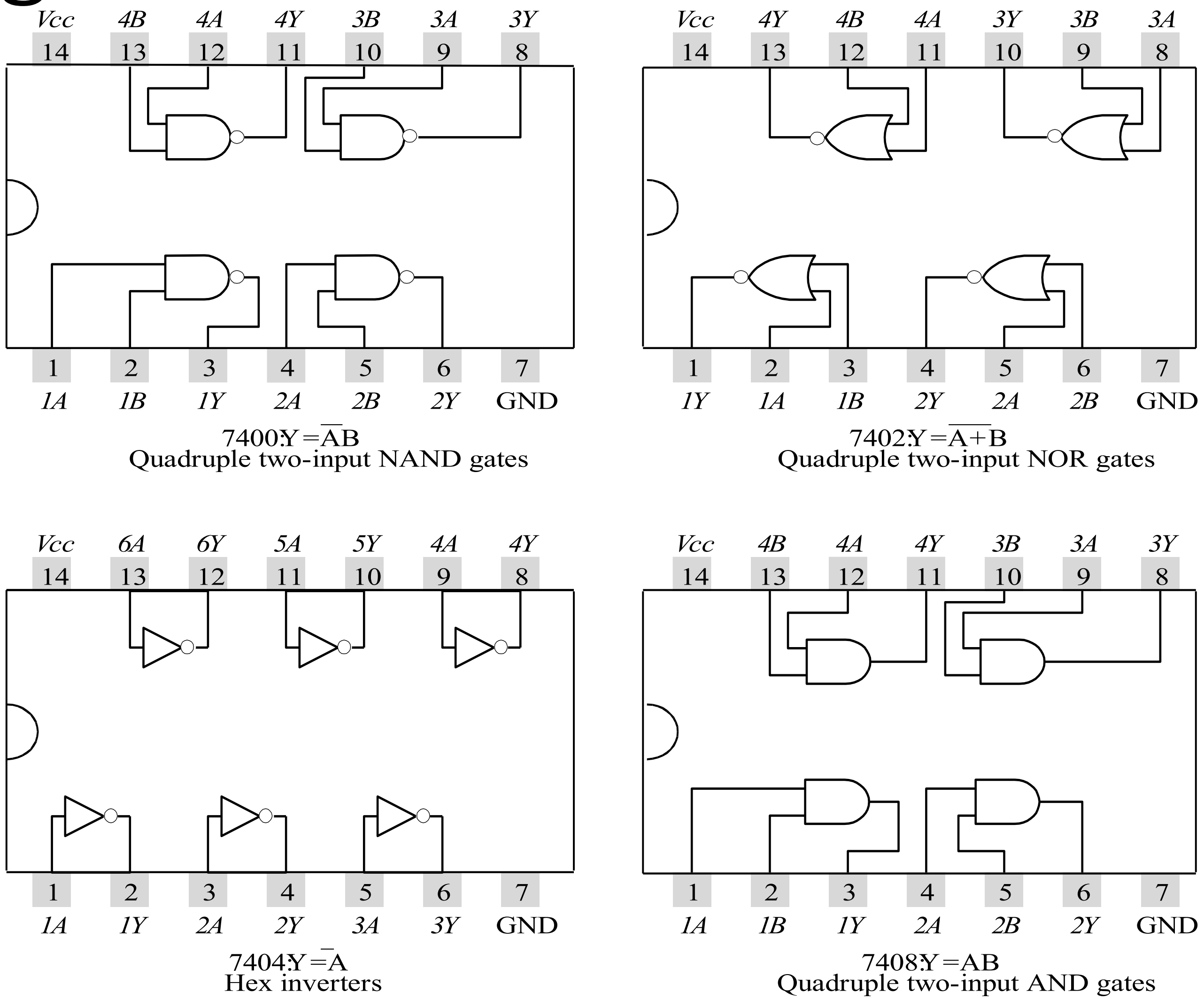


Symbol set 1



Symbol set 2
(ANSI/IEEE Standard 91-1984)

Electronic Logic Gates



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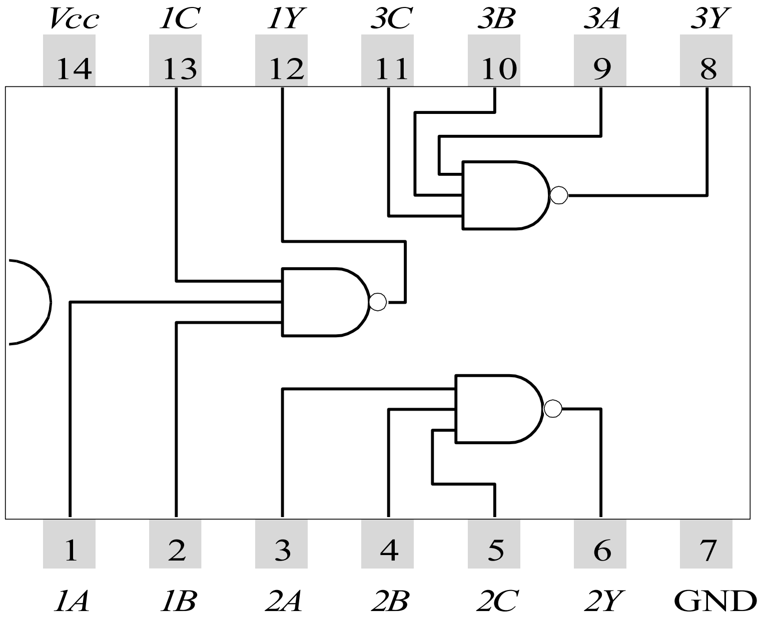
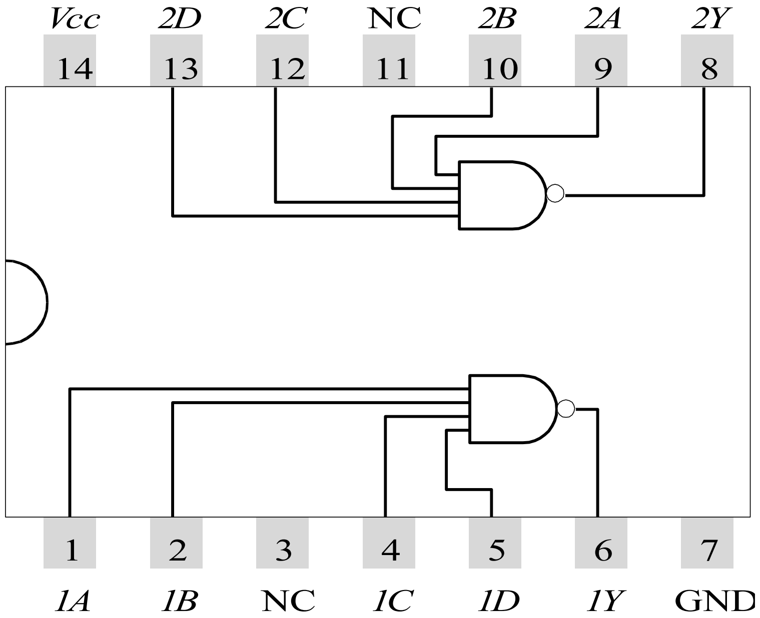
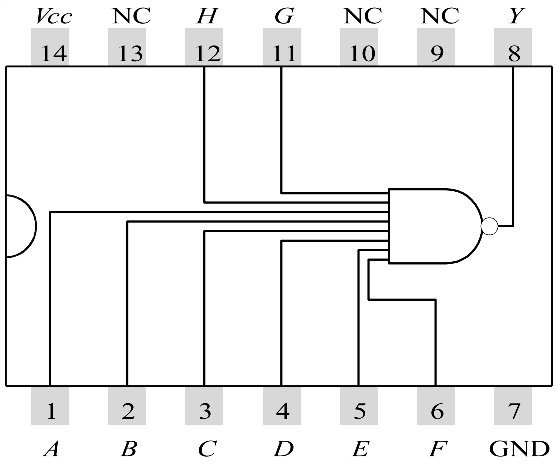


7410:$Y = \overline{ABC}$
Triple three-input NAND gates

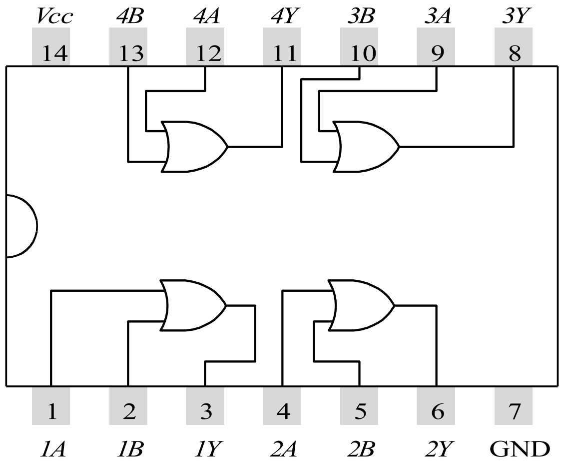


7420:$Y = \overline{ABCD}$
Dual four-input NAND gates

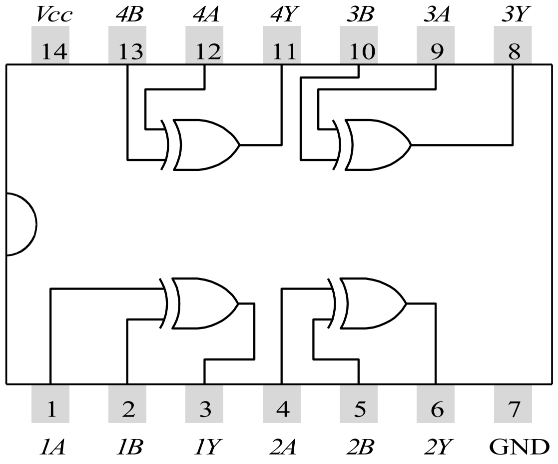
Electronic Logic Gates



7430:$Y=\overline{ABCDEFGH}$
8-input NAND gate



7432:Y=A+B
Quadruple two-input OR gates



7486:Y=AÅB
Quadruple two-input exclusive-OR gates

Basic Functional Components

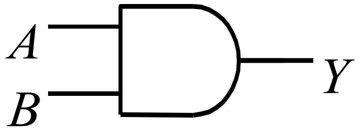
- ***AND***

a	b	$f_{AND}(a, b) = ab$
0	0	0
0	1	0
1	0	0
1	1	1

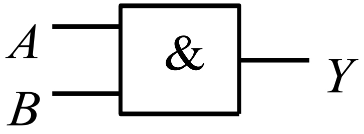
(a)

A	B	Y
L	L	L
L	H	L
H	L	L
H	H	H

(b)



(c)



(d)

(a) AND logic function.
(b) Electronic AND gate.
(c) Standard symbol.
(d) IEEE block symbol.

Basic Functional Components

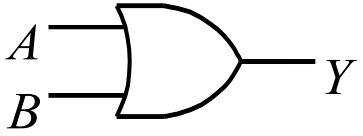
- ***OR***

a	b	$f_{OR}(a, b) = a + b$
0	0	0
0	1	1
1	0	1
1	1	1

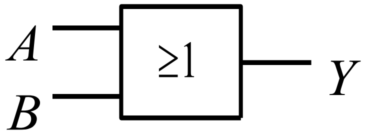
(a)

A	B	Y
L	L	L
L	H	H
H	L	H
H	H	H

(b)



(c)



(d)

(a) OR logic function.
(b) Electronic OR gate.
(c) Standard symbol.
(d) IEEE block symbol.

Basic Functional Components

- Meaning of the designation ≥ 1 in IEEE symbol:

ab	sum(a, b)	sum(a, b) ≥ 1	$f_{OR}(a, b) = a + b$
00	0	False	0
01	1	True	1
10	1	True	1
11	2	True	1

Basic Functional Components (4)

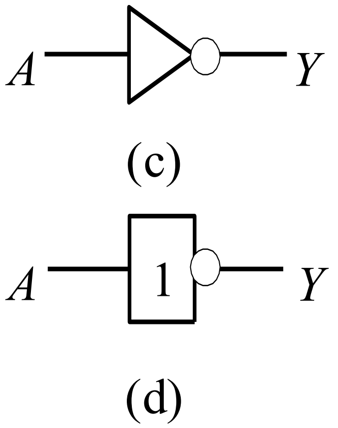
- ***NOT***

a	$f_{NOT}(a) = \bar{a}$
0	1
1	0

(a)

A	Y
L	H
H	L

(b)



(a) NOT logic function.
(b) Electronic NOT gate.
(c) Standard symbol.
(d) IEEE block symbol.

Basic Functional Components

- ***Positive Versus Negative Logic***

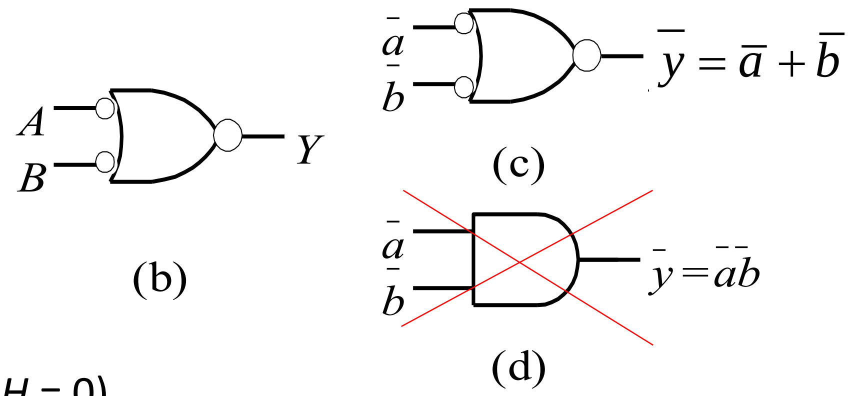
	Positive Logic	Negative Logic
1 is represented by	High Voltage	Low Voltage
0 is represented by	Low Voltage	High Voltage

Basic Functional Components

- ***AND Gate Usage in Negative Logic***

A	B	Y
1	1	1
1	0	1
0	1	1
0	0	0

(a)



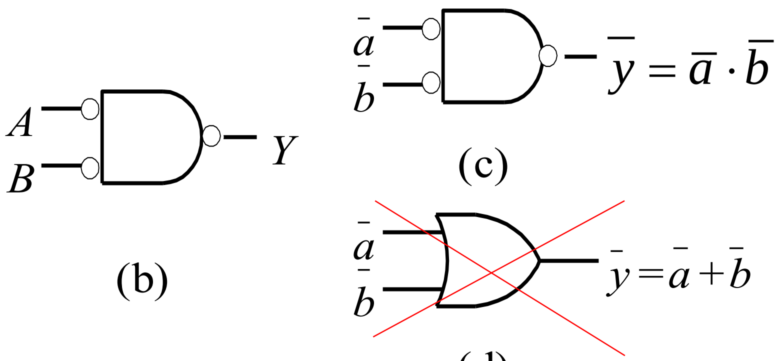
- (a) AND gate truth table (L = 1, H = 0)
- (b) Alternate AND gate symbol (in negative logic)
- (c) Preferred usage $y = a \cdot b = \overline{\overline{a \cdot b}} = \overline{\overline{a} + \overline{b}} = \overline{f}_{OR}(\overline{a}, \overline{b})$
- (d) Improper usage $\overline{y} = \overline{(\overline{\overline{a}}) + (\overline{\overline{b}})} = \overline{a + b} = \overline{f}_{OR}(a, b)$

Basic Functional Components

- ***OR Gate Usage in Negative Logic***

A	B	Y
1	1	1
1	0	0
0	1	0
0	0	0

(a)



  - (a) OR gate truth table(L = 1, H = 0)
  - (b) Alternate OR gate symbol (in negative logic)
  - (c) Preferred usage $y = a + b = \overline{\overline{a+b}} = \overline{\bar a \cdot \bar b} = \bar f_{AND}(\bar a, \bar b)$
  - (d) Improper usage $\bar y = \overline{\overline{(\bar a)} \cdot \overline{(\bar b)}} = \overline{a \cdot b} = \bar f_{AND}(a, b)$

Basic Functional Components

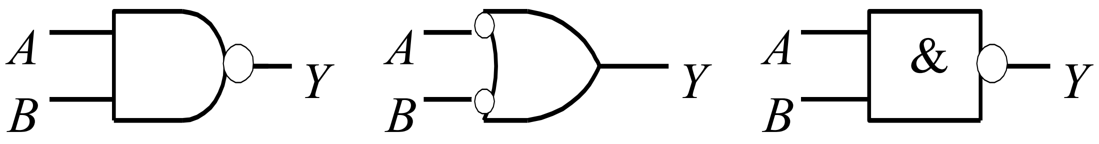
- ***NAND***

a	b	$f_{NAND}(a, b) = \overline{ab}$
0	0	1
0	1	1
1	0	1
1	1	0

(a)

A	B	Y
L	L	H
L	H	H
H	L	H
H	H	L

(b)

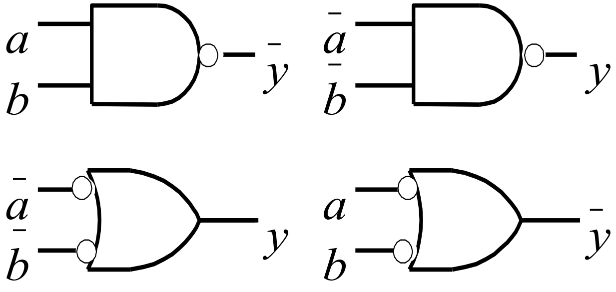


(c) (d) (e)

- (a) NAND logic function
- (b) Electronic NAND gate
- (c) Standard symbol
- (e) IEEE block symbol

Basic Functional Components

- Matching signal polarity to NAND gate inputs/outputs
  - (a) Preferred usage (b) Improper usage



(a) (b)

- Additional properties of NAND gate:

$$f_{NAND}(a,a) = \overline{a \cdot a} = \overline{a} = f_{NOT}(a)$$

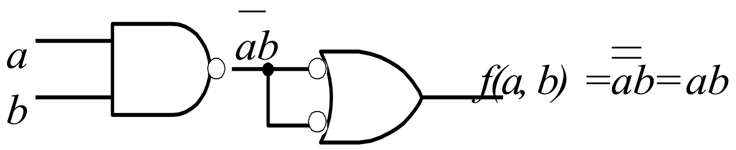
$$\overline{f}_{NAND}(a,b) = \overline{\overline{a \cdot b}} = a \cdot b = f_{AND}(a,b)$$

$$f_{NAND}(\overline{a},\overline{b}) = \overline{\overline{a} \cdot \overline{b}} = a + b = f_{OR}(a,b)$$

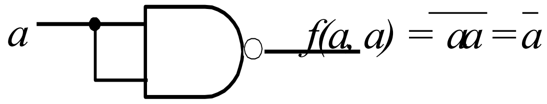
- Hence, NAND gate may be used to implement all three elementary operators.

Basic Functional Components

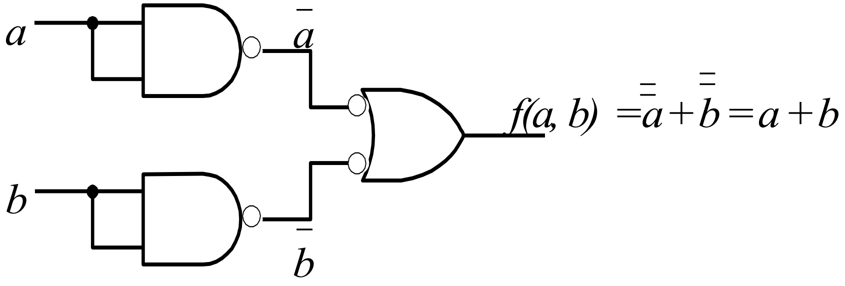
- AND, OR, and NOT gates constructed exclusively from NAND gates



AND gate



NOT gate



OR gate

Basic Functional Components

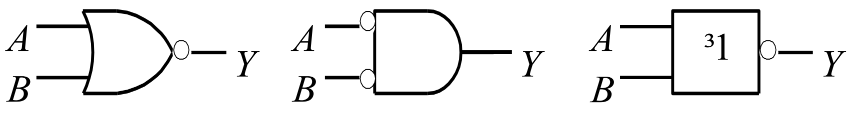
- ***NOR***

a	b	$f_{NOR}(a, b) = \overline{a + b}$
0	0	1
0	1	0
1	0	0
1	1	0

(a)

A	B	Y
L	L	H
L	H	L
H	L	L
H	H	L

(b)

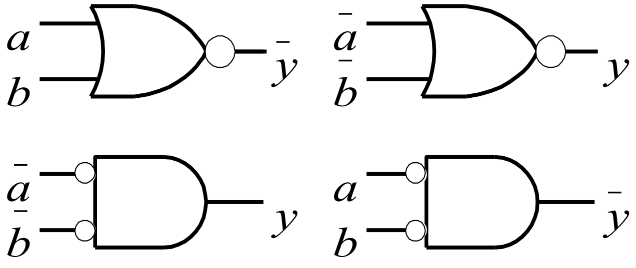


(c) (d) (e)

- (a) NAND logic function
- (b) Electronic NAND gate
- (c) Standard symbol
- (d) IEEE block symbol

Basic Functional Components

- Matching signal polarity to NOR gate inputs/outputs
  - (a) Preferred usage (b) Improper usage



(a) (b)

- Additional properties of NOR gate:

$$f_{NOR}(a,a) = \overline{a+a} = \overline{a} = f_{NOT}(a)$$

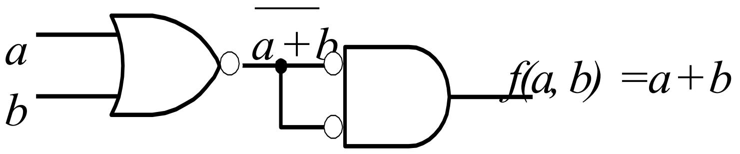
$$\overline{f}_{NOR}(a,b) = \overline{\overline{a+b}} = a+b = f_{OR}(a,b)$$

$$f_{NOR}(\overline{a},\overline{b}) = \overline{\overline{a}+\overline{b}} = a \cdot b = f_{AND}(a,b)$$

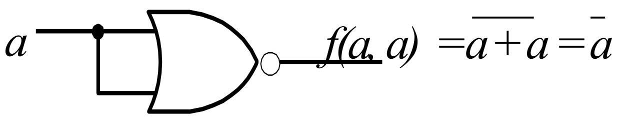
- Hence, NOR gate may be used to implement all three elementary operators.

Basic Functional Components

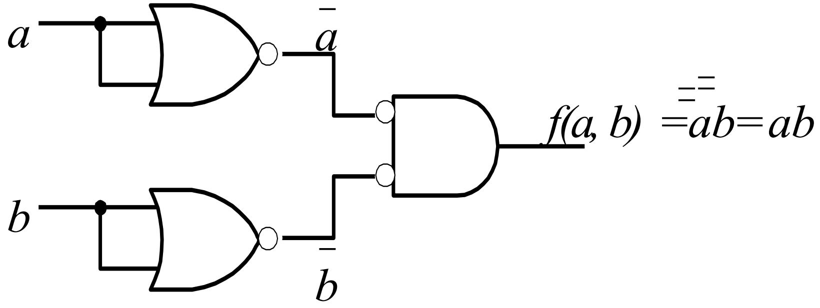
- AND, OR, and NOT gates constructed exclusively from NOR gates.



OR gate



NOT gate



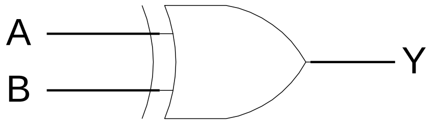
AND gate

Basic Functional Components

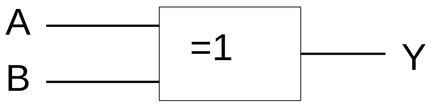
- ***Exclusive-OR (XOR)***
  - $f_{\text{XOR}}(a, b) = a \oplus b = \bar{a}b + a\bar{b}$

$a\ b$	$f_{\text{XOR}}(a, b) = a \oplus b$	$A\ B$	Y
0 0	0	L L	L
0 1	1	L H	H
1 0	1	H L	H
1 1	0	H H	L

(a) XOR logic function (b) Electronic XOR gate



(c) Standard symbol



(d) IEEE block symbol

Basic Functional Components

- POS of XOR

$$
\begin{aligned}
a \oplus b &= \bar{a}b + a\bar{b} \\
&= \bar{a}a + \bar{a}b + a\bar{b} + b\bar{b} && \text{[P2(a), P6(b)]} \\
&= \bar{a}(a+b) + \bar{b}(a+b) && \text{[P5(b)]} \\
&= (\bar{a}+\bar{b})(a+b) && \text{[P5(b)]}
\end{aligned}
$$

- Some other useful relationships
  - $a \oplus a = 0$ (2.25)
  - $a \oplus \bar{a} = 1$ (2.26)
  - $a \oplus 0 = a$ (2.27)
  - $a \oplus 1 = \bar{a}$ (2.28)
  - $\bar{a} \oplus \bar{b} = a \oplus b$ (2.29)
  - $a \oplus b = b \oplus a$ (2.30)
  - $a \oplus (b \oplus c) = (a \oplus b) \oplus c$ (2.31)

Basic Functional Components (17)

- Output of XOR gate is asserted when the mathematical sum of inputs is *one*:

ab	$sum(a, b)$	$sum(a, b) = 1?$	$f(a, b) = a \oplus b$
00	0	False	0
01	1	True	1
10	1	True	1
11	2	False	0

- The output of XOR is the *modulo*-2 sum of its inputs.

Basic Functional Components (18)

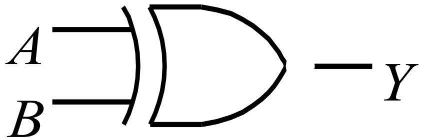
- ***Exclusive-NOR (XNOR)***
  - $f_{XNOR}(a,b) = \overline{a \oplus b} = a \odot b$

a	b	$f_{XNOR}(a,b) = a \odot b$
0	0	1
0	1	0
1	0	0
1	1	1

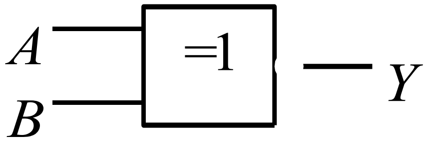
(a)

A	B	Y
L	L	H
L	H	L
H	L	L
H	H	H

(b)



(c)



(d)

- (a) XNOR logic function
- (b) Electronic XNOR gate
- (c) Standard symbol
- (d) IEEE block symbol

Analysis of Combinational Circuits (1)

- Digital Circuit ***Design***:
  - Word description of a function

    $\Rightarrow$ a set of switching equations

    $\Rightarrow$ hardware realization (gates, programmable logic devices, etc.)

- Digital Circuit ***Analysis***:
  - Hardware realization

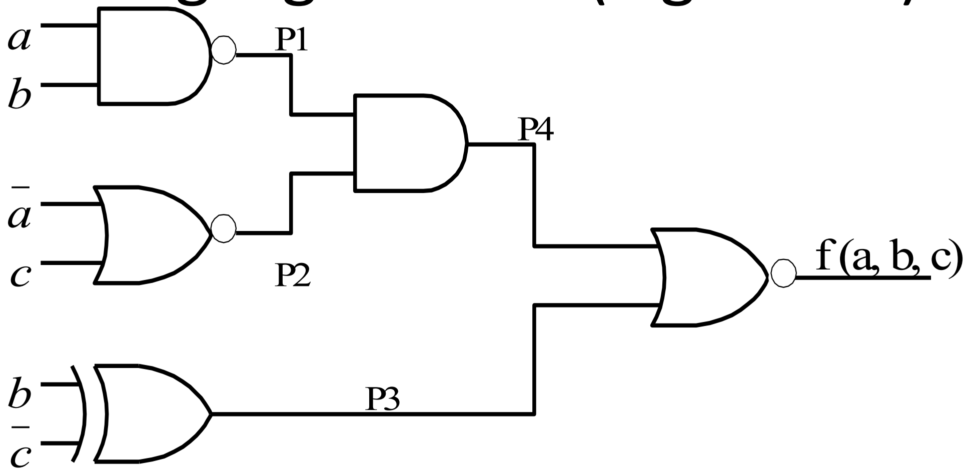
    $\Rightarrow$ switching expressions, truth tables, timing diagrams, etc.

- Analysis is used
  - To determine the behavior of the circuit
  - To verify the correctness of the circuit
  - To assist in converting the circuit to a different form.

Analysis of Combinational Circuits (2)

- ***Algebraic Method***: Use switching algebra to derive a desired form.

- ***Example 2.33***: Find a simplified switching expressions and logic network for the following logic circuit (Fig. 2.21a).



(a)

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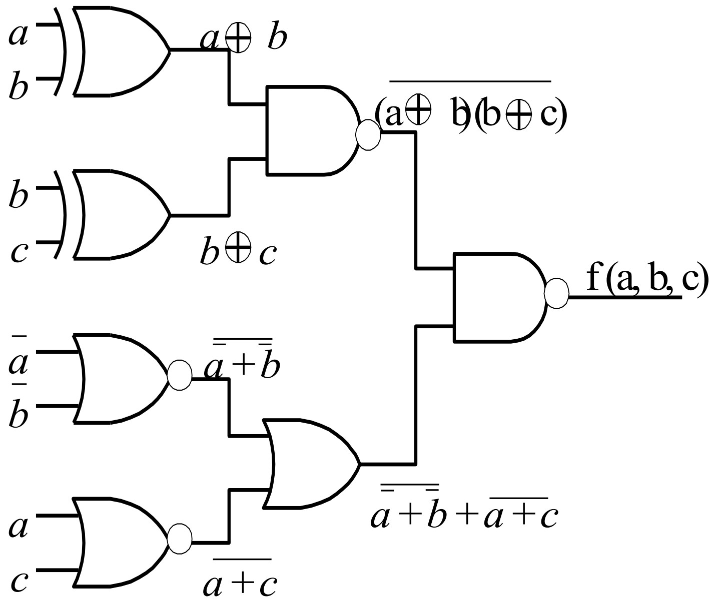
Analysis of Combinational Circuits (4)

- ***Example 2.34***: Find a simplified switching expressions and logic network for the following logic circuit (Fig. 2.22).

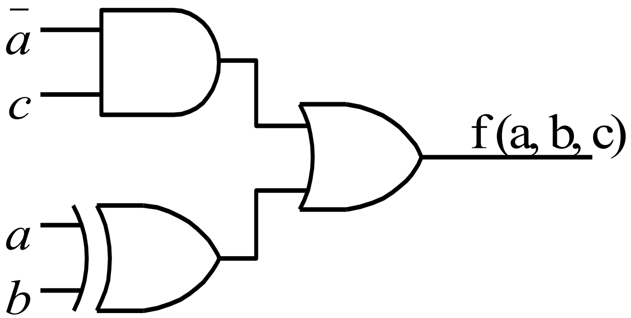


Given circuit

Analysis of Combinational Circuits (5)

- Derive the output expression:

$$
\begin{aligned}
f(a,b,c) &= \overline{\overline{(a\oplus b)(b\oplus c)}\cdot(\overline{\bar{a}+\bar{\bar{b}}}+\overline{a+c})} && [T8(b)]\\
&= \overline{\overline{(a\oplus b)(b\oplus c)}}+\overline{\overline{\bar{a}+\bar{\bar{b}}}+\overline{a+c}} && [T8(a)]\\
&= (a\oplus b)(b\oplus c)+(\bar{a}+\bar{b})(a+c) && [Eq.\ 2.24]\\
&= (a\bar{b}+\bar{a}b)(b\bar{c}+\bar{b}c)+(\bar{a}+\bar{b})(a+c) && [P5(b)]\\
&= a\bar{b}b\bar{c}+a\overline{bb}c+\bar{a}bb\bar{c}+\bar{a}b\bar{b}c+\bar{a}a+\bar{a}c+a\bar{b}+\bar{b}c && [P6(b), T4(a)]\\
&= a\bar{b}c+\bar{a}b\bar{c}+\bar{a}c+a\bar{b}+\bar{b}c && [T4(a)]\\
&= \bar{a}b\bar{c}+\bar{a}c+a\bar{b}+\bar{b}c && [T9(a)]\\
&= \bar{a}b\bar{c}+\bar{a}c+a\bar{b} && [T7(a)]\\
&= \bar{a}b+\bar{a}c+a\bar{b} && [Eq.\ 2.24]\\
&= \bar{a}c+a\oplus b
\end{aligned}
$$



Simplified circuit

Analysis of Combinational Circuits (6)

- ***Truth Table Method***: Derive the truth table one gate at a time.
- The truth table for Example 2.34:

abc	$\overline{a}c$	$a \oplus b$	$f(a,b,c)$
000	0	0	0
001	1	0	1
010	0	1	1
011	1	1	1
100	0	1	1
101	0	1	1
110	0	0	0
111	0	0	0