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FFV1 Video Coding Format Versions 0, 1, and 3

Abstract

This document defines FFV1, a lossless, intra-frame video encoding format. FFV1 is designed to efficiently compress video data in a variety of pixel formats. Compared to uncompressed video, FFV1 offers storage compression, frame fixity, and self-description, which makes FFV1 useful as a preservation or intermediate video format.

Status of This Memo

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1. Introduction

This document describes FFV1, a lossless video encoding format. The design of FFV1 considers the storage of image characteristics, data fixity, and the optimized use of encoding time and storage requirements. FFV1 is designed to support a wide range of lossless video applications such as long-term audiovisual preservation, scientific imaging, screen recording, and other video encoding scenarios that seek to avoid the generational loss of lossy video encodings.

This document defines versions 0, 1, and 3 of FFV1. The distinctions of the versions are provided throughout the document, but in summary:

- Version 0 of FFV1 was the original implementation of FFV1 and was flagged as stable on April 14, 2006 [FFV1_V0].
- Version 1 of FFV1 adds support of more video bit depths and was flagged as stable on April 24, 2009 [FFV1_V1].
- Version 2 of FFV1 only existed in experimental form and is not described by this document, but it is available as a LyX file at <https://github.com/FFmpeg/FFV1/blob/8ad772b6d61c3dd8b0171979a2cd9f11924d5532/ffv1.lyx>.
- Version 3 of FFV1 adds several features such as increased description of the characteristics of the encoding images and embedded Cyclic Redundancy Check (CRC) data to support fixity verification of the encoding. Version 3 was flagged as stable on August 17, 2013 [FFV1_V3].

This document assumes familiarity with mathematical and coding concepts such as Range encoding [Range-Encoding] and YCbCr color spaces [YCbCr].

This specification describes the valid bitstream and how to decode it. Nonconformant bitstreams and the nonconformant handling of bitstreams are outside this specification. A decoder can perform any action that it deems appropriate for an invalid bitstream: reject the bitstream, attempt to perform error concealment, or re-download or use a redundant copy of the invalid part.

2. Notation and Conventions

The key words "**MUST**", "**MUST NOT**", "**REQUIRED**", "**SHALL**", "**SHALL NOT**", "**SHOULD**", "**SHOULD NOT**", "**RECOMMENDED**", "**NOT RECOMMENDED**", "**MAY**", and "**OPTIONAL**" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

2.1. Definitions

FFV1: The chosen name of this video encoding format, which is the short version of "FF Video 1". The letters "FF" come from "FFmpeg", which is the name of the reference decoder whose first letters originally meant "Fast Forward".

Container: A format that encapsulates Frames (see Section 4.4) and (when required) a `Configuration Record` into a bitstream.

Sample: The smallest addressable representation of a color component or a luma component in a Frame. Examples of Sample are Luma (Y), Blue-difference Chroma (Cb), Red-difference Chroma (Cr), Transparency, Red, Green, and Blue.

Symbol: A value stored in the bitstream, which is defined and decoded through one of the methods described in Table 4.

Line: A discrete component of a static image composed of Samples that represent a specific quantification of Samples of that image.

Plane: A discrete component of a static image composed of Lines that represent a specific quantification of Lines of that image.

Pixel: The smallest addressable representation of a color in a Frame. It is composed of one or more Samples.

MSB: Most Significant Bit, the bit that can cause the largest change in magnitude of the symbol.

VLC: Variable Length Code, a code that maps source symbols to a variable number of bits.

RGB: A reference to the method of storing the value of a pixel by using three numeric values that represent Red, Green, and Blue.

YCbCr: A reference to the method of storing the value of a pixel by using three numeric values that represent the luma of the pixel (Y) and the chroma of the pixel (Cb and Cr). The term YCbCr is used for historical reasons and currently references any color space relying on one luma Sample and two chroma Samples, e.g., YCbCr (luma, blue-difference chroma, red-difference chroma), YCgCo, or ICtCp (intensity, blue-yellow, red-green).

2.2. Conventions

2.2.1. Pseudocode

The FFV1 bitstream is described in this document using pseudocode. Note that the pseudocode is used to illustrate the structure of FFV1 and is not intended to specify any particular implementation. The pseudocode used is based upon the C programming language [ISO.9899.2018] and uses its `if/else`, `while`, and `for` keywords as well as functions defined within this document.

In some instances, pseudocode is presented in a two-column format such as shown in Figure 1. In this form, the `type` column provides a symbol as defined in Table 4 that defines the storage of the data referenced in that same line of pseudocode.

```
pseudocode                                                    | type
--------------------------------------------------------------|-----
ExamplePseudoCode( ) {                                        |
    value                                                     | ur
}                                                             |
```

Figure 1: A depiction of type-labeled pseudocode used within this document.

2.2.2. Arithmetic Operators

Note: the operators and the order of precedence are the same as used in the C programming language [ISO.9899.2018], with the exception of `>>` (removal of implementation-defined behavior) and `^` (power instead of XOR) operators, which are redefined within this section.

`a + b` means a plus b.

`a - b` means a minus b.

`-a` means negation of a.

`a * b` means a multiplied by b.

`a / b` means a divided by b.

`a ^ b` means a raised to the b-th power.

`a & b` means bitwise "and" of a and b.

`a | b` means bitwise "or" of a and b.

`a >> b` means arithmetic right shift of the two's complement integer representation of a by b binary digits. This is equivalent to dividing a by 2, b times, with rounding toward negative infinity.

`a << b` means arithmetic left shift of the two's complement integer representation of a by b binary digits.

2.2.3. Assignment Operators

`a = b` means a is assigned b.

`a++` is equivalent to a is assigned a + 1.

`a--` is equivalent to a is assigned a - 1.

`a += b` is equivalent to a is assigned a + b.

`a -= b` is equivalent to a is assigned a - b.

`a *= b` is equivalent to a is assigned a * b.

2.2.4. Comparison Operators

`a > b` is true when a is greater than b.

`a >= b` is true when a is greater than or equal to b.

`a < b` is true when a is less than b.

`a <= b` is true when a is less than or equal b.

`a == b` is true when a is equal to b.

`a != b` is true when a is not equal to b.

`a && b` is true when both a is true and b is true.

`a || b` is true when either a is true or b is true.

`!a` is true when a is not true.

`a ? b : c` if a is true, then b, otherwise c.

2.2.5. Mathematical Functions

`floor(a)` means the largest integer less than or equal to a.

`ceil(a)` means the smallest integer greater than or equal to a.

`sign(a)` extracts the sign of a number, i.e., if a < 0 then -1, else if a > 0 then 1, else 0.

`abs(a)` means the absolute value of a, i.e., `abs(a)` = `sign(a) * a`.

`log2(a)` means the base-two logarithm of a.

`min(a,b)` means the smaller of two values a and b.

`max(a,b)` means the larger of two values a and b.

`median(a,b,c)` means the numerical middle value in a data set of a, b, and c, i.e., `a+b+c-min(a,b,c)-max(a,b,c)`.

`a ==> b` means a implies b.

`a <==> b` means a ==> b, b ==> a.

a_b means the b-th value of a sequence of a.

$a_{b,c}$ means the 'b,c'-th value of a sequence of a.

2.2.6. Order of Operation Precedence

When order of precedence is not indicated explicitly by use of parentheses, operations are evaluated in the following order (from top to bottom, operations of same precedence being evaluated from left to right). This order of operations is based on the order of operations used in Standard C.

```
a++, a--
!a, -a
a ^ b
a * b, a / b
a + b, a - b
a << b, a >> b
a < b, a <= b, a > b, a >= b
a == b, a != b
a & b
a | b
a && b
a || b
a ? b : c
a = b, a += b, a -= b, a *= b
```

2.2.7. Range

`a...b` means any value from a to b, inclusive.

2.2.8. NumBytes

`NumBytes` is a nonnegative integer that expresses the size in 8-bit octets of a particular FFV1 `Configuration Record` or `Frame`. FFV1 relies on its container to store the `NumBytes` values; see Section 4.3.3.

2.2.9. Bitstream Functions

2.2.9.1. remaining_bits_in_bitstream

`remaining_bits_in_bitstream( NumBytes )` means the count of remaining bits after the pointer in that `Configuration Record` or `Frame`. It is computed from the `NumBytes` value multiplied by 8 minus the count of bits of that `Configuration Record` or `Frame` already read by the bitstream parser.

2.2.9.2. remaining_symbols_in_syntax

`remaining_symbols_in_syntax( )` is true as long as the range coder has not consumed all the given input bytes.

2.2.9.3. byte_aligned

`byte_aligned( )` is true if `remaining_bits_in_bitstream( NumBytes )` is a multiple of 8, otherwise false.

2.2.9.4. get_bits

`get_bits( i )` is the action to read the next `i` bits in the bitstream, from most significant bit to least significant bit, and to return the corresponding value. The pointer is increased by `i`.

3. Sample Coding

For each `Slice` (as described in Section 4.5) of a Frame, the Planes, Lines, and Samples are coded in an order determined by the color space (see Section 3.7). Each Sample is predicted by the median predictor as described in Section 3.3 from other Samples within the same Plane, and the difference is stored using the method described in Section 3.8.

3.1. Border

A border is assumed for each coded `Slice` for the purpose of the median predictor and context according to the following rules:

- One column of Samples to the left of the coded Slice is assumed as identical to the Samples of the leftmost column of the coded Slice shifted down by one row. The value of the topmost Sample of the column of Samples to the left of the coded Slice is assumed to be `0`.
- One column of Samples to the right of the coded Slice is assumed as identical to the Samples of the rightmost column of the coded Slice.
- An additional column of Samples to the left of the coded Slice and two rows of Samples above the coded Slice are assumed to be `0`.

Figure 2 depicts a Slice of nine Samples `a`,`b`,`c`,`d`,`e`,`f`,`g`,`h`,`i` in a three-by-three arrangement along with its assumed border.

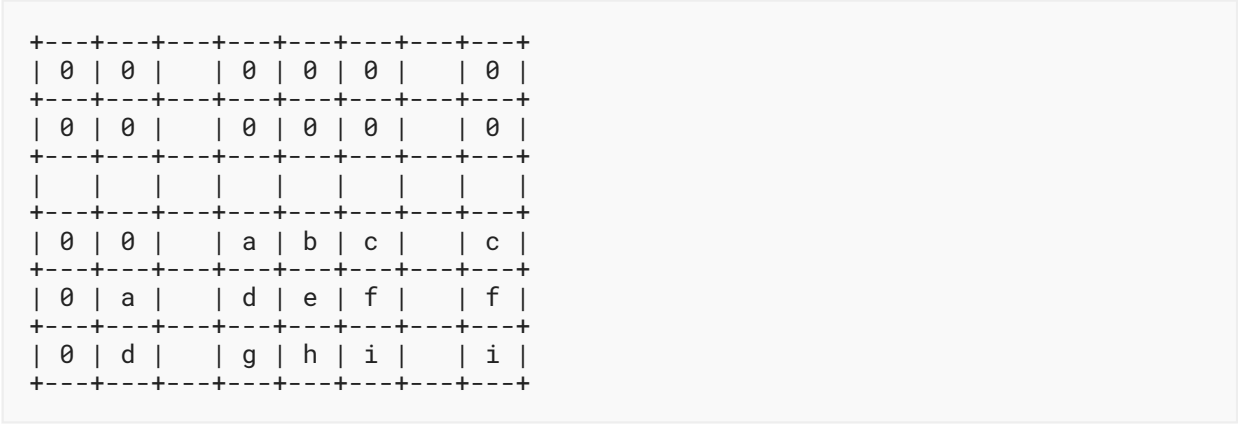


Figure 2: A depiction of FFV1's assumed border for a set of example Samples.

3.2. Samples

Relative to any Sample `X`, six other relatively positioned Samples from the coded Samples and presumed border are identified according to the labels used in Figure 3. The labels for these relatively positioned Samples are used within the median predictor and context.

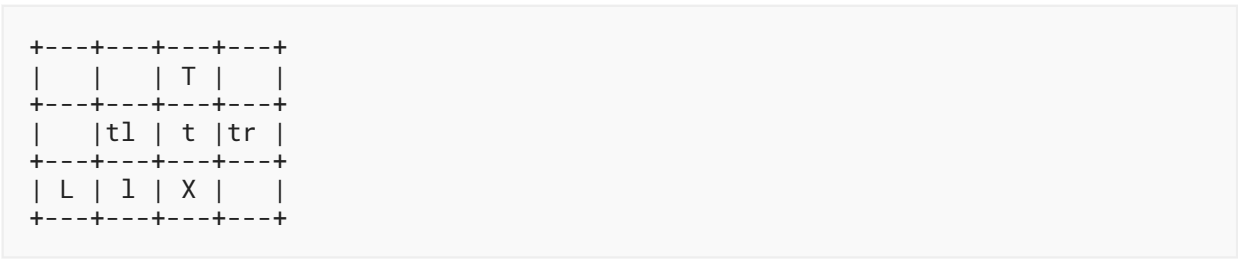


Figure 3: A depiction of how relatively positioned Samples are referenced within this document.

The labels for these relative Samples are made of the first letters of the words Top, Left, and Right.

3.3. Median Predictor

The prediction for any Sample value at position `X` may be computed based upon the relative neighboring values of `l`, `t`, and `tl` via this equation:

```
median(l, t, l + t - tl)
```

Note that this prediction template is also used in [ISO.14495-1.1999] and [HuffYUV].

3.3.1. Exception

If `colorspace_type == 0 && bits_per_raw_sample == 16 && ( coder_type == 1 || coder_type == 2 )` (see Sections 4.2.5, 4.2.7, and 4.2.3), the following median predictor **MUST** be used:

```
median(left16s, top16s, left16s + top16s - diag16s)
```

where:

```
left16s = l  >= 32768 ? ( l  - 65536 ) : l
top16s  = t  >= 32768 ? ( t  - 65536 ) : t
diag16s = tl >= 32768 ? ( tl - 65536 ) : tl
```

Background: a two's complement 16-bit signed integer was used for storing Sample values in all known implementations of FFV1 bitstream (see Appendix C). So in some circumstances, the most significant bit was wrongly interpreted (used as a sign bit instead of the 16th bit of an unsigned integer). Note that when the issue was discovered, the only impacted configuration of all known implementations was the 16-bit YCbCr with no pixel transformation and with the range coder coder type, as the other potentially impacted configurations (e.g., the 15/16-bit JPEG 2000 Reversible Color Transform (RCT) [ISO.15444-1.2019] with range coder or the 16-bit content with the Golomb Rice coder type) were not implemented. Meanwhile, the 16-bit JPEG 2000 RCT with range coder was deployed without this issue in one implementation and validated by one conformance checker. It is expected (to be confirmed) that this exception for the median predictor will be removed in the next version of the FFV1 bitstream.

3.4. Quantization Table Sets

Quantization Tables are used on Sample Differences (see Section 3.8), so Quantized Sample Differences are stored in the bitstream.

The FFV1 bitstream contains one or more Quantization Table Sets. Each Quantization Table Set contains exactly five Quantization Tables with each Quantization Table corresponding to one of the five Quantized Sample Differences. For each Quantization Table, both the number of quantization steps and their distribution are stored in the FFV1 bitstream; each Quantization Table has exactly 256 entries, and the eight least significant bits of the Quantized Sample Difference are used as an index:

$$Q_j[k] = quant\_tables[i][j][k\&255]$$

Figure 4: Description of the mapping from sample differences to the corresponding Quantized Sample Differences.

In this formula, `i` is the Quantization Table Set index, `j` is the Quantized Table index, and `k` is the Quantized Sample Difference (see Section 4.1.1).

3.5. Context

Relative to any Sample `X`, the Quantized Sample Differences `L-l`, `l-tl`, `tl-t`, `T-t`, and `t-tr` are used as context:

$$context = Q_0[l - tl] + Q_1[tl - t] + Q_2[t - tr] + Q_3[L - l] + Q_4[T - t]$$

Figure 5: Description of the computing of the Context.

If `context >= 0` then `context` is used, and the difference between the Sample and its predicted value is encoded as is; else `-context` is used, and the difference between the Sample and its predicted value is encoded with a flipped sign.

3.6. Quantization Table Set Indexes

For each Plane of each Slice, a Quantization Table Set is selected from an index:

- For Y Plane, `quant_table_set_index[ 0 ]` index is used.
- For Cb and Cr Planes, `quant_table_set_index[ 1 ]` index is used.
- For extra Plane, `quant_table_set_index[ (version <= 3 || chroma_planes) ? 2 : 1 ]` index is used.

Background: in the first implementations of the FFV1 bitstream, the index for Cb and Cr Planes was stored even if it was not used (`chroma_planes` set to 0), this index is kept for `version <= 3` in order to keep compatibility with FFV1 bitstreams in the wild.

3.7. Color Spaces

FFV1 supports several color spaces. The count of allowed coded Planes and the meaning of the extra Plane are determined by the selected color space.

The FFV1 bitstream interleaves data in an order determined by the color space. In YCbCr for each Plane, each Line is coded from top to bottom, and for each Line, each Sample is coded from left to right. In JPEG 2000 RCT for each Line from top to bottom, each Plane is coded, and for each Plane, each Sample is encoded from left to right.

3.7.1. YCbCr

This color space allows one to four Planes.

The Cb and Cr Planes are optional, but if they are used, then they **MUST** be used together. Omitting the Cb and Cr Planes codes the frames in gray scale without color data.

An optional transparency Plane can be used to code transparency data.

An FFV1 Frame using YCbCr **MUST** use one of the following arrangements:

- Y
- Y, Transparency
- Y, Cb, Cr
- Y, Cb, Cr, Transparency

The Y Plane **MUST** be coded first. If the Cb and Cr Planes are used, then they **MUST** be coded after the Y Plane. If a transparency Plane is used, then it **MUST** be coded last.

3.7.2. RGB

This color space allows three or four Planes.

An optional transparency Plane can be used to code transparency data.

JPEG 2000 RCT is a Reversible Color Transform that codes RGB (Red, Green, Blue) Planes losslessly in a modified YCbCr color space [ISO.15444-1.2019]. Reversible pixel transformations between YCbCr and RGB use the following formulae:

$$\begin{aligned} Cb &= b - g \\ Cr &= r - g \\ Y &= g + (Cb + Cr) >> 2 \end{aligned}$$

Figure 6: Description of the transformation of pixels from RGB color space to coded, modified YCbCr color space.

$$\begin{aligned} g &= Y - (Cb + Cr) >> 2 \\ r &= Cr + g \\ b &= Cb + g \end{aligned}$$

Figure 7: Description of the transformation of pixels from coded, modified YCbCr color space to RGB color space.

Cb and Cr are positively offset by `1 << bits_per_raw_sample` after the conversion from RGB to the modified YCbCr, and they are negatively offset by the same value before the conversion from the modified YCbCr to RGB in order to have only nonnegative values after the conversion.

When FFV1 uses the JPEG 2000 RCT, the horizontal Lines are interleaved to improve caching efficiency since it is most likely that the JPEG 2000 RCT will immediately be converted to RGB during decoding. The interleaved coding order is also Y, then Cb, then Cr, and then, if used, transparency.

As an example, a Frame that is two pixels wide and two pixels high could comprise the following structure:

```
+-----------------------+-----------------------+
| Pixel(1,1)            | Pixel(2,1)            |
| Y(1,1) Cb(1,1) Cr(1,1) | Y(2,1) Cb(2,1) Cr(2,1) |
+-----------------------+-----------------------+
| Pixel(1,2)            | Pixel(2,2)            |
| Y(1,2) Cb(1,2) Cr(1,2) | Y(2,2) Cb(2,2) Cr(2,2) |
+-----------------------+-----------------------+
```

In JPEG 2000 RCT, the coding order is left to right and then top to bottom, with values interleaved by Lines and stored in this order:

Y(1,1) Y(2,1) Cb(1,1) Cb(2,1) Cr(1,1) Cr(2,1) Y(1,2) Y(2,2) Cb(1,2) Cb(2,2) Cr(1,2) Cr(2,2)

3.7.2.1. RGB Exception

If `bits_per_raw_sample` is between 9 and 15 inclusive and `extra_plane` is 0, the following formulae for reversible conversions between YCbCr and RGB **MUST** be used instead of the ones above:

$$\begin{aligned} Cb &= g - b \\ Cr &= r - b \\ Y &= b + (Cb + Cr) >> 2 \end{aligned}$$

Figure 8: Description of the transformation of pixels from RGB color space to coded, modified YCbCr color space (in case of exception).

$$\begin{aligned} b &= Y - (Cb + Cr) >> 2 \\ r &= Cr + b \\ g &= Cb + b \end{aligned}$$

Figure 9: Description of the transformation of pixels from coded, modified YCbCr color space to RGB color space (in case of exception).

Background: At the time of this writing, in all known implementations of the FFV1 bitstream, when `bits_per_raw_sample` was between 9 and 15 inclusive and `extra_plane` was 0, Green Blue Red (GBR) Planes were used as Blue Green Red (BGR) Planes during both encoding and decoding. Meanwhile, 16-bit JPEG 2000 RCT was implemented without this issue in one implementation and validated by one conformance checker. Methods to address this exception for the transform are under consideration for the next version of the FFV1 bitstream.

3.8. Coding of the Sample Difference

Instead of coding the n+1 bits of the Sample Difference with Huffman or Range coding (or n+2 bits, in the case of JPEG 2000 RCT), only the n (or n+1, in the case of JPEG 2000 RCT) least significant bits are used, since this is sufficient to recover the original Sample. In Figure 10, the term `bits` represents `bits_per_raw_sample + 1` for JPEG 2000 RCT or `bits_per_raw_sample` otherwise:

$$coder\_input = ((sample\_difference + 2^{bits-1})\&(2^{bits} - 1)) - 2^{bits-1}$$

Figure 10: Description of the coding of the Sample Difference in the bitstream.

3.8.1. Range Coding Mode

Early experimental versions of FFV1 used the Context-Adaptive Binary Arithmetic Coding (CABAC) coder from H.264 as defined in [ISO.14496-10.2020], but due to the uncertain patent/royalty situation, as well as its slightly worse performance, CABAC was replaced by a range coder based on an algorithm defined by G. Nigel N. Martin in 1979 [Range-Encoding].

3.8.1.1. Range Binary Values

To encode binary digits efficiently, a range coder is used. A range coder encodes a series of binary symbols by using a probability estimation within each context. The sizes of each of the two subranges are proportional to their estimated probability. The Quantization Table is used to choose the context used from the surrounding image sample values for the case of coding the Sample Differences. The coding of integers is done by coding multiple binary values. The range decoder will read bytes until it can determine into which subrange the input falls to return the next binary symbol.

To describe Range coding for FFV1, the following values are used:

C_i the i-th context.

B_i the i-th byte of the bytestream.

R_i the Range at the i-th symbol.

r_i the boundary between two subranges of R_i: a subrange of r_i values and a subrange R_i - r_i values.

L_i the Low value of the Range at the i-th symbol.

l_i a temporary variable to carry over or adjust the Low value of the Range between range coding operations.

t_i a temporary variable to transmit subranges between range coding operations.

b_i the i-th range-coded binary value.

$S_{0,i}$ the i-th initial state.

j_n the length of the bytestream encoding n binary symbols.

The following range coder state variables are initialized to the following values. The Range is initialized to a value of 65,280 (expressed in base 16 as 0xFF00) as depicted in Figure 11. The Low is initialized according to the value of the first two bytes as depicted in Figure 12. j_i tracks the length of the bytestream encoding while incrementing from an initial value of j_0 to a final value of j_n. j_0 is initialized to 2 as depicted in Figure 13.

$$R_0 = 65280$$

Figure 11: The initial value for the Range.

$$L_0 = 2^8 B_0 + B_1$$

Figure 12: The initial value for Low is set according to the first two bytes of the bytestream.

$$j_0 = 2$$

Figure 13: The initial value for j, the length of the bytestream encoding.

The following equations define how the range coder variables evolve as it reads or writes symbols.

$$r_i = \lfloor \frac{R_i S_{i,C_i}}{2^8} \rfloor$$

Figure 14: This formula shows the positioning of range split based on the state.

$$\begin{array}{lllllllll} b_i = 0 & \iff & L_i < R_i - r_i & \implies & S_{i+1,C_i} = zero\_state_{S_{i,C_i}} & \wedge & l_i = L_i & \wedge & t_i = R_i - r_i \\ b_i = 1 & \iff & L_i \geq R_i - r_i & \implies & S_{i+1,C_i} = one\_state_{S_{i,C_i}} & \wedge & l_i = L_i - R_i + r_i & \wedge & t_i = r_i \end{array}$$

Figure 15: This formula shows the linking of the decoded symbol (represented as b_i), the updated state (represented as S_{i+1,C_i}), and the updated range (represented as a range from l_i to t_i).

$$C_i \neq k \implies S_{i+1,k} = S_{i,k}$$

Figure 16: If the value of k is unequal to the i-th value of context, in other words, if the state is unchanged from the last symbol coding, then the value of the state is carried over to the next symbol coding.

$$t_i < 2^8 \implies R_{i+1} = 2^8 t_i \ \wedge \ L_{i+1} = 2^8 l_i + B_{j_i} \ \wedge \ j_{i+1} = j_i + 1$$
$$t_i \geq 2^8 \implies R_{i+1} = t_i \ \wedge \ L_{i+1} = l_i \ \wedge \ j_{i+1} = j_i$$

Figure 17: This formula shows the linking of the range coder with the reading or writing of the bytestream.

```
    range = 0xFF00;
    end   = 0;
    low   = get_bits(16);
    if (low >= range) {
        low = range;
        end = 1;
    }
```

Figure 18: A pseudocode description of the initialization of range coder variables in Range binary mode.

```
refill() {
    if (range < 256) {
        range = range * 256;
        low   = low * 256;
        if (!end) {
            c.low += get_bits(8);
            if (remaining_bits_in_bitstream( NumBytes ) == 0) {
                end = 1;
            }
        }
    }
}
```

Figure 19: A pseudocode description of refilling the binary value buffer of the range coder.

```
get_rac(state) {
    rangeoff  = (range * state) / 256;
    range    -= rangeoff;
    if (low < range) {
        state = zero_state[state];
        refill();
        return 0;
    } else {
        low   -= range;
        state  = one_state[state];
        range  = rangeoff;
        refill();
        return 1;
    }
}
```

Figure 20: A pseudocode description of the read of a binary value in Range binary mode.

3.8.1.1.1. Termination

The range coder can be used in three modes:

- In Open mode when decoding, every symbol the reader attempts to read is available. In this mode, arbitrary data can have been appended without affecting the range coder output. This mode is not used in FFV1.
- In Closed mode, the length in bytes of the bytestream is provided to the range decoder. Bytes beyond the length are read as 0 by the range decoder. This is generally one byte shorter than the Open mode.
- In Sentinel mode, the exact length in bytes is not known, and thus the range decoder **MAY** read into the data that follows the range-coded bytestream by one byte. In Sentinel mode, the end of the range-coded bytestream is a binary symbol with state 129, which value **SHALL** be discarded. After reading this symbol, the range decoder will have read one byte beyond the end of the range-coded bytestream. This way the byte position of the end can be determined. Bytestreams written in Sentinel mode can be read in Closed mode if the length can be determined. In this case, the last (sentinel) symbol will be read uncorrupted and be of value 0.

The above describes the range decoding. Encoding is defined as any process that produces a decodable bytestream.

There are three places where range coder termination is needed in FFV1. The first is in the `Configuration Record`, which in this case the size of the range-coded bytestream is known and handled as Closed mode. The second is the switch from the `Slice Header`, which is range coded to Golomb-coded Slices as Sentinel mode. The third is the end of range-coded Slices, which need to terminate before the CRC at their end. This can be handled as Sentinel mode or as Closed mode if the CRC position has been determined.

3.8.1.2. Range Nonbinary Values

To encode scalar integers, it would be possible to encode each bit separately and use the past bits as context. However, that would mean 255 contexts per 8-bit symbol, which is not only a waste of memory but also requires more past data to reach a reasonably good estimate of the probabilities. Alternatively, it would also be possible to assume a Laplacian distribution and only deal with its variance and mean (as in Huffman coding). However, for maximum flexibility and simplicity, the chosen method uses a single symbol to encode if a number is 0, and if the number is nonzero, it encodes the number using its exponent, mantissa, and sign. The exact contexts used are best described by Figure 21.

```
int get_symbol(RangeCoder *c, uint8_t *state, int is_signed) {
    if (get_rac(c, state + 0) {
        return 0;
    }

    int e = 0;
    while (get_rac(c, state + 1 + min(e, 9)) { //1..10
        e++;
    }

    int a = 1;
    for (int i = e - 1; i >= 0; i--) {
        a = a * 2 + get_rac(c, state + 22 + min(i, 9));  // 22..31
    }

    if (!is_signed) {
        return a;
    }

    if (get_rac(c, state + 11 + min(e, 10))) { //11..21
        return -a;
    } else {
        return a;
    }
}
```

Figure 21: A pseudocode description of the contexts of Range nonbinary values.

`get_symbol` is used for the read out of `sample_difference` indicated in Figure 10.

`get_rac` returns a boolean computed from the bytestream as described by the formula found in Figure 14 and by the pseudocode found in Figure 20.

3.8.1.3. Initial Values for the Context Model

When the `keyframe` value (see Section 4.4) is 1, all range coder state variables are set to their initial state.

3.8.1.4. State Transition Table

In Range Coding Mode, a state transition table is used, indicating to which state the decoder will move based on the current state and the value extracted from Figure 20.

$$one\_state_i = default\_state\_transition_i + state\_transition\_delta_i$$

Figure 22: Description of the coding of the state transition table for a `get_rac` readout value of 1.

$$zero\_state_i = 256 - one\_state_{256-i}$$

Figure 23: Description of the coding of the state transition table for a `get_rac` readout value of 0.

3.8.1.5. default_state_transition

By default, the following state transition table is used:

```
  0,  0,  0,  0,  0,  0,  0,  0, 20, 21, 22, 23, 24, 25, 26, 27,
 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 37, 38, 39, 40, 41, 42,
 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 56, 57,
 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73,
 74, 75, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88,
 89, 90, 91, 92, 93, 94, 94, 95, 96, 97, 98, 99,100,101,102,103,
104,105,106,107,108,109,110,111,112,113,114,114,115,116,117,118,
119,120,121,122,123,124,125,126,127,128,129,130,131,132,133,133,
134,135,136,137,138,139,140,141,142,143,144,145,146,147,148,149,
150,151,152,152,153,154,155,156,157,158,159,160,161,162,163,164,
165,166,167,168,169,170,171,171,172,173,174,175,176,177,178,179,
180,181,182,183,184,185,186,187,188,189,190,190,191,192,194,194,
195,196,197,198,199,200,201,202,202,204,205,206,207,208,209,209,
210,211,212,213,215,215,216,217,218,219,220,220,222,223,224,225,
226,227,227,229,229,230,231,232,234,234,235,236,237,238,239,240,
241,242,243,244,245,246,247,248,248,  0,  0,  0,  0,  0,  0,  0,
```

Figure 24: Default state transition table for Range coding.

3.8.1.6. Alternative State Transition Table

The alternative state transition table has been built using iterative minimization of frame sizes and generally performs better than the default. To use it, the `coder_type` (see Section 4.2.3) **MUST** be set to 2, and the difference to the default **MUST** be stored in the `Parameters`, see Section 4.2. At the time of this writing, the reference implementation of FFV1 in FFmpeg uses Figure 25 by default when Range coding is used.

```
  0, 10, 10, 10, 10, 16, 16, 16, 28, 16, 16, 29, 42, 49, 20, 49,
 59, 25, 26, 26, 27, 31, 33, 33, 33, 34, 34, 37, 67, 38, 39, 39,
 40, 40, 41, 79, 43, 44, 45, 45, 48, 48, 64, 50, 51, 52, 88, 52,
 53, 74, 55, 57, 58, 58, 74, 60,101, 61, 62, 84, 66, 66, 68, 69,
 87, 82, 71, 97, 73, 73, 82, 75,111, 77, 94, 78, 87, 81, 83, 97,
 85, 83, 94, 86, 99, 89, 90, 99,111, 92, 93,134, 95, 98,105, 98,
105,110,102,108,102,118,103,106,106,113,109,112,114,112,116,125,
115,116,117,117,126,119,125,121,121,123,145,124,126,131,127,129,
165,130,132,138,133,135,145,136,137,139,146,141,143,142,144,148,
147,155,151,149,151,150,152,157,153,154,156,168,158,162,161,160,
172,163,169,164,166,184,167,170,177,174,171,173,182,176,180,178,
175,189,179,181,186,183,192,185,200,187,191,188,190,197,193,196,
197,194,195,196,198,202,199,201,210,203,207,204,205,206,208,214,
209,211,221,212,213,215,224,216,217,218,219,220,222,228,223,225,
226,224,227,229,240,230,231,232,233,234,235,236,238,239,237,242,
241,243,242,244,245,246,247,248,249,250,251,252,252,253,254,255,
```

Figure 25: Alternative state transition table for Range coding.

3.8.2. Golomb Rice Mode

The end of the bitstream of the Frame is padded with zeroes until the bitstream contains a multiple of eight bits.

3.8.2.1. Signed Golomb Rice Codes

This coding mode uses Golomb Rice codes. The VLC is split into two parts: the prefix and suffix. The prefix stores the most significant bits or indicates if the symbol is too large to be stored (this is known as the ESC case, see Section 3.8.2.1.1). The suffix either stores the k least significant bits or stores the whole number in the ESC case.

```
int get_ur_golomb(k) {
    for (prefix = 0; prefix < 12; prefix++) {
        if (get_bits(1)) {
            return get_bits(k) + (prefix << k);
        }
    }
    return get_bits(bits) + 11;
}
```

Figure 26: A pseudocode description of the read of an unsigned integer in Golomb Rice mode.

```
int get_sr_golomb(k) {
    v = get_ur_golomb(k);
    if (v & 1) return - (v >> 1) - 1;
    else       return   (v >> 1);
}
```

Figure 27: A pseudocode description of the read of a signed integer in Golomb Rice mode.

3.8.2.1.1. Prefix

bits	value
1	0
01	1
...	...
0000 0000 01	9
0000 0000 001	10
0000 0000 0001	11
0000 0000 0000	ESC

Table 1: Description of the coding of the prefix of signed Golomb Rice codes.

ESC is an ESCape symbol to indicate that the symbol to be stored is too large for normal storage and that an alternate storage method is used.

3.8.2.1.2. Suffix

non-ESC	the k least significant bits MSB first

ESC	the value - 11, in MSB first order

Table 2: Description of the coding of the suffix of signed Golomb Rice codes.

ESC **MUST NOT** be used if the value can be coded as non-ESC.

3.8.2.1.3. Examples

Table 3 shows practical examples of how signed Golomb Rice codes are decoded based on the series of bits extracted from the bitstream as described by the method above:

k	bits	value
0	1	0
0	001	2
2	1 00	0
2	1 10	2
2	01 01	5
any	000000000000 10000000	139

Table 3: Examples of decoded, signed Golomb Rice codes.

3.8.2.2. Run Mode

Run mode is entered when the context is 0 and left as soon as a nonzero difference is found. The Sample Difference is identical to the predicted one. The run and the first different Sample Difference are coded as defined in Section 3.8.2.4.1.

3.8.2.2.1. Run Length Coding

The run value is encoded in two parts. The prefix part stores the more significant part of the run as well as adjusting the `run_index` that determines the number of bits in the less significant part of the run. The second part of the value stores the less significant part of the run as it is. The `run_index` is reset to zero for each Plane and Slice.

```
log2_run[41] = {
 0, 0, 0, 0, 1, 1, 1, 1,
 2, 2, 2, 2, 3, 3, 3, 3,
 4, 4, 5, 5, 6, 6, 7, 7,
 8, 9,10,11,12,13,14,15,
16,17,18,19,20,21,22,23,
24,
};

if (run_count == 0 && run_mode == 1) {
    if (get_bits(1)) {
        run_count = 1 << log2_run[run_index];
        if (x + run_count <= w) {
            run_index++;
        }
    } else {
        if (log2_run[run_index]) {
            run_count = get_bits(log2_run[run_index]);
        } else {
            run_count = 0;
        }
        if (run_index) {
            run_index--;
        }
        run_mode = 2;
    }
}
```

The `log2_run` array is also used within [ISO.14495-1.1999].

3.8.2.3. Sign Extension

`sign_extend` is the function of increasing the number of bits of an input binary number in two's complement signed number representation while preserving the input number's sign (positive/negative) and value, in order to fit in the output bit width. It **MAY** be computed with the following:

```
sign_extend(input_number, input_bits) {
    negative_bias = 1 << (input_bits - 1);
    bits_mask = negative_bias - 1;
    output_number = input_number & bits_mask; // Remove negative bit
    is_negative = input_number & negative_bias; // Test negative bit
    if (is_negative)
        output_number -= negative_bias;
    return output_number
}
```

3.8.2.4. Scalar Mode

Each difference is coded with the per context mean prediction removed and a per context value for k.

```
get_vlc_symbol(state) {
    i = state->count;
    k = 0;
    while (i < state->error_sum) {
        k++;
        i += i;
    }

    v = get_sr_golomb(k);

    if (2 * state->drift < -state->count) {
        v = -1 - v;
    }

    ret = sign_extend(v + state->bias, bits);

    state->error_sum += abs(v);
    state->drift     += v;

    if (state->count == 128) {
        state->count     >>= 1;
        state->drift     >>= 1;
        state->error_sum >>= 1;
    }
    state->count++;
    if (state->drift <= -state->count) {
        state->bias = max(state->bias - 1, -128);

        state->drift = max(state->drift + state->count,
                           -state->count + 1);
    } else if (state->drift > 0) {
        state->bias = min(state->bias + 1, 127);

        state->drift = min(state->drift - state->count, 0);
    }

    return ret;
}
```

3.8.2.4.1. Golomb Rice Sample Difference Coding

Level coding is identical to the normal difference coding with the exception that the 0 value is removed as it cannot occur:

```
    diff = get_vlc_symbol(context_state);
    if (diff >= 0) {
        diff++;
    }
```

Note that this is different from JPEG-LS (lossless JPEG), which doesn't use prediction in run mode and uses a different encoding and context model for the last difference. On a small set of test Samples, the use of prediction slightly improved the compression rate.

3.8.2.5. Initial Values for the VLC Context State

When `keyframe` (see Section 4.4) value is 1, all VLC coder state variables are set to their initial state.

```
drift     = 0;
error_sum = 4;
bias      = 0;
count     = 1;
```

4. Bitstream

An FFV1 bitstream is composed of a series of one or more Frames and (when required) a `Configuration Record`.

Within the following subsections, pseudocode as described in Section 2.2.1 is used to explain the structure of each FFV1 bitstream component. Table 4 lists symbols used to annotate that pseudocode in order to define the storage of the data referenced in that line of pseudocode.

symbol	definition
u(n)	Unsigned, big-endian integer symbol using n bits
br	Boolean (1-bit) symbol that is range coded with the method described in Section 3.8.1.1
ur	Unsigned scalar symbol that is range coded with the method described in Section 3.8.1.2
sr	Signed scalar symbol that is range coded with the method described in Section 3.8.1.2
sd	Sample Difference symbol that is coded with the method described in Section 3.8

Table 4: Definition of pseudocode symbols for this document.

The following **MUST** be provided by external means during the initialization of the decoder:

`frame_pixel_width` is defined as Frame width in pixels.

`frame_pixel_height` is defined as Frame height in pixels.

Default values at the decoder initialization phase:

`ConfigurationRecordIsPresent` is set to 0.

4.1. Quantization Table Set

The Quantization Table Sets store a sequence of values that are equal to one less than the count of equal concurrent entries for each set of equal concurrent entries within the first half of the table (represented as `len - 1` in the pseudocode below) using the method described in Section 3.8.1.2. The second half doesn't need to be stored as it is identical to the first with flipped sign. `scale` and `len_count[ i ][ j ]` are temporary values used for the computing of `context_count[ i ]` and are not used outside Quantization Table Set pseudocode.

Example:

Table: 0 0 1 1 1 1 2 2 -2 -2 -2 -1 -1 -1 -1 0

Stored values: 1, 3, 1

`QuantizationTableSet` has its own initial states, all set to 128.

```
pseudocode                                                      | type
----------------------------------------------------------------|-----
QuantizationTableSet( i ) {                                     |
    scale = 1                                                   |
    for (j = 0; j < MAX_CONTEXT_INPUTS; j++) {                  |
        QuantizationTable( i, j, scale )                        |
        scale *= 2 * len_count[ i ][ j ] - 1                    |
    }                                                           |
    context_count[ i ] = ceil( scale / 2 )                      |
}                                                               |
```

`MAX_CONTEXT_INPUTS` is 5.

```
pseudocode                                                      | type
----------------------------------------------------------------|-----
QuantizationTable(i, j, scale) {                                |
    v = 0                                                       |
    for (k = 0; k < 128;) {                                     |
        len - 1                                                 | ur
        for (n = 0; n < len; n++) {                             |
            quant_tables[ i ][ j ][ k ] = scale * v             |
            k++                                                 |
        }                                                       |
        v++                                                     |
    }                                                           |
    for (k = 1; k < 128; k++) {                                 |
        quant_tables[ i ][ j ][ 256 - k ] = \                   |
        -quant_tables[ i ][ j ][ k ]                            |
    }                                                           |
    quant_tables[ i ][ j ][ 128 ] = \                           |
    -quant_tables[ i ][ j ][ 127 ]                              |
    len_count[ i ][ j ] = v                                     |
}                                                               |
```

4.1.1. quant_tables

`quant_tables[ i ][ j ][ k ]` indicates the Quantization Table value of the Quantized Sample Difference `k` of the Quantization Table `j` of the Quantization Table Set `i`.

4.1.2. context_count

`context_count[ i ]` indicates the count of contexts for Quantization Table Set `i`. `context_count[ i ]` **MUST** be less than or equal to 32768.

4.2. Parameters

The `Parameters` section, which could be in a global header of a container file that may or may not be considered to be part of the bitstream, contains significant characteristics about the decoding configuration used for all instances of Frame (in FFV1 versions 0 and 1) or the whole FFV1 bitstream (other versions), including the stream version, color configuration, and Quantization Tables. Figure 28 describes the contents of the bitstream.

`Parameters` has its own initial states, all set to 128.

```
pseudocode                                                          | type
--------------------------------------------------------------------|-----
Parameters( ) {                                                     |
    version                                                         | ur
    if (version >= 3) {                                             |
        micro_version                                               | ur
    }                                                               |
    coder_type                                                      | ur
    if (coder_type > 1) {                                           |
        for (i = 1; i < 256; i++) {                                 |
            state_transition_delta[ i ]                             | sr
        }                                                           |
    }                                                               |
    colorspace_type                                                 | ur
    if (version >= 1) {                                             |
        bits_per_raw_sample                                         | ur
    }                                                               |
    chroma_planes                                                   | br
    log2_h_chroma_subsample                                         | ur
    log2_v_chroma_subsample                                         | ur
    extra_plane                                                     | br
    if (version >= 3) {                                             |
        num_h_slices - 1                                            | ur
        num_v_slices - 1                                            | ur
        quant_table_set_count                                       | ur
    }                                                               |
    for (i = 0; i < quant_table_set_count; i++) {                   |
        QuantizationTableSet( i )                                   |
    }                                                               |
    if (version >= 3) {                                             |
        for (i = 0; i < quant_table_set_count; i++) {               |
            states_coded                                            | br
            if (states_coded) {                                     |
                for (j = 0; j < context_count[ i ]; j++) {          |
                    for (k = 0; k < CONTEXT_SIZE; k++) {            |
                        initial_state_delta[ i ][ j ][ k ]          | sr
                    }                                               |
                }                                                   |
            }                                                       |
        }                                                           |
        ec                                                          | ur
        intra                                                       | ur
    }                                                               |
}                                                                   |
```

Figure 28: A pseudocode description of the bitstream contents.

CONTEXT_SIZE is 32.

4.2.1. `version`

`version` specifies the version of the FFV1 bitstream.

Each version is incompatible with other versions: decoders **SHOULD** reject FFV1 bitstreams due to an unknown version.

Decoders **SHOULD** reject FFV1 bitstreams with `version <= 1 && ConfigurationRecordIsPresent == 1`.

Decoders **SHOULD** reject FFV1 bitstreams with `version >= 3 && ConfigurationRecordIsPresent == 0`.

value	version
0	FFV1 version 0
1	FFV1 version 1
2	reserved*
3	FFV1 version 3
Other	reserved for future use

Table 5: The definitions for `version` values.

* Version 2 was experimental and this document does not describe it.

4.2.2. `micro_version`

`micro_version` specifies the micro-version of the FFV1 bitstream.

After a version is considered stable (a micro-version value is assigned to be the first stable variant of a specific version), each new micro-version after this first stable variant is compatible with the previous micro-version: decoders **SHOULD NOT** reject FFV1 bitstreams due to an unknown micro-version equal or above the micro-version considered as stable.

Meaning of `micro_version` for `version` 3:

value	micro_version
0...3	reserved*
4	first stable variant
Other	reserved for future use

Table 6: The definitions for `micro_version` values for FFV1 version 3.

* Development versions may be incompatible with the stable variants.

4.2.3. `coder_type`

`coder_type` specifies the coder used.

value	coder used
0	Golomb Rice
1	Range coder with default state transition table
2	Range coder with custom state transition table
Other	reserved for future use

Table 7: The definitions for `coder_type` values.

Restrictions:

If `coder_type` is 0, then `bits_per_raw_sample` **SHOULD NOT** be > 8.

Background: At the time of this writing, there is no known implementation of FFV1 bitstream supporting the Golomb Rice algorithm with `bits_per_raw_sample` greater than eight, and range coder is preferred.

4.2.4. `state_transition_delta`

`state_transition_delta` specifies the range coder custom state transition table.

If `state_transition_delta` is not present in the FFV1 bitstream, all range coder custom state transition table elements are assumed to be 0.

4.2.5. `colorspace_type`

`colorspace_type` specifies the color space encoded, the pixel transformation used by the encoder, the extra Plane content, as well as interleave method.

value	color space encoded	pixel transformation	extra Plane content	interleave method
0	YCbCr	None	Transparency	Plane then Line
1	RGB	JPEG 2000 RCT	Transparency	Line then Plane
Other	reserved for future use	reserved for future use	reserved for future use	reserved for future use

Table 8: The definitions for `colorspace_type` values.

FFV1 bitstreams with `colorspace_type == 1 && (chroma_planes != 1 || log2_h_chroma_subsample != 0 || log2_v_chroma_subsample != 0)` are not part of this specification.

4.2.6. `chroma_planes`

`chroma_planes` indicates if chroma (color) Planes are present.

value	presence
0	chroma Planes are not present
1	chroma Planes are present

Table 9: The definitions for `chroma_planes` values.

4.2.7. `bits_per_raw_sample`

`bits_per_raw_sample` indicates the number of bits for each Sample. Inferred to be 8 if not present.

value	bits for each Sample
0	reserved*
Other	the actual bits for each Sample

Table 10: The definitions for `bits_per_raw_sample` values.

* Encoders **MUST NOT** store `bits_per_raw_sample = 0`. Decoders **SHOULD** accept and interpret `bits_per_raw_sample = 0` as 8.

4.2.8. `log2_h_chroma_subsample`

`log2_h_chroma_subsample` indicates the subsample factor, stored in powers to which the number 2 is raised, between luma and chroma width (`chroma_width = 2 ^ - log2_h_chroma_subsample * luma_width`).

4.2.9. `log2_v_chroma_subsample`

`log2_v_chroma_subsample` indicates the subsample factor, stored in powers to which the number 2 is raised, between luma and chroma height (`chroma_height = 2 ^ - log2_v_chroma_subsample * luma_height`).

4.2.10. `extra_plane`

`extra_plane` indicates if an extra Plane is present.

value	presence
0	extra Plane is not present
1	extra Plane is present

Table 11: The definitions for `extra_plane` values.

4.2.11. num_h_slices

num_h_slices indicates the number of horizontal elements of the Slice raster.

Inferred to be 1 if not present.

4.2.12. num_v_slices

num_v_slices indicates the number of vertical elements of the Slice raster.

Inferred to be 1 if not present.

4.2.13. quant_table_set_count

quant_table_set_count indicates the number of Quantization Table Sets.
quant_table_set_count **MUST** be less than or equal to 8.

Inferred to be 1 if not present.

MUST NOT be 0.

4.2.14. states_coded

states_coded indicates if the respective Quantization Table Set has the initial states coded.

Inferred to be 0 if not present.

value	initial states
0	initial states are not present and are assumed to be all 128
1	initial states are present

Table 12: The definitions for states_coded values.

4.2.15. initial_state_delta

initial_state_delta[i][j][k] indicates the initial range coder state, and it is encoded using k as context index for the range coder and the following pseudocode:

```
pred = j ? initial_states[ i ][j - 1][ k ] : 128
```

Figure 29: Predictor value for the coding of initial_state_delta[i][j][k].

```
initial_state[ i ][ j ][ k ] = ( pred + initial_state_delta[ i ][ j ][ k ] ) & 255
```

Figure 30: Description of the coding of initial_state_delta[i][j][k].

4.2.16. ec

ec indicates the error detection/correction type.

value	error detection/correction type
0	32-bit CRC in ConfigurationRecord
1	32-bit CRC in Slice and ConfigurationRecord
Other	reserved for future use

Table 13: The definitions for ec values.

4.2.17. intra

intra indicates the constraint on keyframe in each instance of Frame.

Inferred to be 0 if not present.

value	relationship
0	keyframe can be 0 or 1 (non keyframes or keyframes)
1	keyframe **MUST** be 1 (keyframes only)
Other	reserved for future use

Table 14: The definitions for intra values.

4.3. Configuration Record

In the case of a FFV1 bitstream with version >= 3, a Configuration Record is stored in the underlying container as described in Section 4.3.3. It contains the Parameters used for all instances of Frame. The size of the Configuration Record, NumBytes, is supplied by the underlying container.

```
pseudocode                                                  | type
------------------------------------------------------------|-----
ConfigurationRecord( NumBytes ) {                           |
    ConfigurationRecordIsPresent = 1                        |
    Parameters( )                                           |
    while (remaining_symbols_in_syntax(NumBytes - 4)) {     |
        reserved_for_future_use                             | br/ur/sr
    }                                                       |
    configuration_record_crc_parity                         | u(32)
}                                                           |
```

4.3.1. `reserved_for_future_use`

`reserved_for_future_use` is a placeholder for future updates of this specification.

Encoders conforming to this version of this specification **SHALL NOT** write `reserved_for_future_use`.

Decoders conforming to this version of this specification **SHALL** ignore `reserved_for_future_use`.

4.3.2. `configuration_record_crc_parity`

`configuration_record_crc_parity` is 32 bits that are chosen so that the `Configuration Record` as a whole has a CRC remainder of zero.

This is equivalent to storing the CRC remainder in the 32-bit parity.

The CRC generator polynomial used is described in Section 4.9.3.

4.3.3. Mapping FFV1 into Containers

This `Configuration Record` can be placed in any file format that supports `Configuration Records`, fitting as much as possible with how the file format stores `Configuration Records`. The `Configuration Record` storage place and `NumBytes` are currently defined and supported for the following formats:

4.3.3.1. Audio Video Interleave (AVI) File Format

The `Configuration Record` extends the stream format chunk ("AVI ", "hdlr", "strl", "strf") with the `ConfigurationRecord` bitstream.

See [AVI] for more information about chunks.

`NumBytes` is defined as the size, in bytes, of the "strf" chunk indicated in the chunk header minus the size of the stream format structure.

4.3.3.2. ISO Base Media File Format

The `Configuration Record` extends the sample description box ("moov", "trak", "mdia", "minf", "stbl", "stsd") with a "glbl" box that contains the `ConfigurationRecord` bitstream. See [ISO.14496-12.2020] for more information about boxes.

`NumBytes` is defined as the size, in bytes, of the "glbl" box indicated in the box header minus the size of the box header.

4.3.3.3. NUT File Format

The `codec_specific_data` element (in `stream_header` packet) contains the `ConfigurationRecord` bitstream. See [NUT] for more information about elements.

NumBytes is defined as the size, in bytes, of the codec_specific_data element as indicated in the "length" field of codec_specific_data.

4.3.3.4. Matroska File Format

FFV1 **SHOULD** use V_FFV1 as the Matroska Codec ID. For FFV1 versions 2 or less, the Matroska CodecPrivate Element **SHOULD NOT** be used. For FFV1 versions 3 or greater, the Matroska CodecPrivate Element **MUST** contain the FFV1 Configuration Record structure and no other data. See [Matroska] for more information about elements.

NumBytes is defined as the Element Data Size of the CodecPrivate Element.

4.4. Frame

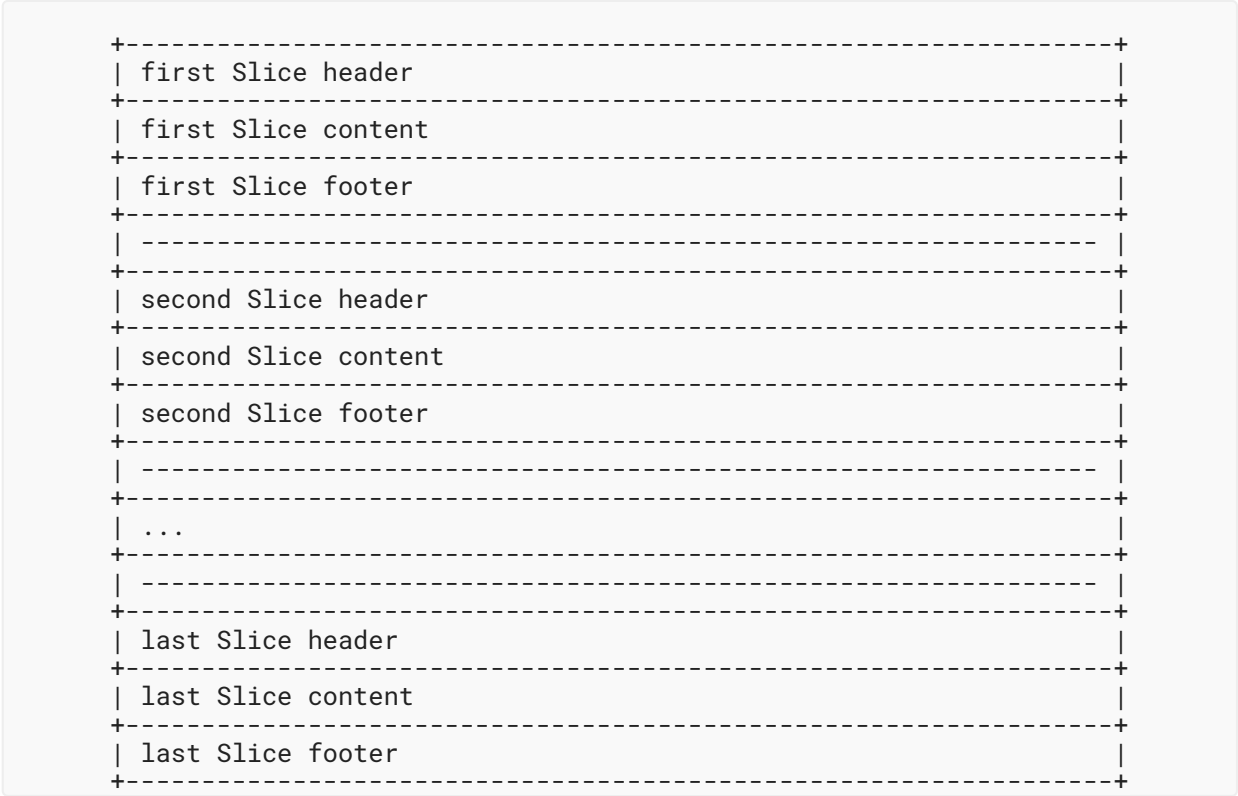
A Frame is an encoded representation of a complete static image. The whole Frame is provided by the underlaying container.

A Frame consists of the keyframe field, Parameters (if version <= 1), and a sequence of independent Slices. The pseudocode below describes the contents of a Frame.

The keyframe field has its own initial state, set to 128.

```
pseudocode                                                      | type
----------------------------------------------------------------|-----
Frame( NumBytes ) {                                             |
    keyframe                                                    | br
    if (keyframe && !ConfigurationRecordIsPresent {             |
        Parameters( )                                           |
    }                                                           |
    while (remaining_bits_in_bitstream( NumBytes )) {           |
        Slice( )                                                |
    }                                                           |
}                                                               |
```

The following is an architecture overview of Slices in a Frame:



4.5. Slice

A `Slice` is an independent, spatial subsection of a Frame that is encoded separately from another region of the same Frame. The use of more than one `Slice` per Frame provides opportunities for taking advantage of multithreaded encoding and decoding.

A `Slice` consists of a `Slice Header` (when relevant), a `Slice Content`, and a `Slice Footer` (when relevant). The pseudocode below describes the contents of a `Slice`.

```
pseudocode                                                      | type
----------------------------------------------------------------|-----
Slice( ) {                                                      |
    if (version >= 3) {                                         |
        SliceHeader( )                                          |
    }                                                           |
    SliceContent( )                                             |
    if (coder_type == 0) {                                      |
        while (!byte_aligned()) {                               |
            padding                                             | u(1)
        }                                                       |
    }                                                           |
    if (version <= 1) {                                         |
        while (remaining_bits_in_bitstream( NumBytes ) != 0) {  |
            reserved                                            | u(1)
        }                                                       |
    }                                                           |
    if (version >= 3) {                                         |
        SliceFooter( )                                          |
    }                                                           |
}                                                               |
```

`padding` specifies a bit without any significance and used only for byte alignment. `padding` **MUST** be 0.

`reserved` specifies a bit without any significance in this specification but may have a significance in a later revision of this specification.

Encoders **SHOULD NOT** fill `reserved`.

Decoders **SHOULD** ignore `reserved`.

4.6. Slice Header

A `Slice Header` provides information about the decoding configuration of the `Slice`, such as its spatial position, size, and aspect ratio. The pseudocode below describes the contents of the `Slice Header`.

`Slice Header` has its own initial states, all set to 128.

```
pseudocode                                                    | type
--------------------------------------------------------------|-----
SliceHeader( ) {                                              |
    slice_x                                                   | ur
    slice_y                                                   | ur
    slice_width - 1                                           | ur
    slice_height - 1                                          | ur
    for (i = 0; i < quant_table_set_index_count; i++) {       |
        quant_table_set_index[ i ]                            | ur
    }                                                         |
    picture_structure                                         | ur
    sar_num                                                   | ur
    sar_den                                                   | ur
}                                                             |
```

4.6.1. slice_x

`slice_x` indicates the x position on the Slice raster formed by `num_h_slices`.

Inferred to be 0 if not present.

4.6.2. slice_y

`slice_y` indicates the y position on the Slice raster formed by `num_v_slices`.

Inferred to be 0 if not present.

4.6.3. slice_width

`slice_width` indicates the width on the Slice raster formed by `num_h_slices`.

Inferred to be 1 if not present.

4.6.4. slice_height

`slice_height` indicates the height on the Slice raster formed by `num_v_slices`.

Inferred to be 1 if not present.

4.6.5. quant_table_set_index_count

`quant_table_set_index_count` is defined as the following:

```
1 + ( ( chroma_planes || version <= 3 ) ? 1 : 0 )
    + ( extra_plane ? 1 : 0 )
```

4.6.6. quant_table_set_index

`quant_table_set_index` indicates the Quantization Table Set index to select the Quantization Table Set and the initial states for the `Slice Content`.

Inferred to be 0 if not present.

4.6.7. `picture_structure`

`picture_structure` specifies the temporal and spatial relationship of each Line of the Frame.

Inferred to be 0 if not present.

value	picture structure used
0	unknown
1	top field first
2	bottom field first
3	progressive
Other	reserved for future use

Table 15: The definitions for `picture_structure` values.

4.6.8. `sar_num`

`sar_num` specifies the Sample aspect ratio numerator.

Inferred to be 0 if not present.

A value of 0 means that aspect ratio is unknown.

Encoders **MUST** write 0 if the Sample aspect ratio is unknown.

If `sar_den` is 0, decoders **SHOULD** ignore the encoded value and consider that `sar_num` is 0.

4.6.9. `sar_den`

`sar_den` specifies the Sample aspect ratio denominator.

Inferred to be 0 if not present.

A value of 0 means that aspect ratio is unknown.

Encoders **MUST** write 0 if the Sample aspect ratio is unknown.

If `sar_num` is 0, decoders **SHOULD** ignore the encoded value and consider that `sar_den` is 0.

4.7. Slice Content

A `Slice Content` contains all Line elements part of the `Slice`.

Depending on the configuration, Line elements are ordered by Plane then by row (YCbCr) or by row then by Plane (RGB).

```
pseudocode                                                      | type
----------------------------------------------------------------|-----
SliceContent( ) {                                               |
    if (colorspace_type == 0) {                                 |
        for (p = 0; p < primary_color_count; p++) {             |
            for (y = 0; y < plane_pixel_height[ p ]; y++) {     |
                Line( p, y )                                    |
            }                                                   |
        }                                                       |
    } else if (colorspace_type == 1) {                          |
        for (y = 0; y < slice_pixel_height; y++) {              |
            for (p = 0; p < primary_color_count; p++) {         |
                Line( p, y )                                    |
            }                                                   |
        }                                                       |
    }                                                           |
}                                                               |
```

4.7.1. primary_color_count

`primary_color_count` is defined as the following:

```
1 + ( chroma_planes ? 2 : 0 ) + ( extra_plane ? 1 : 0 )
```

4.7.2. plane_pixel_height

`plane_pixel_height[ p ]` is the height in pixels of Plane p of the `Slice`. It is defined as the following:

```
chroma_planes == 1 && (p == 1 || p == 2)
    ? ceil(slice_pixel_height / (1 << log2_v_chroma_subsample))
    : slice_pixel_height
```

4.7.3. slice_pixel_height

`slice_pixel_height` is the height in pixels of the Slice. It is defined as the following:

```
floor(
        ( slice_y + slice_height )
        * slice_pixel_height
        / num_v_slices
    ) - slice_pixel_y.
```

4.7.4. slice_pixel_y

`slice_pixel_y` is the Slice vertical position in pixels. It is defined as the following:

```
floor( slice_y * frame_pixel_height / num_v_slices )
```

4.8. Line

A `Line` is a list of the Sample Differences (relative to the predictor) of primary color components. The pseudocode below describes the contents of the `Line`.

```
pseudocode                                                      | type
----------------------------------------------------------------|-----
Line( p, y ) {                                                  |
    if (colorspace_type == 0) {                                 |
        for (x = 0; x < plane_pixel_width[ p ]; x++) {          |
            sample_difference[ p ][ y ][ x ]                    | sd
        }                                                       |
    } else if (colorspace_type == 1) {                          |
        for (x = 0; x < slice_pixel_width; x++) {               |
            sample_difference[ p ][ y ][ x ]                    | sd
        }                                                       |
    }                                                           |
}                                                               |
```

4.8.1. plane_pixel_width

`plane_pixel_width[ p ]` is the width in pixels of Plane `p` of the `Slice`. It is defined as the following:

```
chroma_planes == 1 && (p == 1 || p == 2)
    ? ceil( slice_pixel_width / (1 << log2_h_chroma_subsample) )
    : slice_pixel_width.
```

4.8.2. slice_pixel_width

`slice_pixel_width` is the width in pixels of the Slice. It is defined as the following:

```
floor(
        ( slice_x + slice_width )
        * slice_pixel_width
        / num_h_slices
    ) - slice_pixel_x
```

4.8.3. slice_pixel_x

`slice_pixel_x` is the Slice horizontal position in pixels. It is defined as the following:

```
floor( slice_x * frame_pixel_width / num_h_slices )
```

4.8.4. sample_difference

`sample_difference[ p ][ y ][ x ]` is the Sample Difference for Sample at Plane `p`, y position `y`, and x position `x`. The Sample value is computed based on median predictor and context described in Section 3.2.

4.9. Slice Footer

A `Slice Footer` provides information about Slice size and (optionally) parity. The pseudocode below describes the contents of the `Slice Footer`.

Note: `Slice Footer` is always byte aligned.

```
pseudocode                                                    | type
--------------------------------------------------------------|-----
SliceFooter( ) {                                              |
    slice_size                                                | u(24)
    if (ec) {                                                 |
        error_status                                          | u(8)
        slice_crc_parity                                      | u(32)
    }                                                         |
}                                                             |
```

4.9.1. `slice_size`

`slice_size` indicates the size of the Slice in bytes.

Note: this allows finding the start of Slices before previous Slices have been fully decoded and allows parallel decoding as well as error resilience.

4.9.2. `error_status`

`error_status` specifies the error status.

value	error status
0	no error
1	Slice contains a correctable error
2	Slice contains an uncorrectable error
Other	reserved for future use

Table 16: The definitions for `error_status` values.

4.9.3. `slice_crc_parity`

`slice_crc_parity` is 32 bits that are chosen so that the Slice as a whole has a CRC remainder of 0.

This is equivalent to storing the CRC remainder in the 32-bit parity.

The CRC generator polynomial used is the standard IEEE CRC polynomial (0x104C11DB7) with initial value 0, without pre-inversion, and without post-inversion.

5. Restrictions

To ensure that fast multithreaded decoding is possible, starting with version 3 and if `frame_pixel_width * frame_pixel_height` is more than 101376, `slice_width * slice_height` **MUST** be less or equal to `num_h_slices * num_v_slices / 4`. Note: 101376 is the frame size in pixels of a 352x288 frame also known as CIF (Common Intermediate Format) frame size format.

For each Frame, each position in the Slice raster **MUST** be filled by one and only one Slice of the Frame (no missing Slice position and no Slice overlapping).

For each Frame with a `keyframe` value of 0, each Slice **MUST** have the same value of `slice_x`, `slice_y`, `slice_width`, and `slice_height` as a Slice in the previous Frame.

6. Security Considerations

Like any other codec (such as [RFC6716]), FFV1 should not be used with insecure ciphers or cipher modes that are vulnerable to known plaintext attacks. Some of the header bits as well as the padding are easily predictable.

Implementations of the FFV1 codec need to take appropriate security considerations into account. Those related to denial of service are outlined in Section 2.1 of [RFC4732]. It is extremely important for the decoder to be robust against malicious payloads. Malicious payloads **MUST NOT** cause the decoder to overrun its allocated memory or to take an excessive amount of resources to decode. An overrun in allocated memory could lead to arbitrary code execution by an attacker. The same applies to the encoder, even though problems in encoders are typically rarer. Malicious video streams **MUST NOT** cause the encoder to misbehave because this would allow an attacker to attack transcoding gateways. A frequent security problem in image and video codecs is failure to check for integer overflows. An example is allocating `frame_pixel_width * frame_pixel_height` in pixel count computations without considering that the multiplication result may have overflowed the range of the arithmetic type. The range coder could, if implemented naively, read one byte over the end. The implementation **MUST** ensure that no read outside allocated and initialized memory occurs.

None of the content carried in FFV1 is intended to be executable.

7. IANA Considerations

IANA has registered the following values.

7.1. Media Type Definition

This registration is done using the template defined in [RFC6838] and following [RFC4855].

Type name: video

Subtype name: FFV1

Required parameters: None.

Optional parameters: These parameters are used to signal the capabilities of a receiver implementation. These parameters **MUST NOT** be used for any other purpose.

`version`: The `version` of the FFV1 encoding as defined by Section 4.2.1.

`micro_version`: The `micro_version` of the FFV1 encoding as defined by Section 4.2.2.

`coder_type`: The `coder_type` of the FFV1 encoding as defined by Section 4.2.3.

`colorspace_type`: The `colorspace_type` of the FFV1 encoding as defined by Section 4.2.5.

`bits_per_raw_sample`: The `bits_per_raw_sample` of the FFV1 encoding as defined by Section 4.2.7.

`max_slices`: The value of `max_slices` is an integer indicating the maximum count of Slices within a Frame of the FFV1 encoding.

Encoding considerations: This media type is defined for encapsulation in several audiovisual container formats and contains binary data; see Section 4.3.3. This media type is framed binary data; see Section 4.8 of [RFC6838].

Security considerations: See Section 6 of this document.

Interoperability considerations: None.

Published specification: RFC 9043.

Applications that use this media type: Any application that requires the transport of lossless video can use this media type. Some examples are, but not limited to, screen recording, scientific imaging, and digital video preservation.

Fragment identifier considerations: N/A.

Additional information: None.

Person & email address to contact for further information:
Michael Niedermayer (mailto:michael@niedermayer.cc)

Intended usage: COMMON

Restrictions on usage: None.

Author: Dave Rice (mailto:dave@dericed.com)

Change controller: IETF CELLAR Working Group delegated from the IESG.

8. References

8.1. Normative References

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8.2. Informative References

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Appendix A. Multithreaded Decoder Implementation Suggestions

This appendix is informative.

The FFV1 bitstream is parsable in two ways: in sequential order as described in this document or with the pre-analysis of the footer of each Slice. Each Slice footer contains a `slice_size` field so the boundary of each Slice is computable without having to parse the Slice content. That allows multithreading as well as independence of Slice content (a bitstream error in a Slice header or Slice content has no impact on the decoding of the other Slices).

After having checked the `keyframe` field, a decoder should parse `slice_size` fields, from `slice_size` of the last Slice at the end of the `Frame` up to `slice_size` of the first Slice at the beginning of the `Frame` before parsing Slices, in order to have Slice boundaries. A decoder may fall back on sequential order e.g., in case of a corrupted `Frame` (e.g., frame size unknown or `slice_size` of Slices not coherent) or if there is no possibility of seeking into the stream.

Appendix B. Future Handling of Some Streams Created by Nonconforming Encoders

This appendix is informative.

Some bitstreams were found with 40 extra bits corresponding to `error_status` and `slice_crc_parity` in the `reserved` bits of `Slice`. Any revision of this specification should avoid adding 40 bits of content after `SliceContent` if `version == 0` or `version == 1`, otherwise a decoder conforming to the revised specification could not distinguish between a revised bitstream and such buggy bitstream in the wild.

Appendix C. FFV1 Implementations

This appendix provides references to a few notable implementations of FFV1.

C.1. FFmpeg FFV1 Codec

This reference implementation [REFIMPL] contains no known buffer overflow or cases where a specially crafted packet or video segment could cause a significant increase in CPU load.

The reference implementation [REFIMPL] was validated in the following conditions:

- Sending the decoder valid packets generated by the reference encoder and verifying that the decoder's output matches the encoder's input.
- Sending the decoder packets generated by the reference encoder and then subjected to random corruption.
- Sending the decoder random packets that are not FFV1.

In all of the conditions above, the decoder and encoder was run inside the Valgrind memory debugger [Valgrind] as well as the Clang AddressSanitizer [AddressSanitizer], which tracks reads and writes to invalid memory regions as well as the use of uninitialized memory. There were no errors reported on any of the tested conditions.

C.2. FFV1 Decoder in Go

An FFV1 decoder [FFV1GO] was written in Go by Derek Buitenhuis during the work to develop this document.

C.3. MediaConch

The developers of the MediaConch project [MediaConch] created an independent FFV1 decoder as part of that project to validate FFV1 bitstreams. This work led to the discovery of three conflicts between existing FFV1 implementations and draft versions of this document. These issues are addressed by Section 3.3.1, Section 3.7.2.1, and Appendix B.

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