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Brotli Compressed Data Format

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Abstract

This specification defines a lossless compressed data format that

compresses data using a combination of the LZ77 algorithm and Huffman

coding, with efficiency comparable to the best currently available

general-purpose compression methods.

Специфікація визначає алгоритим стиснення без втрат завдяк якого можна стискати дані використовуючи комбінацію алгоритму LZ77 та кодування Хаффмана.При цьому,даний алгоритм можна назвати не менш ефективним за інші загальні доступні алгоритми стиснення .

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1. Introduction

1.1. Purpose

The purpose of this specification is to define a lossless compressed

data format that:

Мета специфікації визначити формат даних для стиснення без втрат яке б :

\* Is independent of CPU type, operating system, file system,

and character set, and hence can be used for interchange;

Було незалежним від виду процесору ,операційної системи,файлової системи,

А також типу кодування символів,і відповідно його можна було б застосовувати для обміну даними.

\* Can be produced or consumed, even for an arbitrarily long

sequentially presented input data stream, using only an a

priori bounded amount of intermediate storage, and hence

can be used in data communications or similar structures,

such as Unix filters;

Його можна застосувати до довільно великого обсягу даних,які послідовно записані у вхідному потоці ,використовуючи лише обмежене а пріорі сховище для проміжних даних.

\* Compresses data with a compression ratio comparable to the

best currently available general-purpose compression methods,

and in particular, considerably better than the gzip program;

Стискує дані з відношенням стискання яке порівнюване з аналогічними відношеннями інших алгоритмів стиснення.Зокрема,значно кращий за gzip алгоритм стисення даних.

\* Decompresses much faster than current LZMA implementations.

Процесс відновлення даних швидший за сучасну імплементацію LZMA алгоритму.

The data format defined by this specification does not attempt to:

\* Allow random access to compressed data;

\* Compress specialized data (e.g., raster graphics) as well

as the best currently available specialized algorithms.

Проте ,даний алгоритм не призначений для випадкового доступу до будь-якої частини стиснених даних.Також він не здатний стискати спеціалізовані формати даних ,як-от растрову графіку тощо.

1.2. Intended audience

This specification is intended for use by software implementers to

compress data into and/or decompress data from the brotli format.

The text of the specification assumes a basic background in

programming at the level of bits and other primitive data

representations. Familiarity with the technique of Huffman coding is

helpful but not required.

This specification uses heavily the notations and terminology

introduced in the DEFLATE format specification [RFC 1951]. For the

sake of completeness, we always include the whole text of the

relevant parts of RFC 1951, therefore familiarity with the DEFLATE

format is helpful but not required.

The compressed data format defined in this specification is an

integral part of the WOFF 2.0 web font file format [WOFF2], therefore

this specification is also intended for implementers of WOFF 2.0

compressors and decompressors.

1.3. Scope

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The specification specifies a method for representing a sequence of

bytes as a (usually shorter) sequence of bits, and a method for

packing the latter bit sequence into bytes.

В специфікації зазначено метод для представлення послідовності байтів як послідовностей бітів ,та метод для пакування послідовностей бітів в байти назад.

1.4. Compliance

Unless otherwise indicated below, a compliant decompressor must be

able to accept and decompress any data set that conforms to all the

specifications presented here. A compliant compressor must produce

data sets that conform to all the specifications presented here.

1.5. Definitions of terms and conventions used

Byte: 8 bits stored or transmitted as a unit (same as an octet). For

this specification, a byte is exactly 8 bits, even on machines that

store a character on a number of bits different from eight. See

below for the numbering of bits within a byte.

Далі під байтом буде визначено послідовність з 8 бітів збережених як одиниці інформації.

String: a sequence of arbitrary bytes.

Під стрічкою мається на увазі будь-яка послідовність байтів довільної довжини.

Bytes stored within a computer do not have a "bit order", since they

are always treated as a unit. However, a byte considered as an

integer between 0 and 255 does have a most- and least-significant

bit, and since we write numbers with the most-significant digit on

the left, we also write bytes with the most-significant bit on the

left. In the diagrams below, we number the bits of a byte so that bit

0 is the least-significant bit, i.e., the bits are numbered:

У визначенні байту послуговуватимемося позначенням спочатку найбільш важливого біту зліва.

+--------+

|76543210|

+--------+

Within a computer, a number may occupy multiple bytes. All multi-byte

numbers in the format described here are stored with the least-

significant byte first (at the lower memory address). For example,

the decimal number 520 is stored as:

Оскільки число може бути більшим за 1 байт ,будемо розміщувати 1 байт числа зліва(найменш важливий байт),а решту – справа.

0 1

+--------+--------+

|00001000|00000010|

+--------+--------+

^ ^

| |

| + more significant byte = 2 x 256

+ less significant byte = 8

1.5.1. Packing into bytes

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This document does not address the issue of the order in which bits

of a byte are transmitted on a bit-sequential medium, since the final

data format described here is byte- rather than bit-oriented.

However, we describe the compressed block format below as a sequence

of data elements of various bit lengths, not a sequence of bytes. We

must therefore specify how to pack these data elements into bytes to

form the final compressed byte sequence:

Отже,остаточна форма стиснених даних матиме наступні властивості:

\* Data elements are packed into bytes in order of

increasing bit number within the byte, i.e., starting

with the least-significant bit of the byte.

Елементи даних спаковані в байти в порядку зростання бітового числа в байті,починаючи з найменш важливого біту .

\* Data elements other than prefix codes are packed

starting with the least-significant bit of the data

element. These are referred to here as integer values

and are considered unsigned.

\* Prefix codes are packed starting with the most-significant

bit of the code.

Префіксні коди розташовані починаючи з найбільш важливого біту

In other words, if one were to print out the compressed data as a

sequence of bytes, starting with the first byte at the \*right\* margin

and proceeding to the \*left\*, with the most-significant bit of each

byte on the left as usual, one would be able to parse the result from

right to left, with fixed-width elements in the correct msb-to-lsb

order and prefix codes in bit-reversed order (i.e., with the first

bit of the code in the relative lsb position).

Відповідно при прочитанні стиснених даних «справа –наліво» фіксовані елементи стиснення будуть прочитані спочатку від найголовнішого до найменш важливого біту,для прфексних кодів-навпаки.

Приклад:значення 3-бітного числа -6;4-бітного – 2; префіксний код – 110;ще один префікс ний код -10;12 –бітного числа- 3628;

байт 2 байт 1 байт 0

+--------+--------+--------+

|11100010|11000101|10010110|

+--------+--------+--------+

^ ^ ^ ^ ^

| | | | |

| | | | +------ значення 6

| | | +---------- значення 2

| | +-------------- префіксний код 110

| +---------------- префіксний код 10

+----------------------------- значення 3628

As an example, consider packing the following data elements into a

sequence of 3 bytes: 3-bit integer value 6, 4-bit integer value 2,

prefix code 110, prefix code 10, 12-bit integer value 3628.

byte 2 byte 1 byte 0

+--------+--------+--------+

|11100010|11000101|10010110|

+--------+--------+--------+

^ ^ ^ ^ ^

| | | | |

| | | | +------ integer value 6

| | | +---------- integer value 2

| | +-------------- prefix code 110

| +---------------- prefix code 10

+----------------------------- integer value 3628

2. Compressed representation overview

A compressed data set consists of a header and a series of meta-

blocks. Each meta-block decompresses to a sequence of 0 to 16,777,216

(16 MiB) uncompressed bytes. The final uncompressed data is the

concatenation of the uncompressed sequences from each meta-block.

Стисненні дані містять в собі заголовок та послідовність мета-блоків. Кожен мета-блок відновлює від 0 до 16 777 216 нестиснених байтів. Остаточні відновлені дані є конкатенацією всіх відновлених послідовностей з кожного мета-блоку.

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The header contains the size of the sliding window that was used

during compression. The decompressor must retain at least that

amount of uncompressed data prior to the current position in the

stream, in order to be able to decompress what follows. The sliding

window size is a power of two, minus 16, where the power is in the

range of 10 to 24. The possible sliding window sizes range from 1 KiB

- 16 B to 16 MiB - 16 B.

Заголовок містить розмір розсувного вікна яке було використанне під час стиснення .При відновленні це вікно має бути заповнене нестисненим даним для того щоб відновити наступні байти.Розмір розсувного вікна є степеню двійки і може бути зміненим від 1 кілобайта до 16 мегабайт.

Each meta-block is compressed using a combination of the LZ77

algorithm (Lempel-Ziv 1977, [LZ77]) and Huffman coding. The result of

Huffman coding is referred to here as a prefix code. The prefix

codes for each meta-block are independent of those for previous or

subsequent meta-blocks; the LZ77 algorithm may use a reference to a

duplicated string occurring in a previous meta-block, up to the

sliding window size of uncompressed bytes before. In addition, in

the brotli format, a string reference may instead refer to a static

dictionary entry.

Кожен мета-блок стиснений використовуючи комбінацію зLZ77 та алгоритму кодування Хаффмана.

Результатом кодування Хаффмана є префіксні коди.префікні коди для кожного мета-блоку є незалежними від інших кодів з попереднього чи наступного блоку.Алгоритм LZ77 ,в свою чергу,використовує посилання до стрічок які повторилися в попередніх мета-блоках.Також,посилання на стріску може звертатися до статисного словника вбудованого в реалізації словника.

Each meta-block consists of two parts: a meta-block header that

describes the representation of the compressed data part, and a

compressed data part. The compressed data consists of a series of

commands. Each command consists of two parts: a sequence of literal

bytes (of strings that have not been detected as duplicated within

the sliding window), and a pointer to a duplicated string,

represented as a pair <length, backward distance>. There can be zero

literal bytes in the command. The minimum length of the string to be

duplicated is two, but the last command in the meta-block is

permitted to have only literals and no pointer to a string to

duplicate.

Кожен мета-блок складається з двох частин :заголовку мета-блоку який описує представлення частини даних яка стиснута,та цю ж частину стиснених даних. Частина стиснених даних складається з послідовності команд. В свою чергу кожна з команд складається з двох частин :послідовності байтів ,або ж стрічок(які до того не були розпізнані розсувним вікном як такі,що мають повторення),та указник на стрічку з повторенням. ЇЇ представлено у вигляді пари <довжина,відстань>.В команді може бути 0 літеральних байтів(стрічка порожня).Мінімальна довжина стрічки для копіювання -2.Остання команда в блоці може містити лише літерали(байти) та не містить указник на стрічку з повторенням.

Each command in the compressed data is represented using three

categories of prefix codes:

Кожна з команд стиснених даних представлення у вигляді 3 категорій префікс них кодів :

1) One set of prefix codes are for the literal sequence lengths

(also referred to as literal insertion lengths) and

backward copy lengths. That is, a single code word represents

two lengths, one of the literal sequence and one of the

backward copy.

1)Перша множина префікс них кодів призначена для довжин послідовностей літералів та відстаней до копій.таким чином один префікс ний код визначає дві довжини,довжину самої послідовності та відстань до копії.

2)

2) One set of prefix codes are for literals.

2)Другий тільки для літералів

3) One set of prefix codes are for distances.

3)Третій тільки для відстаней

The prefix code descriptions for each meta-block appear in a compact

form just before the compressed data in the meta-block header. The

insert-and-copy length and distance prefix codes may be followed by

extra bits that are added to the base values determined by the codes.

The number of extra bits is determined by the code.

Префіксні коди для кожного блоку знаходяться перед стисненим даним в заголовку мате-блоку.

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One meta-block command then appears as a sequence of prefix codes:

Приклад команди як послідовності префікс них кодів

Insert-and-copy length, literal, literal, ..., literal, distance

Довжина вставки та копії ,літерал,літерал,….,відстань

Довжина вставки визначає кількість літералів які йдуть одразу після нього.

Відстань визначає як далеко слід звернутися назад аби повернутися до копії.

Довжина копії визначає кількість байтів в копії.

В результаті нестиснені дані мають вигляд :

Літерал,літерал,…..,копія,копія.

where the insert-and-copy defines an insertion length and a copy

length. The insertion length determines the number of literals that

immediately follow. The distance defines how far back to go for the

copy and the copy length determines the number of bytes to copy. The

resulting uncompressed data is the sequence of bytes:

literal, literal, ..., literal, copy, copy, ..., copy

where the number of literal bytes and copy bytes are determined by

the insert-and-copy length code. (The number of bytes copied for a

static dictionary entry can vary from the copy length.)

The last command in the meta-block may end with the last literal if

the total uncompressed length of the meta-block has been satisfied.

In that case there is no distance in the last command, and the copy

length is ignored.

Остання команда в мета-блоці може закінчуватися останнім літералом якщо загальна довжина нестиснених даних була повністю заповнена.В цьому випадку немає відстані в цій команді,і довжина копії не потрібна.

There can be more than one prefix code for each category, where the

prefix code to use for the next element of that category is

determined by the context of the compressed stream that precedes that

element. Такоє може бути більше ніж один префікс ний код для кожної категорії,де префікс ний код для наступного лемента цієї категорії визначений в контексті стиснених даних які передують цьому елементові.

Part of that context is three current block types, one for

each category.

Частиною цього контексту є 3 поточні типи блоків,по-одному для кожної категорії.

A block type is in the range of 0..255.Діапазон типу блоку від 0 до 255.

For each

category there is a count of how many elements of that category

remain to be decoded using the current block type.

Для кожної категорії існує лічильник ,стосовно того скільки елементів цієї категорії слід декодувати в поточному типі блоку.

Once that count is

expended, a new block type and block count is read from the stream

immediately preceding the next element of that category, which will

use the new block type.

Як тільки лічильник був розширений,новий тип блоку та новий лічильник дістають з потоку перед наступним елементом категорії ,який буде використовувати новий тип блоку.

The insert-and-copy block type directly determines which prefix code

to use for the next insert-and-copy element.

Тип вставки та копіювання блоку визначає який префікс ний код використати для наступного елементу цього ж типу.

For the literal and

distance elements, the respective block type is used in combination

with other context information to determine which prefix code to use

for the next element.

Для літералів та відстаней,відповідні типи блоків використовують в комбінації з іншою контекстною інформацією для наступного елементу.

Consider the following example:Розглянемо наступний приклад

(IaC0, L0, L1, L2, D0)(IaC1, D1)(IaC2, L3, L4, D2)(IaC3, L5, D3)

The meta-block here has four commands, contained in parentheses for

clarity, where each of the three categories of symbols within these

commands can be interpreted using different block types.

Цей мета-блок має чотири команди ,записані в дужках для ясності,де кожна з 3 категорій символів з цими командам може бути інтерпретована використовуючи різні типи блоків .

Here we

separate out each category as its own sequence to show an example of

block types assigned to those elements.Тут ми розділяємо кожну категорію на свою власну послідовність аби показати приклад типів блоків .

Each square-bracketed group

is a block that uses the same block type:

Кожна група з квадратним дужками використовує один тип блоку.

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[IaC0, IaC1][IaC2, IaC3] <-- insert-and-copy: block types 0 and 1

[L0, L1][L2, L3, L4][L5] <-- literals: block types 0, 1, and 0

[D0][D1, D2, D3] <-- distances: block types 0 and 1

[IaC0, IaC1][IaC2, IaC3] <-- вставка та видалення : типи блоків 0 та 1

[L0, L1][L2, L3, L4][L5] <-- літерали : типи блоків 0 ,1 та 0

[D0][D1, D2, D3] <-- відстані :типи блоків 0 та 1

The subsequent blocks within each block category must have different

block types, but we see that block types can be reused later in the

meta-block. Наступні блоки в кожній категоріх мають мати різні типи блоків,але їх можна потім використовувати заново в мета-блоці.

The block types are numbered from 0 to the maximum block

type number of 255 and the first block of each block category is type

0.Типи блоків нумеровані від 0 до максимального числа блоків (255) і перший блок кожнох категорії має тип 0.

The block structure of a meta-block is represented by the sequence

of block-switch commands for each block category, where a block-

switch command is a pair <block type, block count>. Блочна структура мета-блоку представленя послідовністю команд для кожної категоріх,де команда має вигляд<тип блоку,лічильник блоку>.

The block-switch

commands are represented in the compressed data before the start of

each new block using a prefix code for block types and a separate

prefix code for block counts for each block category. For the above

example the physical layout of the meta-block is then:

IaC0 L0 L1 LBlockSwitch(1, 3) L2 D0 IaC1 DBlockSwitch(1, 3) D1

IaCBlockSwitch(1, 2) IaC2 L3 L4 D2 IaC3 LBlockSwitch(0, 1) L5 D3

where xBlockSwitch(t, n) switches to block type t for a count of n

elements. Note that in this example DBlockSwitch(1, 3) immediately

precedes the next required distance D1. It does not follow the last

distance of the previous block, D0. Whenever an element of a category

is needed, and the block count for that category has reached zero,

then a new block type and count is read from the stream just before

reading that next element.

The block-switch commands for the first blocks of each category are

not part of the meta-block compressed data. Instead the first block

type is defined to be 0, and the first block count for each category

is encoded in the meta-block header. The prefix codes for the block

types and counts, a total of six prefix codes over the three

categories, are defined in a compact form in the meta-block header.

Each category of value (insert-and-copy lengths, literals, and

distances) can be encoded with any prefix code from a collection of

prefix codes belonging to the same category appearing in the meta-

block header. The particular prefix code used can depend on two

factors: the block type of the block the value appears in, and the

context of the value. In the case of the literals, the context is

the previous two bytes in the uncompressed data, and in the case of

distances, the context is the copy length from the same command. For

insert-and-copy lengths, no context is used and the prefix code

depends only on the block type. In the case of literals and

distances, the context is mapped to a context ID in the range 0..63

for literals and 0..3 for distances. The matrix of the prefix code

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indexes for each block type and context ID, called the context map,

is encoded in a compact form in the meta-block header.

For example, the prefix code to use to decode L2 depends on the block

type (1), and the literal context ID determined by the two

uncompressed bytes that were decoded from L0 and L1. Similarly, the

prefix code to use to decode D0 depends on the block type (0), and

the distance context ID determined by the copy length decoded from

IaC0. The prefix code to use to decode IaC3 depends only on the block

type (1).

In addition to the parts listed above (prefix code for insert-and-

copy lengths, literals, distances, block types and block counts, and

the context map), the meta-block header contains the number of

uncompressed bytes coded in the meta-block and two additional

parameters used in the representation of match distances: the number

of postfix bits and the number of direct distance codes.

A compressed meta-block may be marked in the header as the last meta-

block, which terminates the compressed stream.

A meta-block may instead simply store the uncompressed data directly

as bytes on byte boundaries with no coding or matching strings. In

this case the meta-block header information only contains the number

of uncompressed bytes and the indication that the meta-block is

uncompressed. An uncompressed meta-block cannot be the last meta-

block.

A meta-block may also be empty, which generates no uncompressed data

at all. An empty meta-block may contain metadata information as

bytes starting on byte boundaries, which are not part of either the

sliding window or the uncompressed data. Thus, these metadata bytes

cannot be used to create matching strings in subsequent meta-blocks

and are not used as context bytes for literals.

3. Compressed representation of prefix codes

3.1. Introduction to prefix coding

Prefix coding represents symbols from an a priori known alphabet by

bit sequences (codes), one code for each symbol, in a manner such

that different symbols may be represented by bit sequences of

different lengths, but a parser can always parse an encoded string

unambiguously symbol-by-symbol.

We define a prefix code in terms of a binary tree in which the two

edges descending from each non-leaf node are labeled 0 and 1 and in

which the leaf nodes correspond one-for-one with (are labeled with)

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the symbols of the alphabet; then the code for a symbol is the

sequence of 0's and 1's on the edges leading from the root to the

leaf labeled with that symbol. For example:

/\ Symbol Code

0 1 ------ ----

/ \ A 00

/\ B B 1

0 1 C 011

/ \ D 010

A /\

0 1

/ \

D C

A parser can decode the next symbol from the compressed stream by

walking down the tree from the root, at each step choosing the edge

corresponding to the next compressed data bit.

Given an alphabet with known symbol frequencies, the Huffman

algorithm allows the construction of an optimal prefix code (one

which represents strings with those symbol frequencies using the

fewest bits of any possible prefix codes for that alphabet). Such a

prefix code is called a Huffman code. (See [HUFFMAN] in Chapter 5,

references for additional information on Huffman codes.)

Note that in the brotli format, the prefix codes for the various

alphabets must not exceed certain maximum code lengths. This

constraint complicates the algorithm for computing code lengths from

symbol frequencies. Again, see Chapter 5, references for details.

3.2. Use of prefix coding in the brotli format

The prefix codes used for each alphabet in the brotli format are

canonical prefix codes, which have two additional rules:

\* All codes of a given bit length have lexicographically

consecutive values, in the same order as the symbols they

represent;

\* Shorter codes lexicographically precede longer codes.

We could recode the example above to follow this rule as follows,

assuming that the order of the alphabet is ABCD:

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Symbol Code

------ ----

A 10

B 0

C 110

D 111

I.e., 0 precedes 10, which precedes 11x, and 110 and 111 are

lexicographically consecutive.

Given this rule, we can define the canonical prefix code for an

alphabet just by giving the bit lengths of the codes for each symbol

of the alphabet in order; this is sufficient to determine the actual

codes. In our example, the code is completely defined by the sequence

of bit lengths (2, 1, 3, 3). The following algorithm generates the

codes as integers, intended to be read from most- to least-

significant bit. The code lengths are initially in tree[I].Len; the

codes are produced in tree[I].Code.

1) Count the number of codes for each code length. Let

bl\_count[N] be the number of codes of length N, N >= 1.

2) Find the numerical value of the smallest code for each

code length:

code = 0;

bl\_count[0] = 0;

for (bits = 1; bits <= MAX\_BITS; bits++) {

code = (code + bl\_count[bits-1]) << 1;

next\_code[bits] = code;

}

3) Assign numerical values to all codes, using consecutive

values for all codes of the same length with the base

values determined at step 2. Codes that are never used

(which have a bit length of zero) must not be assigned a

value.

for (n = 0; n <= max\_code; n++) {

len = tree[n].Len;

if (len != 0) {

tree[n].Code = next\_code[len];

next\_code[len]++;

}

}

Example:

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Consider the alphabet ABCDEFGH, with bit lengths (3, 3, 3, 3, 3, 2,

4, 4). After step 1, we have:

N bl\_count[N]

- -----------

2 1

3 5

4 2

Step 2 computes the following next\_code values:

N next\_code[N]

- ------------

1 0

2 0

3 2

4 14

Step 3 produces the following code values:

Symbol Length Code

------ ------ ----

A 3 010

B 3 011

C 3 100

D 3 101

E 3 110

F 2 00

G 4 1110

H 4 1111

3.3. Alphabet sizes

Prefix codes are used for different purposes in the brotli format,

and each purpose has a different alphabet size. For literal codes the

alphabet size is 256. For insert-and-copy length codes the alphabet

size is 704. For block count codes, the alphabet size is 26. For

distance codes, block type codes, and the prefix codes used in

compressing the context map, the alphabet size is dynamic and is

based on parameters defined in later sections. The following table

summarizes the alphabet sizes for the various prefix codes and the

sections where they are defined.

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+-----------------+-------------------------+------------+

| Prefix code | Alphabet size | Definition |

+-----------------+-------------------------+------------+

| literal | 256 | |

+-----------------+-------------------------+------------+

| distance | 16 + NDIRECT + | Section 4. |

| | (48 << NPOSTFIX) | |

+-----------------+-------------------------+------------+

| insert-and-copy | 704 | Section 5. |

| length | | |

+-----------------+-------------------------+------------+

| block count | 26 | Section 6. |

+-----------------+-------------------------+------------+

| block type | NBLTYPESx + 2, | Section 6. |

| | (where x is I, L, or D) | |

+-----------------+-------------------------+------------+

| context map | NTREESx + RLEMAXx | Section 7. |

| | (where x is L or D) | |

+-----------------+-------------------------+------------+

3.4. Simple prefix codes

The first two bits of the compressed representation of each prefix

code distinguish between simple and complex prefix codes. If this

value is 1, then a simple prefix code follows as described in this

section. Otherwise, a complex prefix code follows as described in

Section 3.5.

A simple prefix code can have only up to four symbols with non-zero

code length. The format of the simple prefix code is as follows:

2 bits: value of 1 indicates a simple prefix code

2 bits: NSYM - 1, where NSYM = # of symbols coded

NSYM symbols, each encoded using ALPHABET\_BITS bits

1 bit: tree-select, present only for NSYM = 4

The value of ALPHABET\_BITS depends on the alphabet of the prefix

code: it is the smallest number of bits that can represent all

symbols in the alphabet. E.g. for the alphabet of literal bytes,

ALPHABET\_BITS is 8. The value of each of the NSYM symbols above is

the value of the ALPHABETS\_BITS width integer value. If the integer

value is greater than or equal to the alphabet size, or the value is

identical to a previous value, then the stream should be rejected as

invalid.

Note that the NSYM symbols may not be presented in sorted order.

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Prefix codes of the same bit length must be assigned to the symbols

in sorted order.

The (non-zero) code lengths of the symbols can be reconstructed as

follows:

\* if NSYM = 1, the code length for the one symbol is zero --

when encoding this symbol in the

compressed data stream using this prefix code, no

actual bits are emitted. Similarly, when decoding a symbol

using this prefix code, no bits are read and the one symbol

is returned.

\* if NSYM = 2, both symbols have code length 1.

\* if NSYM = 3, the code lengths for the symbols are 1, 2, 2 in

the order they appear in the representation of the simple

prefix code.

\* if NSYM = 4, the code lengths (in order of symbols decoded)

depend on the tree-select bit: 2, 2, 2, 2 (tree-select bit 0),

or 1, 2, 3, 3 (tree-select bit 1).

3.5. Complex prefix codes

A complex prefix code is a canonical prefix code, defined by the

sequence of code lengths, as discussed in Section 3.2., above. For

even greater compactness, the code length sequences themselves are

compressed using a prefix code. The alphabet for code lengths is as

follows:

0..15: Represent code lengths of 0..15

16: Copy the previous non-zero code length 3..6 times

The next 2 bits indicate repeat length

(0 = 3, ... , 3 = 6)

If this is the first code length, or all previous

code lengths are zero, a code length of 8 is

repeated 3..6 times

A repeated code length code of 16 modifies the

repeat count of the previous one as follows:

repeat count = (4 \* (repeat count - 2)) +

(3..6 on the next 2 bits)

Example: Codes 7, 16 (+2 bits 11), 16 (+2 bits 10)

will expand to 22 code lengths of 7

(1 + 4 \* (6 - 2) + 5)

17: Repeat a code length of 0 for 3..10 times.

(3 bits of length)

A repeated code length code of 17 modifies the

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repeat count of the previous one as follows:

repeat count = (8 \* (repeat count - 2)) +

(3..10 on the next 3 bits)

Note that a code of 16 that follows an immediately preceding 16

modifies the previous repeat count, which becomes the new repeat

count. The same is true for a 17 following a 17. A sequence of three

or more 16 codes in a row or three of more 17 codes in a row is

possible, modifying the count each time. Only the final repeat count

is used. The modification only applies if the same code follows. A 16

repeat does not modify an immediately preceding 17 count nor vice

versa.

A code length of 0 indicates that the corresponding symbol in the

alphabet will not occur in the compressed data, and should not

participate in the prefix code construction algorithm given earlier.

A complex prefix code must have at least two non-zero code lengths.

The bit lengths of the prefix code over the code length alphabet are

compressed with the following variable length code (as it appears in

the compressed data, where the bits are parsed from right to left):

Symbol Code

------ ----

0 00

1 0111

2 011

3 10

4 01

5 1111

We can now define the format of the complex prefix code as follows:

2 bits: HSKIP, values of 0, 2, or 3 represent the respective

number of skipped code lengths. The skipped lengths

are taken to be zero. (An HSKIP of 1 indicates a

Simple prefix code.)

Code lengths for symbols in the code length alphabet given

just above, in the order: 1, 2, 3, 4, 0, 5, 17, 6, 16, 7,

8, 9, 10, 11, 12, 13, 14, 15. If HSKIP is 2, then the

code lengths for symbols 1 and 2 are zero, and the first

code length is for symbol 3. If HSKIP is 3, then the code

length for symbol 3 is also zero, and the first code length

is for symbol 4.

The code lengths of code length symbols are between 0 and

5, and they are represented with 2..4 bits according to

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the variable length code above. A code length of 0 means

the corresponding code length symbol is not used.

If HSKIP is 2 or 3, a respective number of leading code

lengths are implicit zeros and are not present in the

code lengths sequence above.

If there are at least two non-zero code lengths, any

trailing zero code lengths are omitted, i.e. the last

code length in the sequence must be non-zero. In this

case, the sum of (32 >> code length) over all the non-zero

code lengths must equal to 32.

If the lengths have been read for the entire code length

alphabet and there was only one non-zero code length,

then the prefix code has one symbol whose code has zero

length. In this case, that symbol results in no bits

being emitted by the compressor, and no bits consumed by

the decompressor. That single symbol is immediately

returned when this code is decoded.

An example of where this occurs is if the

entire code to be represented has symbols of length 8.

E.g. a literal code that represents all literal values

with equal probability. In this case the single symbol

is 16, which repeats the previous length. The previous

length is taken to be 8 before any code length code

lengths are read.

Sequence of at most alphabet size code lengths symbols, encoded

using the code length prefix code. Any trailing 0 or 17 must be

omitted, i.e. the last encoded code length symbol must be

between 1 and 16. The sum of (32768 >> code length) over

all the non-zero code lengths in the alphabet, including

those encoded using repeat code(s) of 16, must equal to

32768. If the number of times to repeat the previous length

or repeat a zero length would result in more lengths in

total than the number of symbols in the alphabet, then the

stream should be rejected as invalid.

4. Encoding of distances

As described in Section 2., one component of a compressed meta-block

is a sequence of backward distances. In this section we provide the

details to the encoding of distances.

Each distance in the compressed data part of a meta-block is

represented with a pair <distance code, extra bits>. The distance

code and the extra bits are encoded back-to-back, the distance code

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is encoded using a prefix code over the distance alphabet, while the

extra bits value is encoded as a fixed-width integer value. The

number of extra bits can be 0..24, and it is dependent on the

distance code.

To convert a distance code and associated extra bits to a backward

distance, we need the sequence of past distances and two additional

parameters, the number of "postfix bits", denoted by NPOSTFIX (0..3),

and the number of direct distance codes, denoted by NDIRECT (0..120).

Both of these parameters are encoded in the meta-block header. We

will also use the following derived parameter:

POSTFIX\_MASK = (1 << NPOSTFIX) - 1

The first 16 distance symbols are special symbols that reference past

distances as follows:

0: last distance

1: second-to-last distance

2: third-to-last distance

3: fourth-to-last distance

4: last distance - 1

5: last distance + 1

6: last distance - 2

7: last distance + 2

8: last distance - 3

9: last distance + 3

10: second-to-last distance - 1

11: second-to-last distance + 1

12: second-to-last distance - 2

13: second-to-last distance + 2

14: second-to-last distance - 3

15: second-to-last distance + 3

The ring buffer of four last distances is initialized by the values

16, 15, 11, and 4 (i.e. the fourth-to-last is set to 16, the third-

to-last to 15, the second-to-last to 11, and the last distance to 4)

at the beginning of the \*stream\* (as opposed to the beginning of the

meta-block) and it is not reset at meta-block boundaries. When a

distance symbol 0 appears, the distance it represents (i.e. the last

distance in the sequence of distances) is not pushed to the ring

buffer of last distances, in other words, the expression "(second,

third, fourth)-to-last distance" means the (second, third,

fourth)-to-last distance that was not represented by a 0 distance

symbol. Similarly, distances that represent static dictionary words

(see Section 8.) are not pushed to the ring buffer of last distances.

If a special distance symbol resolves to a zero or negative value,

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the stream should be rejected as invalid.

If NDIRECT is greater than zero, then the next NDIRECT distance

symbols, from 16 to 15 + NDIRECT, represent distances from 1 to

NDIRECT. Neither the special distance symbols, nor the NDIRECT

direct distance symbols are followed by any extra bits.

Distance symbols 16 + NDIRECT and greater all have extra bits, where

the number of extra bits for a distance symbol "dcode" is given by

the following formula:

ndistbits = 1 + ((dcode - NDIRECT - 16) >> (NPOSTFIX + 1))

The maximum number of extra bits is 24, therefore the size of the

distance symbol alphabet is (16 + NDIRECT + (48 << NPOSTFIX)).

Given a distance symbol "dcode" (>= 16 + NDIRECT), and extra bits

"dextra", the backward distance is given by the following formula:

hcode = (dcode - NDIRECT - 16) >> NPOSTFIX

lcode = (dcode - NDIRECT - 16) & POSTFIX\_MASK

offset = ((2 + (hcode & 1)) << ndistbits) - 4

distance = ((offset + dextra) << NPOSTFIX) + lcode + NDIRECT + 1

5. Encoding of literal insertion lengths and copy lengths

As described in Section 2., the literal insertion lengths and

backward copy lengths are encoded using a single prefix code. This

section provides the details to this encoding.

Each <insertion length, copy length> pair in the compressed data part

of a meta-block is represented with the following triplet:

<insert-and-copy length code, insert extra bits, copy extra bits>

The insert-and-copy length code, the insert extra bits, and the copy

extra bits are encoded back-to-back, the insert-and-copy length code

is encoded using a prefix code over the insert-and-copy length code

alphabet, while the extra bits values are encoded as fixed-width

integer values. The number of insert and copy extra bits can be

0..24, and they are dependent on the insert-and-copy length code.

Some of the insert-and-copy length codes also express the fact that

the distance symbol of the distance in the same command is 0, i.e.

the distance component of the command is the same as that of the

previous command. In this case, the distance code and extra bits for

the distance are omitted from the compressed data stream.

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We describe the insert-and-copy length code alphabet in terms of the

(not directly used) insert length code and copy length code

alphabets. The symbols of the insert length code alphabet, along with

the number of insert extra bits, and the range of the insert lengths

are as follows:

Extra Extra Extra

Code Bits Lengths Code Bits Lengths Code Bits Lengths

---- ---- ------- ---- ---- ------- ---- ---- -------

0 0 0 8 2 10..13 16 6 130..193

1 0 1 9 2 14..17 17 7 194..321

2 0 2 10 3 18..25 18 8 322..577

3 0 3 11 3 26..33 19 9 578..1089

4 0 4 12 4 34..49 20 10 1090..2113

5 0 5 13 4 50..65 21 12 2114..6209

6 1 6,7 14 5 66..97 22 14 6210..22593

7 1 8,9 15 5 98..129 23 24 22594..16799809

The symbols of the copy length code alphabet, along with the number

of copy extra bits, and the range of copy lengths are as follows:

Extra Extra Extra

Code Bits Lengths Code Bits Lengths Code Bits Lengths

---- ---- ------- ---- ---- ------- ---- ---- -------

0 0 2 8 1 10,11 16 5 70..101

1 0 3 9 1 12,13 17 5 102..133

2 0 4 10 2 14..17 18 6 134..197

3 0 5 11 2 18..21 19 7 198..325

4 0 6 12 3 22..29 20 8 326..581

5 0 7 13 3 30..37 21 9 582..1093

6 0 8 14 4 38..53 22 10 1094..2117

7 0 9 15 4 54..69 23 24 2118..16779333

To convert an insert-and-copy length code to an insert length code

and a copy length code, the following table can be used:

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Insert

length Copy length code

code 0..7 8..15 16..23

+----------+----------+

| | |

0..7 | 0..63 | 64..127 | <--- distance symbol 0

| | |

+----------+----------+----------+

| | | |

0..7 | 128..191 | 192..255 | 384..447 |

| | | |

+----------+----------+----------+

| | | |

8..15 | 256..319 | 320..383 | 512..575 |

| | | |

+----------+----------+----------+

| | | |

16..23 | 448..511 | 576..639 | 640..703 |

| | | |

+----------+----------+----------+

First, look up the cell with the 64 value range containing the

insert-and-copy length code, this gives the insert length code and

the copy length code ranges, both 8 values long. The copy length

code within its range is determined by bits 0..2 (counted from the

lsb) of the insert-and-copy length code. The insert length code

within its range is determined by bits 3..5 (counted from the lsb) of

the insert-and-copy length code. Given the insert length and copy

length codes, the actual insert and copy lengths can be obtained by

reading the number of extra bits given by the tables above.

If the insert-and-copy length code is between 0 and 127, the distance

code of the command is set to zero (the last distance reused).

6. Encoding of block switch commands

As described in Section 2., a block-switch command is a pair <block

type, block count>. These are encoded in the compressed data part of

the meta-block, right before the start of each new block of a

particular block category.

Each block type in the compressed data is represented with a block

type code, encoded using a prefix code over the block type code

alphabet. A block type symbol 0 means that the new block type is the

same as the type of the previous block from the same block category,

i.e. the block type that preceded the current type, while a block

type symbol 1 means that the new block type equals the current block

type plus one. If the current block type is the maximal possible,

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then a block type symbol of 1 results in wrapping to a new block type

of 0. Block type symbols 2..257 represent block types 0..255

respectively. The previous and current block types are initialized to

1 and 0, respectively, at the end of the meta-block header.

Since the first block type of each block category is 0, the block

type of the first block-switch command is not encoded in the

compressed data. If a block category has only one block type, the

block count of the first block-switch command is also omitted from

the compressed data, otherwise it is encoded in the meta-block

header.

Since the end of the meta-block is detected by the number of

uncompressed bytes produced, the block counts for any of the three

categories need not count down to exactly zero at the end of the

meta-block.

The number of different block types in each block category, denoted

by NBLTYPESL, NBLTYPESI, and NBLTYPESD for literals, insert-and-copy

lengths, and distances, respectively, is encoded in the meta-block

header, and it must equal to the largest block type plus one in that

block category. In other words, the set of literal, insert-and-copy

length, and distance block types must be [0..NBLTYPESL-1],

[0..NBLTYPESI-1], and [0..NBLTYPESD-1], respectively. From this it

follows that the alphabet size of literal, insert-and-copy length,

and distance block type codes is NBLTYPESL + 2, NBLTYPESI + 2, and

NBLTYPESD + 2, respectively.

Each block count in the compressed data is represented with a pair

<block count code, extra bits>. The block count code and the extra

bits are encoded back-to-back, the block count code is encoded using

a prefix code over the block count code alphabet, while the extra

bits value is encoded as a fixed-width integer value. The number of

extra bits can be 0..24, and it is dependent on the block count code.

The symbols of the block count code alphabet, along with the number

of extra bits, and the range of block counts are as follows:

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Extra Extra Extra

Code Bits Lengths Code Bits Lengths Code Bits Lengths

---- ---- ------- ---- ---- ------- ---- ---- -------

0 2 1..4 9 4 65..80 18 7 369..496

1 2 5..8 10 4 81..96 19 8 497..752

2 2 9..12 11 4 97..112 20 9 753..1264

3 2 13..16 12 5 113..144 21 10 1265..2288

4 3 17..24 13 5 145..176 22 11 2289..4336

5 3 25..32 14 5 177..208 23 12 4337..8432

6 3 33..40 15 5 209..240 24 13 8433..16624

7 3 41..48 16 6 241..304 25 24 16625..16793840

8 4 49..64 17 6 305..368

The first block-switch command of each block category is special in

the sense that it is encoded in the meta-block header, and as

described earlier, the block type code is omitted since it is an

implicit zero.

7. Context modeling

As described in Section 2., the prefix tree used to encode a literal

byte or a distance code depends on the block type and the context ID.

This section specifies how to compute the context ID for a particular

literal and distance code, and how to encode the context map that

maps a <block type, context ID> pair to the index of a prefix code in

the array of literal and distance prefix codes.

7.1. Context modes and context ID lookup for literals

The context for encoding the next literal is defined by the last two

bytes in the stream (p1, p2, where p1 is the most recent byte),

regardless of whether these bytes are produced by uncompressed meta-

blocks, backward references, static dictionary references, or by

literal insertions. At the start of the stream p1 and p2 are

initialized to zero.

There are four methods, called context modes, to compute the Context

ID:

\* LSB6, where the Context ID is the value of six

least-significant bits of p1,

\* MSB6, where the Context ID is the value of six

most-significant bits of p1,

\* UTF8, where the Context ID is a complex function of p1, p2,

optimized for text compression, and

\* Signed, where Context ID is a complex function of p1, p2,

optimized for compressing sequences of signed integers.

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The Context ID for the UTF8 and Signed context modes is computed

using the following lookup tables Lut0, Lut1, and Lut2.

Lut0 :=

0, 0, 0, 0, 0, 0, 0, 0, 0, 4, 4, 0, 0, 4, 0, 0,

0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,

8, 12, 16, 12, 12, 20, 12, 16, 24, 28, 12, 12, 32, 12, 36, 12,

44, 44, 44, 44, 44, 44, 44, 44, 44, 44, 32, 32, 24, 40, 28, 12,

12, 48, 52, 52, 52, 48, 52, 52, 52, 48, 52, 52, 52, 52, 52, 48,

52, 52, 52, 52, 52, 48, 52, 52, 52, 52, 52, 24, 12, 28, 12, 12,

12, 56, 60, 60, 60, 56, 60, 60, 60, 56, 60, 60, 60, 60, 60, 56,

60, 60, 60, 60, 60, 56, 60, 60, 60, 60, 60, 24, 12, 28, 12, 0,

0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1,

0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1,

0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1,

0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1,

2, 3, 2, 3, 2, 3, 2, 3, 2, 3, 2, 3, 2, 3, 2, 3,

2, 3, 2, 3, 2, 3, 2, 3, 2, 3, 2, 3, 2, 3, 2, 3,

2, 3, 2, 3, 2, 3, 2, 3, 2, 3, 2, 3, 2, 3, 2, 3,

2, 3, 2, 3, 2, 3, 2, 3, 2, 3, 2, 3, 2, 3, 2, 3

Lut1 :=

0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,

0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,

0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,

2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 1, 1, 1, 1, 1, 1,

1, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2,

2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 1, 1, 1, 1, 1,

1, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3,

3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 1, 1, 1, 1, 0,

0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,

0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,

0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,

0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,

0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,

0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,

2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2,

2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2

Lut2 :=

0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,

2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2,

2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2,

2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2,

3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3,

3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3,

3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3,

3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3,

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4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4,

4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4,

4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4,

4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4,

5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5,

5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5,

5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5,

6, 6, 6, 6, 6, 6, 6, 6, 6, 6, 6, 6, 6, 6, 6, 7

The lengths and the CRC-32 check values (see Appendix C.) of each of

these tables as a sequence of bytes are as follows:

Table Length CRC-32

----- ------ ------

Lut0 256 0x8e91efb7

Lut1 256 0xd01a32f4

Lut2 256 0x0dd7a0d6

Given p1 is the last uncompressed byte and p2 is the second-to-last

uncompressed byte, the context IDs can be computed as follows:

For LSB6: Context ID = p1 & 0x3f

For MSB6: Context ID = p1 >> 2

For UTF8: Context ID = Lut0[p1] | Lut1[p2]

For Signed: Context ID = (Lut2[p1] << 3) | Lut2[p2]

From the lookup tables defined above and the operations to compute

the context IDs, we can see that context IDs for literals are in the

range of 0..63.

The context modes LSB6, MSB6, UTF8, and Signed are denoted by

integers 0, 1, 2, 3.

A context mode is defined for each literal block type and they are

stored in a consecutive array of bits in the meta-block header,

always two bits per block type.

7.2. Context ID for distances

The context for encoding a distance code is defined by the copy

length corresponding to the distance. The context IDs are 0, 1, 2,

and 3 for copy lengths 2, 3, 4, and more than 4, respectively.

7.3. Encoding of the context map

There are two context maps, one for literals and one for distances.

The size of the context map is 64 \* NBLTYPESL for literals, and 4 \*

NBLTYPESD for distances. Each value in the context map is an integer

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between 0 and 255, indicating the index of the prefix code to be used

when encoding the next literal or distance.

The context maps are two-dimensional matrices, encoded as one-

dimensional arrays:

CMAPL[0..(64 \* NBLTYPESL - 1)]

CMAPD[0..(4 \* NBLTYPESD - 1)]

The index of the prefix code for encoding a literal or distance code

with block type, BTYPE\_x, and context ID, CIDx, is:

index of literal prefix code = CMAPL[64 \* BTYPE\_L + CIDL]

index of distance prefix code = CMAPD[4 \* BTYPE\_D + CIDD]

The values of the context map are encoded with the combination of run

length encoding for zero values and prefix coding. Let RLEMAX denote

the number of run length codes and NTREES denote the maximum value in

the context map plus one. NTREES must equal the number of different

values in the context map, in other words, the different values in

the context map must be the [0..NTREES-1] interval. The alphabet of

the prefix code has the following RLEMAX + NTREES symbols:

0: value zero

1: repeat a zero 2 to 3 times, read 1 bit for repeat length

2: repeat a zero 4 to 7 times, read 2 bits for repeat length

...

RLEMAX: repeat a zero (1 << RLEMAX) to (1 << (RLEMAX+1))-1

times, read RLEMAX bits for repeat length

RLEMAX + 1: value 1

...

RLEMAX + NTREES - 1: value NTREES - 1

If RLEMAX = 0, the run length coding is not used, and the symbols of

the alphabet are directly the values in the context map. We can now

define the format of the context map (the same format is used for

literal and distance context maps):

1..5 bits: RLEMAX, 0 is encoded with one 0 bit, and values

1..16 are encoded with bit pattern xxxx1 (so 01001

is 5)

Prefix code with alphabet size NTREES + RLEMAX

Context map size values encoded with the above prefix code

and run length coding for zero values. If a run length

would result in more lengths in total than the size of

the context map, then the stream should be rejected as

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invalid.

1 bit: IMTF bit, if set, we do an inverse move-to-front

transform on the values in the context map to get

the prefix code indexes

Note that RLEMAX may be larger than the value necessary to represent

the longest sequence of zero values. Also, the NTREES value is

encoded right before the context map as described in Section 9.2.

We define the inverse move-to-front transform used in this

specification by the following C language function:

void InverseMoveToFrontTransform(uint8\_t\* v, int v\_len) {

uint8\_t mtf[256];

int i;

for (i = 0; i < 256; ++i) {

mtf[i] = (uint8\_t)i;

}

for (i = 0; i < v\_len; ++i) {

uint8\_t index = v[i];

uint8\_t value = mtf[index];

v[i] = value;

for (; index; --index) {

mtf[index] = mtf[index - 1];

}

mtf[0] = value;

}

}

Note that the inverse move-to-front transform will not produce values

outside the [0..NTREES-1] interval.

8. Static dictionary

At any given point during decoding the compressed data, a reference

to a duplicated string in the uncompressed data produced so far has a

maximum backward distance value, which is the minimum of the window

size and the number of uncompressed bytes produced. However, decoding

a distance from the compressed stream, as described in Section 4.,

can produce distances that are greater than this maximum allowed

value. In this case, the distance is treated as a reference to a word

in the static dictionary given in Appendix A. The copy length for a

static dictionary reference must be between 4 and 24. The static

dictionary has three parts:

\* DICT[0..DICTSIZE], an array of bytes

\* DOFFSET[0..24], an array of byte offset values for each length

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\* NDBITS[0..24], an array of bit-depth values for each length

The number of static dictionary words for a given length is:

NWORDS[length] = 0 (if length < 4)

NWORDS[length] = (1 << NDBITS[length]) (if length >= 4)

DOFFSET and DICTSIZE are defined by the following recursion:

DOFFSET[0] = 0

DOFFSET[length + 1] = DOFFSET[length] + length \* NWORDS[length]

DICTSIZE = DOFFSET[24] + 24 \* NWORDS[24]

The offset of a word within the DICT array for a given length and

index is:

offset(length, index) = DOFFSET[length] + index \* length

Each static dictionary word has 121 different forms, given by

applying a word transformation to a base word in the DICT array. The

list of word transformations is given in Appendix B. The static

dictionary word for a <length, distance> pair can be reconstructed as

follows:

word\_id = distance - (max allowed distance + 1)

index = word\_id % NWORDS[length]

base\_word = DICT[offset(length, index)..offset(length, index+1)-1]

transform\_id = word\_id >> NDBITS[length]

The string copied to the uncompressed stream is computed by applying

the transformation to the base dictionary word. If transform\_id is

greater than 120, or the length is smaller than 4 or greater than 24,

then the compressed stream should be rejected as invalid.

Each word transformation has the following form:

transform\_i(word) = prefix\_i + T\_i(word) + suffix\_i

where the \_i subscript denotes the transform\_id above. Each T\_i is

one of the following 21 elementary transforms:

Identity, FermentFirst, FermentAll,

OmitFirst1, ..., OmitFirst9, OmitLast1, ..., OmitLast9

The form of these elementary transforms is as follows:

Identity(word) = word

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FermentFirst(word) = see below

FermentAll(word) = see below

OmitFirstk(word) = the last (length(word) - k) bytes of word, or

empty string if length(word) < k

OmitLastk(word) = the first (length(word) - k) bytes of word, or

empty string if length(word) < k

We define the FermentFirst and FermentAll transforms used in this

specification by the following C language functions:

int Ferment(uint8\_t\* word, int word\_len, int pos) {

if (word[pos] < 192) {

if (word[pos] >= 97 and word[pos] <= 122) {

word[pos] = word[pos] ^ 32;

}

return 1;

} else if (word[pos] < 224) {

if (pos + 1 < word\_len) {

word[pos + 1] = word[pos + 1] ^ 32;

}

return 2;

} else {

if (pos + 2 < word\_len) {

word[pos + 2] = word[pos + 2] ^ 5;

}

return 3;

}

}

void FermentFirst(uint8\_t\* word, int word\_len) {

if (word\_len > 0) {

Ferment(word, word\_len, 0);

}

}

void FermentAll(uint8\_t\* word, int word\_len) {

int i = 0;

while (i < word\_len) {

i += Ferment(word, word\_len, i);

}

}

Appendix B. contains the list of transformations by specifying the

prefix, elementary transform and suffix components of each of them.

Note that the OmitFirst8 elementary transform is not used in the list

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of transformations. The strings in Appendix B. are in C string format

with respect to escape (backslash) characters.

The maximum number of additional bytes that a transform may add to a

base word is 13. Since the largest base word is 24 bytes long, a

buffer of 38 bytes is sufficient to store any transformed words

(counting a terminating zero byte).

9. Compressed data format

In this section we describe the format of the compressed data set in

terms of the format of the individual data items described in the

previous sections.

9.1. Format of the stream header

The stream header has only the following one field:

1..7 bits: WBITS, a value in the range 10..24, encoded with

the following variable length code (as it appears in

the compressed data, where the bits are parsed from

right to left):

Value Bit Pattern

----- -----------

10 0100001

11 0110001

12 1000001

13 1010001

14 1100001

15 1110001

16 0

17 0000001

18 0011

19 0101

20 0111

21 1001

22 1011

23 1101

24 1111

Note that bit pattern 0010001 is invalid and must not

be used.

The size of the sliding window, which is the maximum value of any

non-dictionary reference backward distance, is given by the following

formula:

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window size = (1 << WBITS) - 16

9.2. Format of the meta-block header

A compliant compressed data set has at least one meta-block. Each

meta-block contains a header with information about the uncompressed

length of the meta-block, and a bit signaling if the meta-block is

the last one. The format of the meta-block header is the following:

1 bit: ISLAST, set to 1 if this is the last meta-block

1 bit: ISLASTEMPTY, if set to 1, the meta-block is empty;

this field is only present if ISLAST bit is set -- if

it is 1, then the meta-block and the brotli stream ends

at that bit, with any remaining bits in the last byte

of the compressed stream filled with zeros (if the

fill bits are not zero, then the stream should be

rejected as invalid)

2 bits: MNIBBLES, # of nibbles to represent the uncompressed

length, encoded with the following fixed-length code:

Value Bit Pattern

----- -----------

0 11

4 00

5 01

6 10

If MNIBBLES is 0, the meta-block is empty, i.e. it does

not generate any uncompressed data. In this case, the

rest of the meta-block has the following format:

1 bit: reserved, must be zero

2 bits: MSKIPBYTES, # of bytes to represent metadata

length

MSKIPBYTES x 8 bits: MSKIPLEN - 1, where MSKIPLEN is

the number of metadata bytes; this field is

only present if MSKIPBYTES is positive,

otherwise MSKIPLEN is 0 (if MSKIPBYTES is

greater than 1, and the last byte is all

zeros, then the stream should be rejected

as invalid)

0..7 bits: fill bits until the next byte boundary,

must be all zeros

MSKIPLEN bytes of metadata, not part of the

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uncompressed data or the sliding window

MNIBBLES x 4 bits: MLEN - 1, where MLEN is the length

of the meta-block uncompressed data in bytes (if

MNIBBLES is greater than 4, and the last

nibble is all zeros, then the stream should be

rejected as invalid)

1 bit: ISUNCOMPRESSED, if set to 1, any bits of compressed

data up to the next byte boundary are ignored, and

the rest of the meta-block contains MLEN bytes of

literal data; this field is only present if the

ISLAST bit is not set (if the ignored bits are not

all zeros, the stream should be rejected as invalid)

1..11 bits: NBLTYPESL, # of literal block types, encoded with

the following variable length code (as it appears in

the compressed data, where the bits are parsed from

right to left, so 0110111 has the value 12):

Value Bit Pattern

----- -----------

1 0

2 0001

3..4 x0011

5..8 xx0101

9..16 xxx0111

17..32 xxxx1001

33..64 xxxxx1011

65..128 xxxxxx1101

129..256 xxxxxxx1111

Prefix code over the block type code alphabet for

literal block types, appears only if NBLTYPESL >= 2

Prefix code over the block count code alphabet for

literal block counts, appears only if NBLTYPESL >= 2

Block count code + extra bits for first literal

block count, appears only if NBLTYPESL >= 2

1..11 bits: NBLTYPESI, # of insert-and-copy block types, encoded

with the same variable length code as above

Prefix code over the block type code alphabet for

insert-and-copy block types, appears only if NBLTYPESI >= 2

Prefix code over the block count code alphabet for

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insert-and-copy block counts, appears only if NBLTYPESI >= 2

Block count code + extra bits for first insert-and-copy

block count, appears only if NBLTYPESI >= 2

1..11 bits: NBLTYPESD, # of distance block types, encoded

with the same variable length code as above

Prefix code over the block type code alphabet for

distance block types, appears only if NBLTYPESD >= 2

Prefix code over the block count code alphabet for

distance block counts, appears only if NBLTYPESD >= 2

Block count code + extra bits for first distance

block count, appears only if NBLTYPESD >= 2

2 bits: NPOSTFIX, parameter used in the distance coding

4 bits: four most-significant bits of NDIRECT, to get the

actual value of the parameter NDIRECT, left-shift

this four-bit number by NPOSTFIX bits

NBLTYPESL x 2 bits: context mode for each literal block type

1..11 bits: NTREESL, # of literal prefix trees, encoded

with the same variable length code as NBLTYPESL

Literal context map, encoded as described in Section 7.3.,

appears only if NTREESL >= 2, otherwise the context map

has only zero values

1..11 bits: NTREESD, # of distance prefix trees, encoded

with the same variable length code as NBLTYPESD

Distance context map, encoded as described in Section 7.3.,

appears only if NTREESD >= 2, otherwise the context map

has only zero values

NTREESL prefix codes for literals

NBLTYPESI prefix codes for insert-and-copy lengths

NTREESD prefix codes for distances

9.3. Format of the meta-block data

The compressed data part of a meta-block consists of a series of

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commands. Each command has the following format:

Block type code for next insert-and-copy block type, appears

only if NBLTYPESI >= 2 and the previous insert-and-copy

block count is zero

Block count code + extra bits for next insert-and-copy

block count, appears only if NBLTYPESI >= 2 and the

previous insert-and-copy block count is zero

Insert-and-copy length, encoded as in Section 5., using the

insert-and-copy length prefix code with the current

insert-and-copy block type index

Insert length number of literals, with the following format:

Block type code for next literal block type, appears

only if NBLTYPESL >= 2 and the previous literal

block count is zero

Block count code + extra bits for next literal

block count, appears only if NBLTYPESL >= 2 and the

previous literal block count is zero

Next byte of the uncompressed data, encoded with the

literal prefix code with the index determined by the

previous two bytes of the uncompressed data, the

current literal block type, and the context map, as

described in Section 7.3.

Block type code for next distance block type, appears

only if NBLTYPESD >= 2 and the previous distance

block count is zero

Block count code + extra bits for next distance

block count, appears only if NBLTYPESD >= 2 and the

previous distance block count is zero

Distance code, encoded as in Section 4., using the distance

prefix code with the current distance block type index,

appears only if the distance code is not an implicit 0,

as indicated by the insert-and-copy length code

The number of commands in the meta-block is such that the sum of the

uncompressed bytes produced (i.e. the number of literals inserted

plus the number of bytes copied from past data or generated from the

static dictionary) over all the commands gives the uncompressed

length, MLEN encoded in the meta-block header.

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If the total number of uncompressed bytes produced after the insert

part of the last command equals MLEN, then the copy length of the

last command is ignored and will not produce any uncompressed output.

In this case the copy length of the last command can have any value.

In any other case, if the number of literals to insert, the copy

length, or the resulting dictionary word length would cause MLEN to

be exceeded, then the stream should be rejected as invalid.

If the last command of the last non-empty meta-block does not end on

a byte boundary, the unused bits in the last byte must be zeros.

10. Decoding algorithm

The decoding algorithm that produces the uncompressed data is as

follows:

read window size

do

read ISLAST bit

if ISLAST

read ISLASTEMPTY bit

if ISLASTEMPTY

break from loop

read MNIBBLES

if MNIBBLES is zero

verify reserved bit is zero

read MSKIPLEN

skip any bits up to the next byte boundary

skip MSKIPLEN bytes

continue to the next meta-block

else

read MLEN

if not ISLAST

read ISUNCOMPRESSED bit

if ISUNCOMPRESSED

skip any bits up to the next byte boundary

copy MLEN bytes of compressed data as literals

continue to the next meta-block

loop for each three block categories (i = L, I, D)

read NBLTYPESi

if NBLTYPESi >= 2

read prefix code for block types, HTREE\_BTYPE\_i

read prefix code for block counts, HTREE\_BLEN\_i

read block count, BLEN\_i

set block type, BTYPE\_i to 0

initialize second-to-last and last block types to 0 and 1

else

set block type, BTYPE\_i to 0

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set block count, BLEN\_i to 16777216

read NPOSTFIX and NDIRECT

read array of literal context modes, CMODE[]

read NTREESL

if NTREESL >= 2

read literal context map, CMAPL[]

else

fill CMAPL[] with zeros

read NTREESD

if NTREESD >= 2

read distance context map, CMAPD[]

else

fill CMAPD[] with zeros

read array of literal prefix codes, HTREEL[]

read array of insert-and-copy length prefix codes, HTREEI[]

read array of distance prefix codes, HTREED[]

do

if BLEN\_I is zero

read block type using HTREE\_BTYPE\_I and set BTYPE\_I

save previous block type

read block count using HTREE\_BLEN\_I and set BLEN\_I

decrement BLEN\_I

read insert-and-copy length symbol using HTREEI[BTYPE\_I]

compute insert length, ILEN, and copy length, CLEN

loop for ILEN

if BLEN\_L is zero

read block type using HTREE\_BTYPE\_L and set BTYPE\_L

save previous block type

read block count using HTREE\_BLEN\_L and set BLEN\_L

decrement BLEN\_L

look up context mode CMODE[BTYPE\_L]

compute context ID, CIDL from last two uncompressed bytes

read literal using HTREEL[CMAPL[64\*BTYPE\_L + CIDL]]

write literal to uncompressed stream

if number of uncompressed bytes produced in the loop for

this meta-block is MLEN, then break from loop (in this

case the copy length is ignored and can have any value)

if distance code is implicit zero from insert-and-copy code

set backward distance to the last distance

else

if BLEN\_D is zero

read block type using HTREE\_BTYPE\_D and set BTYPE\_D

save previous block type

read block count using HTREE\_BLEN\_D and set BLEN\_D

decrement BLEN\_D

compute context ID, CIDD from CLEN

read distance code using HTREED[CMAPD[4\*BTYPE\_D + CIDD]]

compute distance by distance short code substitution

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if distance code is not zero,

and distance is not a static dictionary reference,

push distance to the ring buffer of last distances

if distance is less than the max allowed distance plus one

move backwards distance bytes in the uncompressed data,

and copy CLEN bytes from this position to

the uncompressed stream

else

look up the static dictionary word, transform the word as

directed, and copy the result to the uncompressed stream

while number of uncompressed bytes for this meta-block < MLEN

while not ISLAST

If the stream ends before the completion of the last meta-block, then

the stream should be rejected as invalid.

Note that a duplicated string reference may refer to a string in a

previous meta-block, i.e. the backward distance may cross one or more

meta-block boundaries. However a backward copy distance will not

refer past the beginning of the uncompressed stream or the window

size; any such distance is interpreted as a reference to a static

dictionary word. Also note that the referenced string may overlap the

current position, for example, if the last 2 bytes decoded have

values X and Y, a string reference with <length = 5, distance = 2>

adds X,Y,X,Y,X to the uncompressed stream.

11. Considerations for compressor implementations

Since the intent of this document is to define the brotli compressed

data format without reference to any particular compression

algorithm, the material in this section is not part of the definition

of the format, and a compressor need not follow it in order to be

compliant.

11.1. Trivial compressor

In this section we present a very simple algorithm that produces a

valid brotli stream representing an arbitrary sequence of

uncompressed bytes in the form of the following C++ language

function.

string BrotliCompressTrivial(const string& u) {

if (u.empty()) {

return string(1, 6);

}

int i;

string c;

c.append(1, 12);

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for (i = 0; i + 65535 < u.size(); i += 65536) {

c.append(1, 248);

c.append(1, 255);

c.append(1, 15);

c.append(&u[i], 65536);

}

if (i < u.size()) {

int r = u.size() - i - 1;

c.append(1, (r & 31) << 3);

c.append(1, r >> 5);

c.append(1, 8 + (r >> 13));

c.append(&u[i], r + 1);

}

c.append(1, 3);

return c;

}

Note that this simple algorithm does not actually compress data, that

is, the brotli representation will always be bigger than the

original, but it shows that every sequence of N uncompressed bytes

can be represented with a valid brotli stream that is not longer than

N + (3 \* (N >> 16) + 5) bytes.

11.2. Aligning compressed meta-blocks to byte boundaries

As described in Section 9., only those meta-blocks that immediately

follow an uncompressed meta-block or a metadata meta-block are

guaranteed to start on a byte boundary. In some applications, it

might be required that every non-metadata meta-block starts on a byte

boundary. This can be achieved by appending an empty metadata meta-

block after every non-metadata meta-block that does not end on a byte

boundary.

11.3. Creating self-contained parts within the compressed data

In some encoder implementations it might be required to make a

sequence of bytes within a brotli stream self-contained, that is,

such that they can be decompressed independently from previous parts

of the compressed data. This is a useful feature for three reasons.

First, if a large compressed file is damaged, it is possible to

recover some of the file after the damage. Second, it is useful when

doing differential transfer of compressed data. If a sequence of

uncompressed bytes is unchanged and compressed independently from

previous data, then the compressed representation may also be

unchanged and can therefore be transferred very cheaply. Third, if

sequences of uncompressed bytes are compressed independently, it

allows for parallel compression of these byte sequences within the

same file, in addition to parallel compression of multiple files.

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Given two sequences of uncompressed bytes, U0 and U1, we will now

describe how to create two sequences of compressed bytes, C0 and C1,

such that the concatenation of C0 and C1 is a valid brotli stream,

and that C0 and C1 (together with the first byte of C0 that contains

the window size) can be decompressed independently from each other to

U0 and U1.

When compressing the byte sequence U0 to produce C0, we can use any

compressor that works on the complete set of uncompressed bytes U0,

with the following two changes. First, the ISLAST bit of the last

meta-block of C0 must not be set. Second, C0 must end at a byte-

boundary, which can be ensured by appending an empty metadata meta-

block to it, as in Section 11.2.

When compressing the byte sequence U1 to produce C1, we can use any

compressor that starts a new meta-block at the beginning of U1 within

the U0+U1 input stream, with the following two changes. First,

backward distances in C1 must not refer to static dictionary words or

uncompressed bytes in U0. Even if a sequence of bytes in U1 would

match a static dictionary word, or a sequence of bytes that overlaps

U0, the compressor must represent this sequence of bytes with a

combination of literal insertions and backward references to bytes in

U1 instead. Second, the ring buffer of last four distances must be

replenished first with distances in C1 before using it to encode

other distances in C1. Note that both compressors producing C0 and C1

have to use the same window size, but the stream header is emitted

only by the compressor that produces C0.

Note that this method can be easily generalized to more than two

sequences of uncompressed bytes.

12. Security Considerations

As with any compressed file formats, decompressor implementations

should handle all compressed data byte sequences, not only those that

conform to this specification, where non-conformant compressed data

sequences should be rejected as invalid.

A possible attack against a system containing a decompressor

implementation (e.g. a web browser) is to exploit a buffer overflow

triggered by invalid compressed data. Therefore decompressor

implementations should perform bounds-checking for each memory access

that result from values decoded from the compressed stream and

derivatives therof.

Another possible attack against a system containing a decompressor

implementation is to provide it (either valid or invalid) compressed

data that can make the decompressor system's resource consumption

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(cpu, memory, or storage) to be disproportionately large compared to

the size of the compressed data. In addition to the size of the

compressed data, the amount of cpu, memory and storage required to

decompress a single compressed meta-block within a brotli stream is

controlled by the following two paramters: the size of the

uncompressed meta-block, which is encoded at the start of the

compressed meta-block, and the size of the sliding window, which is

encoded at the start of the brotli stream. Decompressor

implementations in systems where memory or storage is constrained

should perform a sanity-check on these two parameters. The

uncompressed meta-block size that was decoded from the compressed

stream should be compared against either a hard limit, given by the

system's constraints or some expectation about the uncompressed data,

or against a certain multiple of the size of the compressed data. If

the uncompressed meta-block size is determined to be too high, the

compressed data should be rejected. Likewise, when the complete

uncompressed stream is kept in the system containing the decompressor

implementation, the total uncompressed size of the stream should be

checked before decompressing each additional meta-block. If the size

of the sliding window that was decoded from the start of the

compressed stream is greater than a certain soft limit, then the

decompressor implementation should, at first, allocate a smaller

sliding window that fits the first uncompressed meta-block, and

afterwards, before decompressing each additional meta-block, it

should increase the size of the sliding window until the sliding

window size specified in the compressed data is reached.

Correspondingly, possible attacks against a system containing a

compressor implementation (e.g. a web server) are to exploit a buffer

overflow or cause disproportionately large resource consumption by

providing e.g. uncompressible data. As described in Section 11.1.,

an output buffer of

S(N) = N + (3 \* (N >> 16) + 5)

bytes is sufficient to hold a valid compressed brotli stream

representing an arbitrary sequence of N uncompressed bytes.

Therefore compressor implementations should allocate at least S(N)

bytes of output buffer before compressing N bytes of data with

unknown compressibility and should perform bounds-checking for each

write into this output buffer. If their output buffer is full,

compresor implementations should revert to the trivial compression

algorithm described in Section 11.1. The resourse consumption of a

compressor implementation for a particular input data depends mostly

on the algorithm used to find backward matches and on the algorithm

used to construct context maps and prefix codes and only to a lesser

extent on the input data itself. If the system containing a

compressor implementation is overloaded, a possible way to reduce

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resource usage is to switch to more simple algorithms for backward

reference search and prefix code construction, or to fall back to the

trivial compression algorithm described in Section 11.1.

A possible attack against a system that sends compressed data over an

encrypted channel is the following. An attacker who can repeatedly

mix arbitrary (attacker-supplied) data with secret data (passwords,

cookies) and observe the length of the ciphertext can potentially

reconstruct the secret data. To protect against this kind of attack,

applications should not mix sensitive data with non-sensitive,

potentially attacker-supplied data in the same compressed stream.

13. IANA Considerations

The "HTTP Content Coding Registry" has been updated with the

registration below:

+-------+-------------------------------------+------------+

| Name | Description | Reference |

+-------+-------------------------------------+------------+

| br | Brotli Compressed Data Format | RFCXXXX |

+-------+-------------------------------------+------------+

14. Informative References

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15. Source code

Source code for a C language implementation of a brotli compliant

decompressor and a C++ language implementation of a compressor is

available in the brotli open-source project:

https://github.com/google/brotli

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16. Acknowledgments

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and suggesting improvements to the format and the text of the

specification.

Appendix A. Static dictionary data

The hexadecimal form of the DICT array is the following, where the

length is 122,784 bytes and the CRC-32 of the byte sequence is

0x5136cb04.

74696d65646f776e6c6966656c6566746261636b636f64656461746173686f77

6f6e6c7973697465636974796f70656e6a7573746c696b6566726565776f726b

74657874796561726f766572626f64796c6f7665666f726d626f6f6b706c6179

6c6976656c696e6568656c70686f6d65736964656d6f7265776f72646c6f6e67

7468656d7669657766696e64706167656461797366756c6c686561647465726d

656163686172656166726f6d747275656d61726b61626c6575706f6e68696768

646174656c616e646e6577736576656e6e65787463617365626f7468706f7374

757365646d61646568616e6468657265776861746e616d654c696e6b626c6f67

73697a656261736568656c646d616b656d61696e757365722729202b686f6c64

656e6473776974684e65777372656164776572657369676e74616b6568617665

67616d657365656e63616c6c7061746877656c6c706c75736d656e7566696c6d

706172746a6f696e746869736c697374676f6f646e6565647761797377657374

6a6f62736d696e64616c736f6c6f676f72696368757365736c6173747465616d

61726d79666f6f646b696e6777696c6c65617374776172646265737466697265

506167656b6e6f77617761792e706e676d6f76657468616e6c6f616467697665

73656c666e6f74656d756368666565646d616e79726f636b69636f6e6f6e6365

6c6f6f6b6869646564696564486f6d6572756c65686f7374616a6178696e666f

636c75626c6177736c65737368616c66736f6d65737563687a6f6e6531303025

6f6e65736361726554696d6572616365626c7565666f75727765656b66616365

686f706567617665686172646c6f73747768656e7061726b6b65707470617373

73686970726f6f6d48544d4c706c616e54797065646f6e65736176656b656570

666c61676c696e6b736f6c6466697665746f6f6b72617465746f776e6a756d70

746875736461726b6361726466696c6566656172737461796b696c6c74686174

66616c6c6175746f657665722e636f6d74616c6b73686f70766f746564656570

6d6f6465726573747475726e626f726e62616e6466656c6c726f736575726c28

736b696e726f6c65636f6d6561637473616765736d656574676f6c642e6a7067

6974656d7661727966656c747468656e73656e6464726f7056696577636f7079

312e30223c2f613e73746f70656c73656c696573746f75727061636b2e676966

706173746373733f677261796d65616e2667743b7269646573686f746c617465

73616964726f6164766172206665656c6a6f686e7269636b706f727466617374

2755412d646561643c2f623e706f6f7262696c6c74797065552e532e776f6f64

6d7573743270783b496e666f72616e6b7769646577616e7477616c6c6c656164

5b305d3b7061756c776176657375726524282723776169746d61737361726d73

676f65736761696e6c616e6770616964212d2d206c6f636b756e6974726f6f74

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77616c6b6669726d77696665786d6c22736f6e6774657374323070786b696e64

726f7773746f6f6c666f6e746d61696c73616665737461726d617073636f7265

7261696e666c6f77626162797370616e736179733470783b3670783b61727473

666f6f747265616c77696b696865617473746570747269706f72672f6c616b65

7765616b746f6c64466f726d6361737466616e7362616e6b7665727972756e73

6a756c797461736b3170783b676f616c67726577736c6f776564676569643d22

736574733570783b2e6a733f3430707869662028736f6f6e736561746e6f6e65

747562657a65726f73656e747265656466616374696e746f676966746861726d

3138707863616d6568696c6c626f6c647a6f6f6d766f69646561737972696e67

66696c6c7065616b696e6974636f73743370783b6a61636b7461677362697473

726f6c6c656469746b6e65776e6561723c212d2d67726f774a534f4e64757479

4e616d6573616c65796f75206c6f74737061696e6a617a7a636f6c6465796573

666973687777772e7269736b7461627370726576313070787269736532357078

426c756564696e673330302c62616c6c666f72646561726e77696c64626f782e

666169726c61636b76657273706169726a756e6574656368696628217069636b

6576696c242822237761726d6c6f7264646f657370756c6c2c30303069646561

647261776875676573706f7466756e646275726e6872656663656c6c6b657973

7469636b686f75726c6f73736675656c31327078737569746465616c52535322

6167656467726579474554226561736561696d736769726c616964733870783b

6e617679677269647469707323393939776172736c61647963617273293b207d

7068703f68656c6c74616c6c77686f6d7a683ae52a2f0d0a2031303068616c6c

2e0a0a413770783b70757368636861743070783b637265772a2f3c2f68617368

37357078666c6174726172652026262074656c6c63616d706f6e746f6c616964

6d697373736b697074656e7466696e656d616c6567657473706c6f743430302c

0d0a0d0a636f6f6c666565742e7068703c62723e657269636d6f737467756964

62656c6c64657363686169726d61746861746f6d2f696d67262338326c75636b

63656e743030303b74696e79676f6e6568746d6c73656c6c6472756746524545

6e6f64656e69636b3f69643d6c6f73656e756c6c7661737477696e6452535320

7765617272656c796265656e73616d6564756b656e6173616361706577697368

67756c665432333a68697473736c6f74676174656b69636b626c757274686579

313570782727293b293b223e6d73696577696e7362697264736f727462657461

7365656b5431383a6f726473747265656d616c6c363070786661726de2809973

626f79735b305d2e27293b22504f5354626561726b696473293b7d7d6d617279

74656e6428554b29717561647a683ae62d73697a2d2d2d2d70726f7027293b0d

6c6966745431393a76696365616e6479646562743e525353706f6f6c6e65636b

626c6f775431363a646f6f726576616c5431373a6c6574736661696c6f72616c

706f6c6c6e6f7661636f6c7367656e6520e28094736f6674726f6d6574696c6c

726f73733c68333e706f75726661646570696e6b3c74723e6d696e69297c2128

6d696e657a683ae862617273686561723030293b6d696c6b202d2d3e69726f6e

667265646469736b77656e74736f696c707574732f6a732f686f6c795432323a

4953424e5432303a6164616d736565733c68323e6a736f6e272c2027636f6e74

5432313a205253536c6f6f70617369616d6f6f6e3c2f703e736f756c4c494e45

666f7274636172745431343a3c68313e38307078212d2d3c3970783b5430343a

6d696b653a34365a6e696365696e6368596f726b726963657a683ae42729293b

707572656d61676570617261746f6e65626f6e643a33375a5f6f665f275d293b

3030302c7a683ae774616e6b79617264626f776c627573683a35365a4a617661

333070780a7c7d0a254333253a33345a6a656666455850496361736876697361

676f6c66736e6f777a683ae9717565722e6373737369636b6d6561746d696e2e

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62696e6464656c6c686972657069637372656e743a33365a485454502d323031

666f746f776f6c66454e442078626f783a35345a424f44596469636b3b0a7d0a

657869743a33355a7661727362656174277d293b646965743939393b616e6e65

7d7d3c2f5b695d2e4c616e676b6dc2b277697265746f7973616464737365616c

616c65783b0a097d6563686f6e696e652e6f726730303529746f6e796a657773

73616e646c656773726f6f66303030292032303077696e6567656172646f6773

626f6f74676172796375747374796c6574656d7074696f6e2e786d6c636f636b

67616e672428272e3530707850682e446d697363616c616e6c6f616e6465736b

6d696c657279616e756e697864697363293b7d0a64757374636c6970292e0a0a

373070782d32303044564473375d3e3c7461706564656d6f692b2b2977616765

6575726f7068696c6f707473686f6c65464151736173696e2d3236546c616273

7065747355524c2062756c6b636f6f6b3b7d0d0a484541445b305d2961626272

6a75616e283139386c6573687477696e3c2f693e736f6e79677579736675636b

706970657c2d0a21303032296e646f775b315d3b5b5d3b0a4c6f672073616c74

0d0a090962616e677472696d62617468297b0d0a303070780a7d293b6b6f3aec

6665657361643e0d733a2f2f205b5d3b746f6c6c706c756728297b0a7b0d0a20

2e6a7327323030706475616c626f61742e4a5047293b0a7d71756f74293b0a0a

27293b0a0d0a7d0d323031343230313532303136323031373230313832303139

3230323032303231323032323230323332303234323032353230323632303237

3230323832303239323033303230333132303332323033333230333432303335

3230333632303337323031333230313232303131323031303230303932303038

3230303732303036323030353230303432303033323030323230303132303030

3139393931393938313939373139393631393935313939343139393331393932

3139393131393930313938393139383831393837313938363139383531393834

3139383331393832313938313139383031393739313937383139373731393736

3139373531393734313937333139373231393731313937303139363931393638

3139363731393636313936353139363431393633313936323139363131393630

3139353931393538313935373139353631393535313935343139353331393532

31393531313935303130303031303234313339343030303039393939636f6d6f

6dc3a17365737465657374617065726f746f646f686163656361646161c3b16f

6269656e64c3ad616173c3ad766964616361736f6f74726f666f726f736f6c6f

6f7472616375616c64696a6f7369646f6772616e7469706f74656d6164656265

616c676f7175c3a96573746f6e61646174726573706f636f6361736162616a6f

746f646173696e6f6167756170756573756e6f73616e7465646963656c756973

656c6c616d61796f7a6f6e61616d6f727069736f6f627261636c6963656c6c6f

64696f73686f726163617369d0b7d0b0d0bdd0b0d0bed0bcd180d0b0d180d183

d182d0b0d0bdd0b5d0bfd0bed0bed182d0b8d0b7d0bdd0bed0b4d0bed182d0be

d0b6d0b5d0bed0bdd0b8d185d09dd0b0d0b5d0b5d0b1d18bd0bcd18bd092d18b

d181d0bed0b2d18bd0b2d0bed09dd0bed0bed0b1d09fd0bed0bbd0b8d0bdd0b8

d0a0d0a4d09dd0b5d09cd18bd182d18bd09ed0bdd0b8d0bcd0b4d0b0d097d0b0

d094d0b0d09dd183d09ed0b1d182d0b5d098d0b7d0b5d0b9d0bdd183d0bcd0bc

d0a2d18bd183d0b6d981d98ad8a3d986d985d8a7d985d8b9d983d984d8a3d988

d8b1d8afd98ad8a7d981d989d987d988d984d985d984d983d8a7d988d984d987

d8a8d8b3d8a7d984d8a5d986d987d98ad8a3d98ad982d8afd987d984d8abd985

d8a8d987d984d988d984d98ad8a8d984d8a7d98ad8a8d983d8b4d98ad8a7d985

d8a3d985d986d8aad8a8d98ad984d986d8add8a8d987d985d985d8b4d988d8b4

6669727374766964656f6c69676874776f726c646d656469617768697465636c

6f7365626c61636b7269676874736d616c6c626f6f6b73706c6163656d757369

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3e3c2f6469763e3c64697620636c6173733d3c2f613e3c2f6c693e0a3c6c6920

636c6173733d226373732220747970653d22746578742f63737322203c666f72

6d20616374696f6e3d22687474703a2f2f78742f6373732220687265663d2268

7474703a2f2f6c696e6b2072656c3d22616c7465726e61746522200d0a3c7363

7269707420747970653d22746578742f206f6e636c69636b3d226a6176617363

726970743a286e65772044617465292e67657454696d6528297d686569676874

3d2231222077696474683d2231222050656f706c6527732052657075626c6963

206f6620203c6120687265663d22687474703a2f2f7777772e746578742d6465

636f726174696f6e3a756e64657274686520626567696e6e696e67206f662074

6865203c2f6469763e0a3c2f6469763e0a3c2f6469763e0a65737461626c6973

686d656e74206f6620746865203c2f6469763e3c2f6469763e3c2f6469763e3c

2f642376696577706f72747b6d696e2d6865696768743a0a3c73637269707420

7372633d22687474703a2f2f6f7074696f6e3e3c6f7074696f6e2076616c7565

3d6f6674656e20726566657272656420746f206173202f6f7074696f6e3e0a3c

6f7074696f6e2076616c753c21444f43545950452068746d6c3e0a3c212d2d5b

496e7465726e6174696f6e616c20416972706f72743e0a3c6120687265663d22

687474703a2f2f7777773c2f613e3c6120687265663d22687474703a2f2f77e0

b8a0e0b8b2e0b8a9e0b8b2e0b984e0b897e0b8a2e183a5e18390e183a0e18397

e183a3e1839ae18398e6ada3e9ab94e4b8ade696872028e7b981e9ab9429e0a4

a8e0a4bfe0a4b0e0a58de0a4a6e0a587e0a4b6e0a4a1e0a4bee0a489e0a4a8e0

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a4b2e0a58be0a4a1e0a495e0a58de0a4b7e0a587e0a4a4e0a58de0a4b0e0a49c

e0a4bee0a4a8e0a495e0a4bee0a4b0e0a580e0a4b8e0a482e0a4ace0a482e0a4

a7e0a4bfe0a4a4e0a4b8e0a58de0a4a5e0a4bee0a4aae0a4a8e0a4bee0a4b8e0

a58de0a4b5e0a580e0a495e0a4bee0a4b0e0a4b8e0a482e0a4b8e0a58de0a495

e0a4b0e0a4a3e0a4b8e0a4bee0a4aee0a497e0a58de0a4b0e0a580e0a49ae0a4

bfe0a49fe0a58de0a4a0e0a58be0a482e0a4b5e0a4bfe0a49ce0a58de0a49ee0

a4bee0a4a8e0a485e0a4aee0a587e0a4b0e0a4bfe0a495e0a4bee0a4b5e0a4bf

e0a4ade0a4bfe0a4a8e0a58de0a4a8e0a497e0a4bee0a4a1e0a4bfe0a4afe0a4

bee0a481e0a495e0a58de0a4afe0a58be0a482e0a495e0a4bfe0a4b8e0a581e0

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6f636174696f6e2e70726f742e676574456c656d656e747342795461674e616d

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747970653d22746578742f637373223e747970653d22746578742f6373732220

687265663d2277332e6f72672f313939392f7868746d6c2220786d6c74797065

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782d69636f6e22202f3e63656c6c70616464696e673d2230222063656c6c7370

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6c693e3c6120687265663d22222077696474683d223122206865696768743d22

3122223e3c6120687265663d22687474703a2f2f7777772e7374796c653d2264

6973706c61793a6e6f6e653b223e616c7465726e6174652220747970653d2261

70706c692d2f2f5733432f2f445444205848544d4c20312e3020656c6c737061

63696e673d2230222063656c6c70616420747970653d2268696464656e222076

616c75653d222f613e266e6273703b3c7370616e20726f6c653d22730a3c696e

70757420747970653d2268696464656e22206c616e67756167653d224a617661

536372697074222020646f63756d656e742e676574456c656d656e747342673d

2230222063656c6c73706163696e673d223022207970653d22746578742f6373

7322206d656469613d22747970653d27746578742f6a61766173637269707427

776974682074686520657863657074696f6e206f66207970653d22746578742f

637373222072656c3d227374206865696768743d2231222077696474683d2231

22203d272b656e636f6465555249436f6d706f6e656e74283c6c696e6b207265

6c3d22616c7465726e61746522200a626f64792c2074722c20696e7075742c20

746578746d657461206e616d653d22726f626f74732220636f6e6d6574686f64

3d22706f73742220616374696f6e3d223e0a3c6120687265663d22687474703a

2f2f7777772e637373222072656c3d227374796c65736865657422203c2f6469

763e3c2f6469763e3c64697620636c6173736c616e67756167653d226a617661

736372697074223e617269612d68696464656e3d2274727565223ec2b73c7269

70742220747970653d22746578742f6a617661736c3d303b7d2928293b0a2866

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756e6374696f6e28297b6261636b67726f756e642d696d6167653a2075726c28

2f613e3c2f6c693e3c6c693e3c6120687265663d226809093c6c693e3c612068

7265663d22687474703a2f2f61746f722220617269612d68696464656e3d2274

72753e203c6120687265663d22687474703a2f2f7777772e6c616e6775616765

3d226a61766173637269707422202f6f7074696f6e3e0a3c6f7074696f6e2076

616c75652f6469763e3c2f6469763e3c64697620636c6173733d7261746f7222

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54696d652829706f7274756775c3aa732028646f2042726173696c29d0bed180

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d0bed181d182d18cd0bed0b1d180d0b0d0b7d0bed0b2d0b0d0bdd0b8d18fd180

d0b5d0b3d0b8d181d182d180d0b0d186d0b8d0b8d0b2d0bed0b7d0bcd0bed0b6

d0bdd0bed181d182d0b8d0bed0b1d18fd0b7d0b0d182d0b5d0bbd18cd0bdd0b0

3c21444f43545950452068746d6c205055424c494320226e742d547970652220

636f6e74656e743d22746578742f3c6d65746120687474702d65717569763d22

436f6e746572616e736974696f6e616c2f2f454e222022687474703a3c68746d

6c20786d6c6e733d22687474703a2f2f7777772d2f2f5733432f2f4454442058

48544d4c20312e3020544454442f7868746d6c312d7472616e736974696f6e61

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78742f6a617661736372697074273b3c6d657461206e616d653d226465736372

697074696f6e706172656e744e6f64652e696e736572744265666f72653c696e

70757420747970653d2268696464656e22206e616a732220747970653d227465

78742f6a6176617363726928646f63756d656e74292e72656164792866756e63

746973637269707420747970653d22746578742f6a61766173696d6167652220

636f6e74656e743d22687474703a2f2f55412d436f6d70617469626c65222063

6f6e74656e743d746d6c3b20636861727365743d7574662d3822202f3e0a6c69

6e6b2072656c3d2273686f72746375742069636f6e3c6c696e6b2072656c3d22

7374796c65736865657422203c2f7363726970743e0a3c736372697074207479

70653d3d20646f63756d656e742e637265617465456c656d656e3c6120746172

6765743d225f626c616e6b2220687265663d20646f63756d656e742e67657445

6c656d656e747342696e70757420747970653d227465787422206e616d653d61

2e74797065203d2027746578742f6a617661736372696e70757420747970653d

2268696464656e22206e616d6568746d6c3b20636861727365743d7574662d38

22202f3e647464223e0a3c68746d6c20786d6c6e733d22687474702d2f2f5733

432f2f4454442048544d4c20342e30312054656e747342795461674e616d6528

277363726970742729696e70757420747970653d2268696464656e22206e616d

3c73637269707420747970653d22746578742f6a6176617322207374796c653d

22646973706c61793a6e6f6e653b223e646f63756d656e742e676574456c656d

656e7442794964283d646f63756d656e742e637265617465456c656d656e7428

2720747970653d27746578742f6a61766173637269707427696e707574207479

70653d227465787422206e616d653d22642e676574456c656d656e7473427954

61674e616d6528736e6963616c2220687265663d22687474703a2f2f7777772e

432f2f4454442048544d4c20342e3031205472616e7369743c7374796c652074

7970653d22746578742f637373223e0a0a3c7374796c6520747970653d227465

78742f637373223e696f6e616c2e647464223e0a3c68746d6c20786d6c6e733d

687474702d65717569763d22436f6e74656e742d5479706564696e673d223022

2063656c6c73706163696e673d22302268746d6c3b20636861727365743d7574

662d3822202f3e0a207374796c653d22646973706c61793a6e6f6e653b223e3c

3c6c693e3c6120687265663d22687474703a2f2f7777772e20747970653d2774

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6578742f6a617661736372697074273ed0b4d0b5d18fd182d0b5d0bbd18cd0bd

d0bed181d182d0b8d181d0bed0bed182d0b2d0b5d182d181d182d0b2d0b8d0b8

d0bfd180d0bed0b8d0b7d0b2d0bed0b4d181d182d0b2d0b0d0b1d0b5d0b7d0be

d0bfd0b0d181d0bdd0bed181d182d0b8e0a4aae0a581e0a4b8e0a58de0a4a4e0

a4bfe0a495e0a4bee0a495e0a4bee0a482e0a497e0a58de0a4b0e0a587e0a4b8

e0a489e0a4a8e0a58de0a4b9e0a58be0a482e0a4a8e0a587e0a4b5e0a4bfe0a4

a7e0a4bee0a4a8e0a4b8e0a4ade0a4bee0a4abe0a4bfe0a495e0a58de0a4b8e0

a4bfe0a482e0a497e0a4b8e0a581e0a4b0e0a495e0a58de0a4b7e0a4bfe0a4a4

e0a495e0a589e0a4aae0a580e0a4b0e0a4bee0a487e0a49fe0a4b5e0a4bfe0a4

9ce0a58de0a49ee0a4bee0a4aae0a4a8e0a495e0a4bee0a4b0e0a58de0a4b0e0

a4b5e0a4bee0a488e0a4b8e0a495e0a58de0a4b0e0a4bfe0a4afe0a4a4e0a4be

The number of words for each length is given by the following

bit-depth array:

NDBITS := 0, 0, 0, 0, 10, 10, 11, 11, 10, 10,

10, 10, 10, 9, 9, 8, 7, 7, 8, 7,

7, 6, 6, 5, 5

Appendix B. List of word transformations

The string literals are in C format, with respect to the use of

backslash escape characters.

In order to generate a length and check value, the transforms can be

converted to a series of bytes, where each transform is the prefix

sequence of bytes plus a terminating zero byte, a single byte value

identifying the transform, and the suffix sequence of bytes plus a

terminating zero. The value for the transforms are 0 for Identity, 1 for

FermentFirst, 2 for FermentAll, 3 to 11 for OmitFirst1 to OmitFirst9,

and 12 to 20 for OmitLast1 to OmitLast9. The byte sequences that

represent the 121 transforms are then concatenated to a single sequence

of bytes. The length of that sequence is 648 bytes, and the CRC-32 is

0x3d965f81.

ID Prefix Transform Suffix

-- ------ --------- ------

0 "" Identity ""

1 "" Identity " "

2 " " Identity " "

3 "" OmitFirst1 ""

4 "" FermentFirst " "

5 "" Identity " the "

6 " " Identity ""

7 "s " Identity " "

8 "" Identity " of "

9 "" FermentFirst ""

10 "" Identity " and "

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11 "" OmitFirst2 ""

12 "" OmitLast1 ""

13 ", " Identity " "

14 "" Identity ", "

15 " " FermentFirst " "

16 "" Identity " in "

17 "" Identity " to "

18 "e " Identity " "

19 "" Identity "\""

20 "" Identity "."

21 "" Identity "\">"

22 "" Identity "\n"

23 "" OmitLast3 ""

24 "" Identity "]"

25 "" Identity " for "

26 "" OmitFirst3 ""

27 "" OmitLast2 ""

28 "" Identity " a "

29 "" Identity " that "

30 " " FermentFirst ""

31 "" Identity ". "

32 "." Identity ""

33 " " Identity ", "

34 "" OmitFirst4 ""

35 "" Identity " with "

36 "" Identity "'"

37 "" Identity " from "

38 "" Identity " by "

39 "" OmitFirst5 ""

40 "" OmitFirst6 ""

41 " the " Identity ""

42 "" OmitLast4 ""

43 "" Identity ". The "

44 "" FermentAll ""

45 "" Identity " on "

46 "" Identity " as "

47 "" Identity " is "

48 "" OmitLast7 ""

49 "" OmitLast1 "ing "

50 "" Identity "\n\t"

51 "" Identity ":"

52 " " Identity ". "

53 "" Identity "ed "

54 "" OmitFirst9 ""

55 "" OmitFirst7 ""

56 "" OmitLast6 ""

57 "" Identity "("

58 "" FermentFirst ", "

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59 "" OmitLast8 ""

60 "" Identity " at "

61 "" Identity "ly "

62 " the " Identity " of "

63 "" OmitLast5 ""

64 "" OmitLast9 ""

65 " " FermentFirst ", "

66 "" FermentFirst "\""

67 "." Identity "("

68 "" FermentAll " "

69 "" FermentFirst "\">"

70 "" Identity "=\""

71 " " Identity "."

72 ".com/" Identity ""

73 " the " Identity " of the "

74 "" FermentFirst "'"

75 "" Identity ". This "

76 "" Identity ","

77 "." Identity " "

78 "" FermentFirst "("

79 "" FermentFirst "."

80 "" Identity " not "

81 " " Identity "=\""

82 "" Identity "er "

83 " " FermentAll " "

84 "" Identity "al "

85 " " FermentAll ""

86 "" Identity "='"

87 "" FermentAll "\""

88 "" FermentFirst ". "

89 " " Identity "("

90 "" Identity "ful "

91 " " FermentFirst ". "

92 "" Identity "ive "

93 "" Identity "less "

94 "" FermentAll "'"

95 "" Identity "est "

96 " " FermentFirst "."

97 "" FermentAll "\">"

98 " " Identity "='"

99 "" FermentFirst ","

100 "" Identity "ize "

101 "" FermentAll "."

102 "\xc2\xa0" Identity ""

103 " " Identity ","

104 "" FermentFirst "=\""

105 "" FermentAll "=\""

106 "" Identity "ous "

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107 "" FermentAll ", "

108 "" FermentFirst "='"

109 " " FermentFirst ","

110 " " FermentAll "=\""

111 " " FermentAll ", "

112 "" FermentAll ","

113 "" FermentAll "("

114 "" FermentAll ". "

115 " " FermentAll "."

116 "" FermentAll "='"

117 " " FermentAll ". "

118 " " FermentFirst "=\""

119 " " FermentAll "='"

120 " " FermentFirst "='"

Appendix C. Computing CRC-32 check values

For the purpose of this specification, we define the CRC-32 check value

of a byte sequence with the following C language function:

uint32\_t CRC32(const uint8\_t\* v, const int len) {

const uint32\_t poly = 0xedb88320UL;

uint32\_t crc, c;

int i, k;

crc = 0xffffffffUL;

for (i = 0; i < len; ++i) {

c = (crc ^ v[i]) & 0xff;

for (k = 0; k < 8; k++) c = c & 1 ? poly ^ (c >> 1) : c >> 1;

crc = c ^ (crc >> 8);

}

return crc ^ 0xffffffffUL;

}

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