Thus, if a 64-bit hash code is used, the level of effort required is only on the order of 2^{64}.

3. MD5, SECURE HASH ALGORITHM

- **Explain about MD5 in detail. (April/May'11, April/May'10 & May/June'12)**
- **Explain Secure Hashing Algorithm (SHA) (April/May'15, Nov/Dec'13, May/June'13 & April/May'10)**
- **Explain the process of deriving eighty 64-bit words from the 1024-bits for processing of a single block and also discuss single round function in SHA-512 algorithm. Show the results of W_{16}, W_{17}, W_{18} and W_{19}. (Nov/Dec'14)**

a. MESSAGE DIGEST 5: MD5

- ✔ Developed by Ron Rivest at MIT
- ✔ Input: a message of arbitrary length
- ✔ Output: 128-bit message digest
- ✔ 32-bit word units, 512-bit blocks

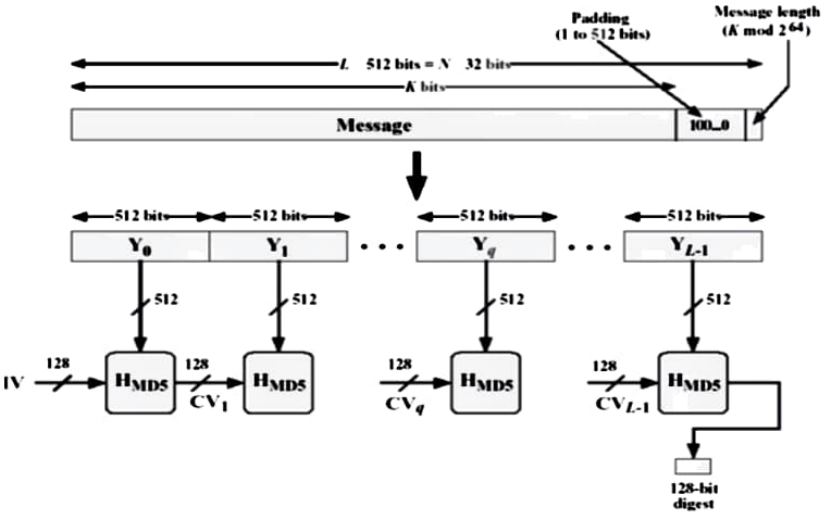


Figure: MD5 Logic

MD5 Logic:

Step 1: Append padding bits

- ✔ The message is Padded so that its bit length ≡ 448 mod 512 (i.e., the length of padded message is 64 bits less than an integer multiple of 512 bits)
- ✔ Padding is always added, even if the message is already of the desired length (1 to 512 bits)
- ✔ Padding bits: 1000….0 (a single 1-bit followed by the necessary number of 0-bits)

Step 2: Append length

- ✔ A 64-bit length: contains the length of the original message modulo 264
- ✔ The expanded message is $Y_0, Y_1, \ldots, Y_{L-1}$; the total length is L × 512 bits
- ✔ The expanded message can be thought of as a multiple of 16 32-bit words
- ✔ Let M[0 … N-1] denote the word of the resulting message, where N = L × 16

Step 3: Initialize MD buffer

- ✔ 128-bit buffer (four 32-bit registers A,B,C,D) is used to hold intermediate and final results of the hash function

- ✔ A,B,C,D are initialized to the following values

  A = 67452301
  B = EFCDAB89
  C = 98BADCFE
  D = 10325476

- ✔ Stored in *little-endian* format (least significant byte of a word in the low-address byte position)
  - o E.g. word A : 01 23 45 67 (low address … high address)
  - o word B : 89 AB CD EF
  - o word C : FE DC BA 98
  - o word D : 76 54 32 10

Step 4: Process message in 512-bit (16-word) blocks

- ✔ Heart of the algorithm called a *compression function* Consists of 4 rounds
- ✔ The 4 rounds have a similar structure, but each uses a different *primitive logical functions*, referred to as F, G, H, and I
- ✔ Each round takes as input the current 512-bit block (Yq), 128-bit buffer value ABCD and updates the contents of the buffer
- ✔ Each round also uses the table T[1 … 64], constructed from the sine function;
  - T[i] = 232 × abs(sin(i))
- ✔ The output of 4th round is added to the CVq to produce CVq+1

Step 5: Output

- ✔ After all L 512-bit blocks have been processed, the output from the Lth stage is the 128-bit message digest

  $\mathbf{CV_0 = IV}$
  CVq+1 = SUM32(CVq, RFI[Yq, RFH[Yq, RFG[Yq, RFF[Yq, CVq]]])
  $\mathbf{MD = CV_L}$

Where IV = initial value of the ABCD buffer, defined in step 3
Yq = the qth 512-bit block of the message
L = the number of blocks in the message (including padding and length fields) CVq = chaining variable processed with the qth block of the message
RFx = round function using primitive logical function x
MD = final message digest value
SUM32 = addition modulo 232 performed separately on each word

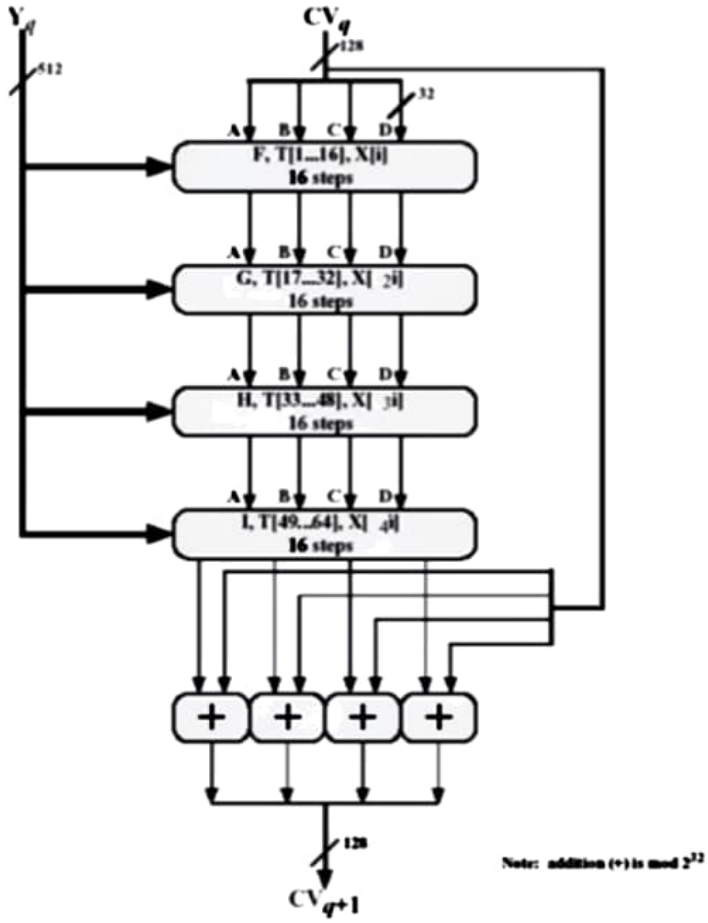


Figure: MD5 processing of a single 512-bit block (MD5 compression function)

MD5 Compression Function:

- ✔ Each round consists of a sequence of 16 steps operating on the buffer ABCD
- ✔ Each step is of the form

$$a \leftarrow b + ((\ a + g(b, c, d) + X[k] + T[i] <<< s\ )$$

where

a,b,c,d = the 4 words of the buffer, in a specified order that varies across steps

g = one of the primitive functions F, G, H, I

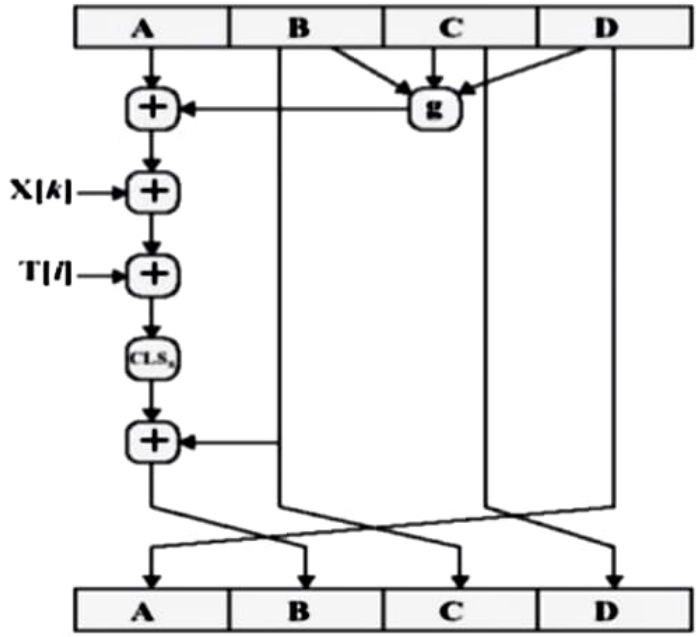
<<s = circular left shift (rotation) of the 32-bit arguments by s bits

X[k] = M[q × 16 + k] = the kth 32-bit word in the qth 512-bit block of the message

T[i] = the ith 32-bit word in table T

+ = addition modulo 232

MD5 Operation



- ✔ One of the 4 primitive logical functions is used in each 4 rounds of the algorithm
- ✔ Each primitive function takes three 32-bit words as input and produces a 32-bit word output
- ✔ Each function performs a set of bitwise logical operations

Round	Primitive function g	g(b, c, d)
1	F(b, c, d)	(b ∧ c) ∨ (b' ∧ d)
2	G(b, c, d)	(b ∧ d) ∨ (c ∧ d')
3	H(b, c, d)	b ⊕ c ⊕ d
4	I(b c, d)	c ⊕ (b ∨ d')

TRUTH TABLE						
b	**C**	**d**	**F**	**G**	**H**	**I**
0	0	0	0	0	0	1
0	0	1	1	0	1	0
0	1	0	0	1	1	0
0	1	1	1	0	0	1
1	0	0	0	0	1	1
1	0	1	0	1	0	1

1	1	0	1	1	0	0

- ✔ The array of 32-bit words X[0..15] holds the value of current 512-bit input block being processed
- ✔ Within a round, each of the 16 words of X[i] is used exactly once, during one step
  - o The order in which these words is used varies from round to round
  - o In the first round, the words are used in their original order
  - o For rounds 2 through 4, the following permutations are used
    - » $\rho 2(i) = (1 + 5i) \bmod 16$
    - » $\rho 3(i) = (5 + 3i) \bmod 16$
    - » $\rho 4(I) = 7i \bmod 16$