Intel® QuickAssist Technology (Intel® QAT): Using Adler-32 Checksum and CRC32 Hash to Ensure Data Compression Integrity

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1 Overview

Data integrity practices refer to the methods used to ensure a digital copy (data set) is identical to the original. Data *compression* integrity deals with the ability to ensure that a compressed data set can be decompressed at a later time and that decompressed data set will be identical to the original data (before compression).

This paper focuses on the use of both Adler-32 (a checksum algorithm) and CRC32 (a hash algorithm) as a method to determine if the decompressed data set matches the original data set. We show that the Adler-32 checksum and the CRC32 hash have no correlation in the methods used to calculate their respective checksum and hash. Thus, an empirical examination of Adler-32 collision and CRC32 collision can lead to a determination of data integrity with a high degree of confidence.

1.1 Audience

Networking and storage infrastructure architects who want an in-depth understanding of the Intel® QuickAssist Technology (Intel® QAT) Compress and Verify feature to support the planning of reliability, accessibility, and serviceability features in the server environment.

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2 Introduction

Intel has introduced the Compress and Verify feature of Intel® QAT, which ensures data compression integrity. And this paper discusses the implementation of the Verify component of this feature, which uses Adler-32 checksum and CRC32 hash as a detection mechanism to ensure data compression integrity.

To ensure that compressed data has retained its integrity, an application can immediately decompress the data and test for correctness. If correctness has been established, the compressed data can be safely stored and correctly decompressed later. Alternatively, if the compressed data cannot be correctly decompressed, other remedial actions can be taken immediately (preferable to discovering incorrect data at a later decompression time when the original data may not be available).

Note: Correctness is established by comparing the Adler-32 checksum and the CRC32 hash values of the original (uncompressed data) with the decompressed data.

Adler-32 checksum and CRC32 hash are chosen for this study as they are commonly used in the zlib* block and gzip* block footers, respectively. Implementations of the checksum and hash exist for many compressors and decompressors that support the standard deflate block. At the heart of the question of effectiveness of using checksum and hash values is collisions (also known as aliasing). All algorithms that execute a transformation of multiple data sets to checksum or hash will eventually suffer collisions if the originating data set is larger than the size of the checksum or hash.

For example, if the originating data set is a four kilobyte buffer and the algorithm is a standard CRC32 hash, at some point two different input buffers will generate the same CRC32 hash.

We will show that there is no correlation between the construction of Adler-32 checksums and CRC32 hash. Showing that there is no correlation allows the likelihood of collisions to be analyzed independently. Results of an empirical experiment to simulate loss of data integrity (combined with the number of Adler-32 and CRC32 collisions between the original data set and the corrupted data set) can be found in Appendix A and Appendix B.

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3 Scope of Discussion

We discuss the effectiveness of using the Adler-32 checksum and CRC32 hash together as a detection mechanism for ensuring data compression integrity. And we address the likelihood of simultaneous Adler-32 and CRC32 collisions in corrupted data sets. The discussion will be centered on common buffer lengths for compression workloads and references will be made to data set composition (where applicable).

This paper will not address the probability of a loss of integrity, nor the probability that a corrupted data set would correctly decompress, creating a data set with the same length as the original data set. It does include examples of why corruption introduced by the compressor tends to cause a larger impact on the decompressed data.

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4 How we Define Data Compression Integrity

Data compression integrity as part of the Intel® QAT Compress and Verify feature is defined as the logical AND of four terms:

$$val = (rc_d == OK)\ \&\&\ (len_d == len_s)\ \&\&\ (Adler32_d == Adler32_s)\ \&\&\ (crc32_d == crc32_s)$$

Table 1. Description of Parameters for Data Compression Integrity

Parameters	Description
rc_d	Indication of whether or not the decompression operation indicated success
len_s	Clear text length of the original clear text source data
len_d	Clear text length of decompressed data
$Adler32_s$	Adler-32 checksum calculated across the source data
$Adler32_d$	Adler-32 checksum calculated across the decompressed data
$crc32_s$	Standard 32-bit CRC hash calculated across the source data.
$crc32_d$	Standard 32-bit CRC hash calculated across the decompressed data

It’s expected that most compression errors would be detected by an error during the decompression operation ($rc_d == OK$) or a decompression operation that results in an incorrect length ($len_d == len_s$). An error in compression that still results in a data set that decompresses without error to a different data set of the same length is highly unlikely. By its nature, the act of compressing a data set reduces multiple identical patterns of data to one data pattern, and then references to the original for the other patterns.

4.1 Example

The following

```
0         1         2         3         4         5         6
0123456789012345678901234567890123456789012345678901234567890

I don't know half of you half as well as I should like; and I
                                      1        1
6       7         8         9         0        1
23456789012345678901234567890123456789012345678901234567890123456
like less than half of you half as well as you deserve.
```

can be represented as:

```
I don't know half of you[12,6]as well[8,4]I should like;
and[19,3][12,4] less than[64,28][20,5]deserve.
```

During compression, if any of the original characters in "half" become corrupted, the action of copying those characters to the data set to satisfy [distance, length] notations will propagate the corruption multiple times. In the above example, this would result in three errors.

Similarly, if a single length value is misrepresented, then a copy operation will be of the wrong size and the rest of the decompressed data will be the wrong size. If all length values of a specific length are encoded incorrectly, then the problem compounds. In the example above, if a logical error existed to cause all instances of the length [n,4] to be encoded incorrectly, then the overall length of the decompressed data would be incorrect due to two usages of the length 4. The same argument holds for distances.

4.2 Correct Length but Invalid Data

It is hypothetically possible for a compressor to misbehave and create a file with the same number of bytes that it successfully decompresses. If the compressor produces the bits for a different, valid literal (for example, the representation of the letter 'A'), and if the encoding for both literals (the literal that was encoded vs. the literal the should have been encoded) are the same length, then a decompressor would be able to successfully decompress the compressed data set, and it would be the same length. The same would apply to the output of bits for a different, valid distance symbol of the same length.

4.2.1 Example: Static Compression Mismatch

During a compress operation to create an RFC compliant deflate block with static Huffman trees, it is relatively easy to construct a deflate block that, when decompressed, would produce valid data of the same length. From RFC 1951, the static encoding for two literals are shown below:

Table 2. Static Encoding for Two Literals

Literal	ASCII hex	Static encoding
'A'	0x41	0111 0001
'm'	0x6d	0110 1101

Source: https://www.ietf.org/rfc/rfc1951.txt

If the compressor outputs the bits for the letter 'm' instead of the letter 'A', the resulting compressed data could be successfully decompressed and would result in a data set of the same length as the original.

This example extends to dynamic compression and to distance tokens. The example can be generalized as follows:

If a compressor does not output a correct literal or distance token, substituting it for a different, incorrect literal or distance code that is the same length and valid, then the resulting deflate block will be valid, per the standards, and will decompress without error. And the result of the decompression operation will be incorrect.

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5 Adler-32 Checksum

Adler-32, a 32-bit character-by-character checksum, is a computationally straight-forward mechanism for detecting errors after decompression.

5.1 Checksum Method

The formula for Adler-32 can be represented by the following code segment:

```
const uint32_t MOD_ADLER = 65521;
/*
    65521 is the largest prime number less than 2^16
*/

uint32_t adler32(unsigned char *data, size_t len)
/*
    where data is the location of the data in physical memory and
    len is the length of the data in bytes
*/
{
    uint32_t a = 1, b = 0;
    size_t index;

    // Process each byte of the data in order
    for (index = 0; index < len; ++index)
    {
        a = (a + data[index]) % MOD_ADLER;
        b = (b + a) % MOD_ADLER;
    }
    return (b << 16) | a;
}
```

Source: https://en.wikipedia.org/wiki/Adler-32

5.1.1 Example

The Adler-32 checksum of the ASCII string "QuickAssist" would be calculated as follows:

Table 3. Adler-32 Checksum of an ASCII String

Character	ASCII Code	a (init=1)				b(init=0)			
		prev a +	data	new a	new a (hex)	prev b +	a	new b	new b (hex)
Q	81	1	81	82	0052	0	82	82	0052
u	117	82	117	199	00C7	82	199	281	0119
i	105	199	105	304	0130	281	304	585	0249
c	99	304	99	403	0193	585	403	988	03DC
k	107	403	107	510	01FE	988	510	1498	05DA
A	65	510	65	575	023F	1498	575	2073	0819
s	115	575	115	690	02B2	2073	690	2763	0ACB
s	115	690	115	805	0325	2763	805	3568	0DF0
i	105	805	105	910	038E	3568	910	4478	117E
s	115	910	115	1025	0401	4478	1025	5503	157F
t	116	1025	116	1141	0475	5503	1141	6644	19F4

```
a = 1141= 0x0475 (base 16); b = 6644 = 0x19F4
Output (Checksum) = 0x19F4 << 16 + 0x0475 = 0x19F40475
```

In this example, the upper 16 bits of the Adler-32 checksum are the ‘b’ value, 6644 (decimal), and the lower 16 bits are the ‘a’ value, 1141 (decimal). Converting to hexadecimal, the entire checksum (output) is 0x19F40475.

Note: The modulo operation had no effect in this example, as none of the values reached 65521.

5.2 Collisions

5.2.1 Character Sets and Collisions

For an Adler-32 checksum collision to occur, both modulo operations must occur. Until both of these events happen, the checksum will be unique with respect to previous Adler-32 calculations on the same buffer. And any change in the buffer due to an error will result in a different checksum. The rate of modulo operations occurring during calculation can be interpreted as representative of the rate of potential collisions.

5.2.2 ASCII Values

5.2.2.1 Lower (0-85)

If the bytes of data provided to the Adler-32 function are at the lower end of the ASCII character set, the rate of the modulo operations occurring will be less than if the data is in the midrange or higher end of the ASCII table. If an error is introduced into the data, the lower modulation rate will mean the error is less likely to collide with the original data

5.2.2.2 Mid-range (86-170)

If the data is predominantly in the middle range of the ASCII character set, the rate of collisions is highest. This is an artifact of both higher modulation rates, and higher likelihood of a three-byte change collision, or a variant.

5.2.2.3 High (170-255)

If the bytes of data are at the higher (upper) end of the ASCII character set, then there will be more frequent modulation. However, because larger ASCII values are used, it is less likely the error will induce the three-byte change collision, or a variant, in the checksum.

See Appendix A and Appendix B for an empirical analysis of these statements.

5.2.3 Three-Byte Change Collisions

The most commonly studied collisions in the Adler-32 checksum involve a change of three consecutive bytes. The collision is derived from studying the algorithm itself. Since the algorithm itself is built on additions, then it is a simple matter of selecting three bytes whose relative values will result in a zero-sum difference to the Adler-32 checksum itself.

This has been researched and any multiple of the vector `{1, -2, 1}` will satisfy. For example, assume a character array ends with the letters “…234”, and it has the Adler-32 “A”. If those last three character are changed to “…305”, then the Adler-32 will still be the same, assuming no modulation occurs.

Source: http://www.leviathansecurity.com/blog/analysis-of-adler32

5.3 Non-Collisions

The Adler-32 checksum has the following known properties:

1. All single bit flips will be detected.
2. All double bit flips will be detected.
3. Burst errors up to seven bits are always detected.

Source: https://www.zlib.net/maxino06_fletcher-adler.pdf

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6 *CRC32 Hash Function*

The hash function used to calculate the check-value for the gzip footer is a 32-bit CRC with the `0xebd88320` polynomial.

CRC32 is calculated by a polynomial division and the data buffer is divided by the polynomial. The remainder is the CRC32. A concise example can be studied at the referenced source below.

Source: http://cs.newpaltz.edu/~easwaran/CN/Module7/CRC2.pdf

6.1 Bit Changes in the Hash

CRC (Cyclic Redundancy Check) functions are designed to provide an even distribution of hash values. The mechanism used to provide the even distribution is division, with the remainder becoming the hash value.

The division used in the CRC function is an XOR operation (instead of a subtraction) and leading zeroes are dropped. Also, the use of remainders in subsequent division operations has the effect of making changes in multiple locations of the final CRC.

6.1.1 Example:

If the divisor is `110011`, and the dividend is `1100101010011`, then the CRC would be:

```
        ------------------
110011 |110010101001100000 ← dividend lengthened by 5 bits for CRC
        110011
        -------
             1101001100000
             11011
             --------
                 101100000
                 11011
                 -------------
                  11010000
                  110011
                   ------
                     11100 ← remainder is CRC
```

If one bit is changed in the dividend:

```
        ----------------------
110011 |1101 1010 1001 1000 00
        1100 11
        --------
           1 0110 1001 1000 00
           1 1001 1
           --------
             1111 0001 1000 00
             1100 11
            ----------
               11 1101 1000 00
               11 0011
              --------
                  1110 1000 00
                  1100 11
                --------
                    10 0100 00
                    11 0011
                  --------
                     1 0111 00
                     1 1001 1
                   ---------
                       1110 10
                       1100 11
                    -----------
                        010 01   ← remainder is the CRC
```

The example above shows that one changed bit changes three of the bits in the 5-bit CRC. And this very important concept indicates that localized changes in the data buffer are reflected with non-localized changes in the CRC.

6.2 Byte-by-byte

Due to the nature of the type of algorithms being implemented, it's usually implemented as a lookup table of 256 remainders. See the source referenced below for details and a concise explanation.

Source: https://barrgroup.com/Embedded-Systems/How-To/CRC-Calculation-C-Code

The effect of bit changes on the CRC32 can be clearly seen with a standard table based implementation. The standard CRC32 with the `0xedb88320` polynomial can be implemented with a table of remainders. Select values are shown below:

For select values:

```
'x' crc_table[0x78] = 0x5edef90e =
01011110110111101111100100001110
'y' crc_table[0x79] = 0x29d9c998 =
00101001110110011100100110011000
```

As can be seen, if a single bit is changed, for example `'x'(0x78)` to `'y'(0x79)`, then the cumulative calculation of the CRC32 is impacted by 15 bit changes, spread across the length of the remainder.

For select values:

```
'M' crc_table[0x4d] = 0x86d3d2d
'N' crc_table[0x4e] = 0x91646c97
'O' crc_table[0x4f] = 0xe6635c01
```

The same mixing of hash values, relative to the number of changed bits, is observed.

See Appendix C for example source code to create the remainder table.

6.3 Non-Collisions

The industry standard CRC32 with the `0xedb88320` polynomial has the following known properties:

1. All single bit flips will be detected.
2. All double bit flips will be detected.
3. All 32-bit bursts of errors will be detected.
4. The CRC32 has a hamming distance of 4 for data lengths up to 91706 bytes.
5. A hamming distance of 5 for data lengths up to 2974 bytes.

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7 Summary

It can be concluded from examining the implementation of the Adler-32 checksum and the CRC32 hash that the values are uncorrelated. The Adler-32 checksum is derived from modulated additions and the CRC32 hash is derived from integer division (with remainders).

Empirical studies were performed to measure the collision rate of Adler-32, with the worst case being one in 52 million. Empirically, the worst case measured for the CRC32 collision was one in 1.04 billion. All data corruptions in the study that resulted in a CRC32 collision were detected by the Adler-32 checksum, and all data corruptions that resulted in an Adler-32 collision were detected by the CRC32 hash. The observed rate of both an Adler-32 collision and CRC32 collision on the same data was 0 in 1.5 trillion corruptions.

In conclusion, testing for data compression integrity using Adler-32 checksum and CRC32 hash together provides increased likelihood of detecting corruption when compared to using either in isolation. See Appendix A for a complete test description and Appendix B for complete test results.

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Appendix A Empirical Study Description

Three data set sizes of 4, 8, and 32 kilobytes were selected and the empirical study was conducted as follows:

For each data set size

Five data set content ranges were selected:

1. Low ASCII values (0-85)
2. Mid-range ASCII values (86-170)
3. High ASCII values (170-255)
4. The set of printable ASCII values (32-127)
5. The full ASCII set (0-255)

For each data set range

- Thirty-two different `clean_buffers` were created by random selection of ASCII characters within the data set range.
- The Adler-32 and CRC32 of the `clean_buffer` were calculated.

For each `clean_buffer` 3,125,000,000 loops

- A `corrupted_buffer` was created by replacing a random number of up to 100 characters. The location in the buffer was randomized from start to end, and the replacement character was randomized from the full set of ASCII values.
- The Adler-32 checksum was calculated, and compared with the Adler-32 from the `clean_buffer`. If these checksums were the same, a collision was recorded.
- The CRC32 hash was calculated, and compared with the CRC32 from the `clean_buffer`. If these hash values were the same, a collision was recorded.

For each data set size and data set range, a total of 100,000,000,000 corrupted buffers were constructed and the checksum and hash were compared. This number was chosen to represent more than an order of magnitude greater than the optimal expected collision rate of 1 in 4,294,967,296 for a 32-bit checksum or hash.

Note: The standard Linux* `rand()` function seeded with the `time()` function was used to generate random values.

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Appendix B Full Empirical Results

Table 4. Full Empirical Results

Input Data size (bytes)	Location in ASCII Table	CRC32 Collisions (in 100 billion corrupted data sets)	Adler-32 collisions (in 100 billion corrupted data sets)	Double collision
4096	Low	29	11	0
4096	Med	16	1303	0
4096	High	18	20	0
4096	Printable ASCII	30	102	0
4096	Full/(Unicode)	24	942	0
8192	Low	27	15	0
8192	Med	24	1340	0
8192	High	21	30	0
8192	Printable ASCII	31	115	0
8192	Full	20	965	0
32768	Low	20	17	0
32768	Med	25	1299	0
32768	High	24	11	0
32768	Printable ASCII	29	101	0
32768	Full	21	606	0

7.1 Summary

In summary, the empirical study generated 480 buffers, and then corrupted each buffer 3,125,000,000 times for a total of 1.5 trillion corruptions. The Adler-32 and CRC32 of the original clean buffer and the corrupted buffer were compared and the number of collisions are summarized in the table below. In every corrupted data set, either the CRC32 or the Adler-32 or both were different from that of the clean buffer (refer to the double collisions in the tables below). No corrupted buffer was not detected by examining the Adler-32 and CRC32.

Table 5. Empirical Study Results

	CRC32	Adler-32
Total Collisions (in 1.5 trillion corruptions)	359	6877
One in (approximately):	4,178,272,980	218,118,365
Double Collisions	0	0

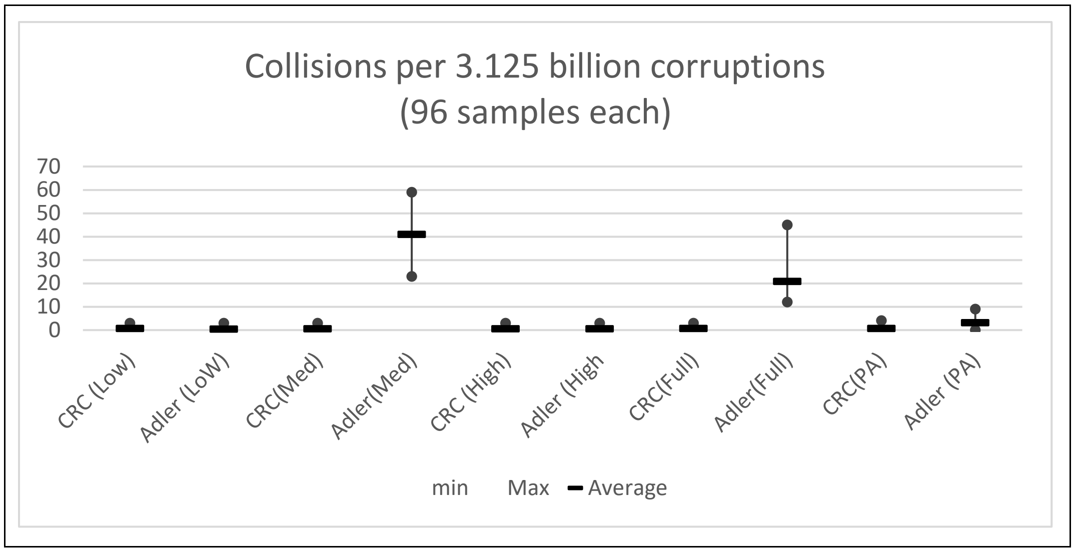
As previously noted in this paper, the likelihood of collision by Adler-32 changes is based on the data set in use. The largest number of collisions for the Adler-32 checksum was 59. This was observed in the 8 kilobyte dataset with the mid-range ASCII data set. Independently, there were several tests that showed three CRC32 collisions out of 3,125,000,000 corruptions. This worst case scenario is summarized below.

Table 6. Worst Case Scenario

	CRC32	Adler-32
Collisions (in 3.125 billion corruptions)	3	59
one in (approximately):	1,041,666,667	52,966,101
Double Collisions	0	0

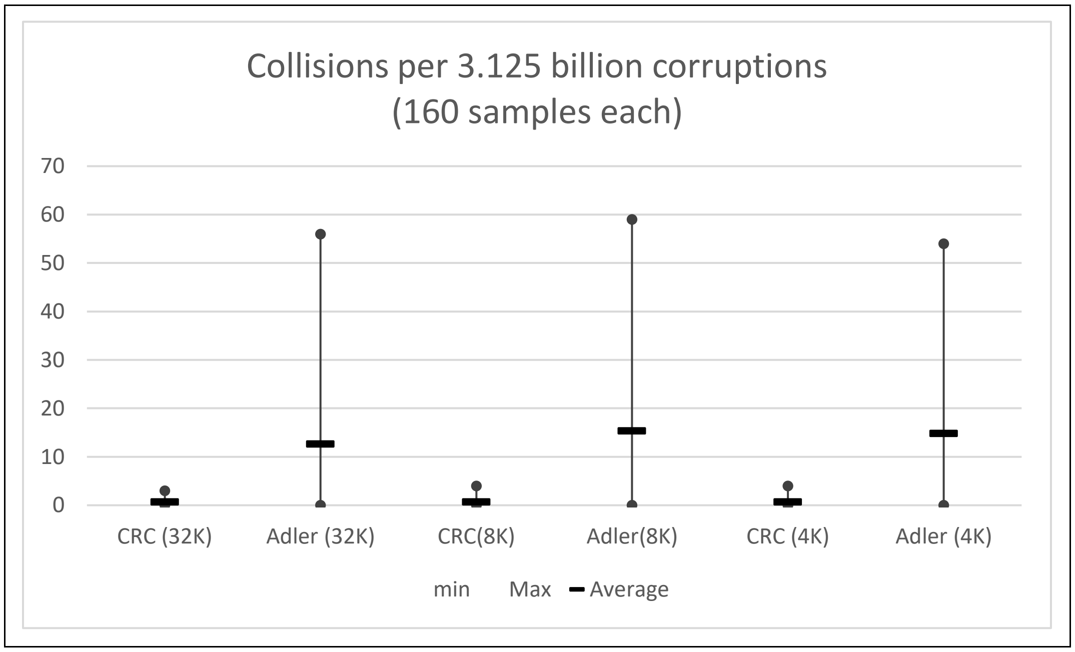
7.2 View by ASCII Data Set

Figure 1. 96 Samples



7.3 View by Data Set Size

Figure 2. 160 Samples



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Appendix C Code to Create full CRC32 Table

Code source: https://www.ietf.org/rfc/rfc1952.txt

```
/* Table of CRCs of all 8-bit messages. */
 unsigned long crc_table[256];

 /* Flag: has the table been computed? Initially false. */
 int crc_table_computed = 0;

 /* Make the table for a fast CRC. */
 void make_crc_table(void)
 {
   unsigned long c;
   int n, k;
   for (n = 0; n < 256; n++) {
     c = (unsigned long) n;
     for (k = 0; k < 8; k++) {
       if (c & 1) {
         c = 0xedb88320L ^ (c >> 1);
       } else {
         c = c >> 1;
       }
     }
     crc_table[n] = c;
   }
   crc_table_computed = 1;
 }
```

```
/*
   Update a running crc with the bytes buf[0..len-1] and
return the updated crc. The crc should be initialized to zero.
Pre- and post-conditioning (one's complement) is performed within
this function so it shouldn't be done by the caller. Usage
example:
   unsigned long crc = 0L;
   while (read_buffer(buffer, length) != EOF) {
     crc = update_crc(crc, buffer, length);
   }
   if (crc != original_crc) error();
*/
unsigned long update_crc(unsigned long crc,
                unsigned char *buf, int len)
{
  unsigned long c = crc ^ 0xffffffffL;
  int n;

  if (!crc_table_computed)
    make_crc_table();
  for (n = 0; n < len; n++) {
    c = crc_table[(c ^ buf[n]) & 0xff] ^ (c >> 8);
  }
  return c ^ 0xffffffffL;
}

/* Return the CRC of the bytes buf[0..len-1]. */
unsigned long crc(unsigned char *buf, int len)
{
  return update_crc(0L, buf, len);
}
```

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