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M. Niedermayer

D. Rice

J. Martinez

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FF Video Codec 1
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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

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

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This Internet-Draft will expire on January 3, 2018.

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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 a version 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 has been in non-experimental use since April 14, 2006 [FFV1_V0].

- Version 1 of FFV1 adds support of more video bit depths and has been in use since April 24, 2009 [FFV1_V1].

- Version 2 of FFV1 only existed in experimental form and is not described by this document.

- Version 3 of FFV1 adds several features such as increased description of the characteristics of the encoding images and embedded CRC data to support fixity verification of the encoding. Version 3 has been in non-experimental use since August 17, 2013 [FFV1_V3].

The latest version of this document is available at <https://raw.github.com/FFmpeg/FFV1/master/ffv1.md>

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

2. Notation and Conventions

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119].

2.1. Definitions

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

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

"RCT": Reversible Color Transform, a near linear, exactly reversible integer transform that converts between RGB and YCbCr representations of a sample.

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

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

"YCbCr": A reference to the method of storing the value of a sample by using three numeric values that represent the luminance of the sample (Y) and the chrominance of the sample (Cb and Cr).

"TBA": To Be Announced. Used in reference to the development of future iterations of the FFV1 specification.

2.2. Conventions

Note: the operators and the order of precedence are the same as used in the C programming language [ISO.9899.1990].

2.2.1. Arithmetic operators

"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 bit-wise "and" of a and b.

"a | b" means bit-wise "or" of a and b.

"a >> b" means arithmetic right shift of two's complement integer representation of a by b binary digits.

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

2.2.2. 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.

2.2.3. Comparison operators

"a > b" means a is greater than b.

"a >= b" means a is greater than or equal to b.

"a < b" means a is less than b.

"a <= b" means a is less than or equal b.

"a == b" means a is equal to b.

"a != b" means a is not equal to b.

"a && b" means Boolean logical "and" of a and b.

"a || b" means Boolean logical "or" of a and b.

"!a" means Boolean logical "not" of a.

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

2.2.4. Mathematical functions

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

ceil(a) the largest integer less 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) the absolute value of a, i.e. abs(a) = sign(a)*a

log2(a) the base-two logarithm of a

min(a,b) the smallest of two values a and b

max(a,b) the largest of two values a and b

median(a,b,c) 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} the b-th value of a sequence of a

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

2.2.5. 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
```

2.2.6. Pseudo-code

Several components of FFV1 are described in this document using pseudo-code. Note that the pseudo-code is used for clarity in order to illustrate the structure of FFV1 and not intended to specify any particular implementation. The pseudo-code used is based upon the C programming language [ISO.9899.1990] as uses its "if/else", "while" and "for" functions as well as functions defined within this document.

2.2.7. Range

"a...b" means any value starting from a to b, inclusive.

2.2.8. NumBytes

NumBytes is a non-negative integer that expresses the size in 8-bit octets of particular FFV1 components such as the Configuration Record and Frame. FFV1 relies on its container to store the NumBytes values, see Section 4.1.3.

2.2.9. Bitstream functions

2.2.9.1. remaining_bits_in_bitstream

"remaining_bits_in_bitstream( )" means the count of remaining bits after the current position in that bitstream component. It is computed from the NumBytes value multiplied by 8 minus the count of bits of that component already read by the bitstream parser.

2.2.9.2. byte_aligned

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

3. General Description

Samples within a plane are coded in raster scan order (left->right, top->bottom). Each sample is predicted by the median predictor from samples in the same plane and the difference is stored see Section 3.8.

3.1. Border

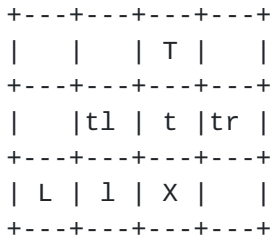
A border is assumed for each coded slice for the purpose of the predictor and context according to the following rules:

- 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
- 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"

The following table depicts a slice of samples "a,b,c,d,e,f,g,h,i" along with its assumed border.

3.2. Samples

Positions used for context and median predictor are:



"X" is the current processed Sample.
The identifers 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, this prediction template is also used in [ISO.14495-1.1999] and [HuffYUV].

Exception for the media predictor: if colorspace_type == 0 && bits_per_raw_sample == 16 && (coder_type == 1 || coder_type == 2), the following media 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 signed 16-bit signed integer was used for storing pixel values in all known implementations of FFV1 bitstream. 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 is discovered, the only configuration of all known implementations being impacted is 16-bit YCbCr color space with Range Coder coder, as other potentially impacted configurations (e.g. 15/16-bit JPEG2000-RCT color space with Range Coder coder, or 16-bit any color space with Golomb Rice coder) were implemented nowhere. In the meanwhile, 16-bit JPEG2000-RCT color space with Range Coder coder was implemented without this issue in one implementation and validated by one conformance checker. It is expected (to be confirmed) to remove this exception for the media predictor in the next version of the bitstream.

3.4. 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]
```

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.

3.5. Quantization Table Sets

The bitstream contains 1 or more Quantization Table Sets.
Each Quantization Table Set contains exactly 5 Quantization Tables, each Quantization Table corresponding to 1 of the 5 Quantized Sample Differences.
For each Quantization Table, both the number of quantization steps and their distribution are stored in the bitstream; each Quantization Table has exactly 256 entries, and the 8 least significant bits of the Quantized Sample Difference are used as index:

```
Q_{j}[k] = quant_tables[i][j][k&255]
```

In this formula, "i" is the Quantization Table Set index, "j" is the Quantized Table index, "k" the Quantized Sample Difference.

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 Alpha plane, "quant_table_set_index [(version <= 3 || chroma_planes) ? 2 : 1]" index is used

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

3.7. Color space

FFV1 supports two color spaces: YCbCr and JPEG2000-RCT. Both color spaces allow an optional Alpha plane that can be used to code transparency data.

3.7.1. YCbCr

In YCbCr color space, the Cb and Cr planes are optional, but if used then MUST be used together. Omitting the Cb and Cr planes codes the frames in grayscale without color data. An FFV1 frame using YCbCr MUST use one of the following arrangements:

- Y
- Y, Alpha
- Y, Cb, Cr
- Y, Cb, Cr, Alpha

When FFV1 uses the YCbCr color space, 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 an Alpha (transparency) plane is used, then it MUST be coded last.

3.7.2. JPEG2000-RCT

JPEG2000-RCT is a Reversible Color Transform that codes RGB (red, green, blue) planes losslessly in a modified YCbCr color space. Reversible conversions between YCbCr and RGB use the following formulae.

```
Cb=b-g

Cr=r-g

Y=g+(Cb+Cr)>>2

g=Y-(Cb+Cr)>>2

r=Cr+g

b=Cb+g
```

Exception for the reversible conversions between YCbCr and RGB: if bits_per_raw_sample is between 9 and 15 inclusive, the following formulae for reversible conversions between YCbCr and RGB MUST be used instead of the ones above:

```
Cb=g-b

Cr=r-b

Y=b+(Cb+Cr)>>2

b=Y-(Cb+Cr)>>2

r=Cr+b

g=Cb+b
```

Background: At the time of this writing, in all known implementations of FFV1 bitstream, when bits_per_raw_sample was between 9 and 15 inclusive, GBR planes were used as BGR planes during both encoding and decoding. In the meanwhile, 16-bit JPEG2000-RCT color space 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 bitstream.

[ISO.15444-1.2016]

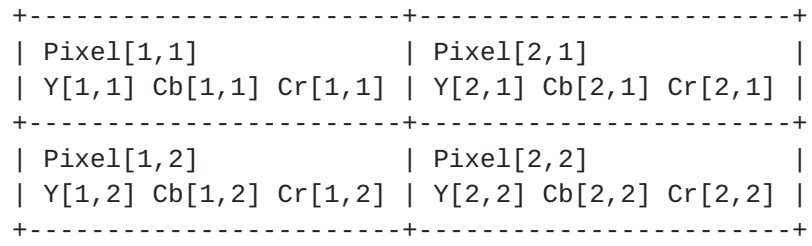
An FFV1 frame using JPEG2000-RCT MUST use one of the following arrangements:

o Y, Cb, Cr

o Y, Cb, Cr, Alpha

When FFV1 uses the JPEG2000-RCT color space, the horizontal lines are interleaved to improve caching efficiency since it is most likely that the RCT will immediately be converted to RGB during decoding. The interleaved coding order is also Y, then Cb, then Cr, and then if used Alpha.

As an example, a frame that is two pixels wide and two pixels high, could be comprised of the following structure:



In JPEG2000-RCT color space, the coding order would be 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]

3.8. 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 RCT), only the n (or n+1) least significant bits are used, since this is sufficient to recover the original sample. In the equation below, the term "bits" represents bits_per_raw_sample+1 for RCT or bits_per_raw_sample otherwise:

```
coder_input =
    [(sample_difference + 2^(bits-1)) & (2^bits - 1)] - 2^(bits-1)
```

3.8.1. Range coding mode

Early experimental versions of FFV1 used the CABAC Arithmetic coder from H.264 as defined in [ISO.14496-10.2014] 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_ and _N. Martin_ in 1979 [range-coding].

3.8.1.1. Range binary values

To encode binary digits efficiently a Range coder is used. "C_{i}" is the i-th Context. "B_{i}" is the i-th byte of the bytestream. "b_{i}" is the i-th Range coded binary value, "S_{0,i}" is the i-th initial state, which is 128. The length of the bytestream encoding n binary symbols is "j_{n}" bytes.

```
r_{i} = floor( ( R_{i} * S_{i,C_{i}} ) / 2^8 )

 S_{i+1,C_{i}} =  zero_state_{S_{i,C_{i}}} XOR
          l_i =  L_i                       XOR
          t_i =  R_i - r_i                 <==
          b_i =  0                         <==>
          L_i <  R_i - r_i

 S_{i+1,C_{i}} =  one_state_{S_{i,C_{i}}}  XOR
          l_i =  L_i - R_i + r_i           XOR
          t_i =  r_i                       <==
          b_i =  1                         <==>
          L_i >= R_i - r_i

      S_{i+1,k} = S_{i,k} <== C_i != k

 R_{i+1} =  2^8 * t_{i}                    XOR
 L_{i+1} =  2^8 * l_{i} + B_{j_{i}}        XOR
 j_{i+1} =  j_{i} + 1                      <==
 t_{i}   <  2^8

 R_{i+1} =  t_{i}                          XOR
 L_{i+1} =  l_{i}                          XOR
 j_{i+1} =  j_{i}                          <==
 t_{i}   >= 2^8

                R_{0} = 65280

          L_{0} = 2^8 * B_{0} + B_{1}

                  j_{0} = 2
```

3.8.1.2. Range non binary 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 assuming a Laplacian distribution and only dealing with its variance and mean (as in Huffman coding) would also be possible, however, for maximum flexibility and simplicity, the chosen method uses a single symbol to encode if a number is 0 and if not encodes the number using its exponent, mantissa and sign. The exact contexts used are best described by the following code, followed by some comments.

```
pseudo-code                                                    | type
---------------------------------------------------------------|-----
void put_symbol(RangeCoder *c, uint8_t *state, int v, int \    |
is_signed) {                                                   |
    int i;                                                     |
    put_rac(c, state+0, !v);                                   |
    if (v) {                                                   |
        int a= abs(v);                                         |
        int e= log2(a);                                        |
                                                               |
        for (i=0; i<e; i++)                                    |
            put_rac(c, state+1+min(i,9), 1);  //1..10          |
                                                               |
        put_rac(c, state+1+min(i,9), 0);                       |
        for (i=e-1; i>=0; i--)                                 |
            put_rac(c, state+22+min(i,9), (a>>i)&1); //22..31  |
                                                               |
        if (is_signed)                                         |
            put_rac(c, state+11 + min(e, 10), v < 0); //11..21|
    }                                                          |
}                                                              |
```

3.8.1.3. Initial values for the context model

At keyframes all Range coder state variables are set to their initial state.

3.8.1.4. State transition table

$$one\_state_{i} = default\_state\_transition_{i} + state\_transition\_delta_{i}$$

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

3.8.1.5. default_state_transition

```
  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,
```

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 MUST be set to 2 and the difference to the default MUST be stored in the parameters. The reference implementation of FFV1 in FFmpeg uses this table by default at the time of this writing 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,
```

3.8.2. Huffman coding mode

This coding mode uses Golomb Rice codes. The VLC code is split into 2 parts, the prefix stores the most significant bits, the suffix stores the k least significant bits or stores the whole number in the ESC case. The end of the bitstream (of the frame) is filled with 0-bits until that the bitstream contains a multiple of 8 bits.

3.8.2.1. Prefix

bits	value
1	0
01	1
...	...
0000 0000 0001	11
0000 0000 0000	ESC

3.8.2.2. Suffix

non ESC	the k least significant bits MSB first
ESC	the value - 11, in MSB first order, ESC may only be used if the value cannot be coded as non ESC

3.8.2.3. Examples

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

3.8.2.4. Run mode

Run mode is entered when the context is 0 and left as soon as a non-0 difference is found. The level is identical to the predicted one. The run and the first different level is coded.

3.8.2.5. Run length coding

The run value is encoded in 2 parts, the prefix part stores the more significant part of the run as well as adjusting the run_index which determines the number of bits in the less significant part of the run. The 2nd part of the value stores the less significant part of the run as it is. The run_index is reset for each plane and slice to 0.

```
pseudo-code                                                    | type
---------------------------------------------------------------|-----
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_bits1()) {                                         |
        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 function is also used within [ISO.14495-1.1999].

3.8.2.6. Level coding

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

```
if (diff>0) diff--;
encode(diff);
```

Note, this is different from JPEG-LS, 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.

4. Bitstream

Symbol	Definition
u(n)	unsigned big endian integer using n bits
sg	Golomb Rice coded signed scalar symbol coded with the method described in Section 3.8.2
br	Range coded Boolean (1-bit) symbol with the method described in Section 3.8.1.1
ur	Range coded unsigned scalar symbol coded with the method described in Section 3.8.1.2
sr	Range coded signed scalar symbol coded with the method described in Section 3.8.1.2

The same context which is initialized to 128 is used for all fields in the header.

The following MUST be provided by external means during 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. Configuration Record

In the case of a bitstream with "version >= 3", a Configuration Record is stored in the underlying container, at the track header level. It contains the parameters used for all frames. The size of the Configuration Record, NumBytes, is supplied by the underlying container.

pseudo-code	type
ConfigurationRecord(NumBytes) {	
ConfigurationRecordIsPresent = 1	
Parameters( )	
while(remaining_bits_in_bitstream(NumBytes) > 32)	
reserved_for_future_use	u(1)
configuration_record_crc_parity	u(32)
}	

4.1.1. reserved_for_future_use

"reserved_for_future_use" has semantics that are reserved for future use. Encoders conforming to this version of this specification SHALL NOT write this value. Decoders conforming to this version of this specification SHALL ignore its value.

4.1.2. configuration_record_crc_parity

"configuration_record_crc_parity" 32 bits that are chosen so that the Configuration Record 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.

4.1.3. Mapping FFV1 into Containers

This Configuration Record can be placed in any file format supporting Configuration Records, fitting as much as possible with how the file format uses to store Configuration Records. The Configuration Record storage place and NumBytes are currently defined and supported by this version of this specification for the following container formats:

4.1.3.1. In 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.

4.1.3.2. In ISO/IEC 14496-12 (MP4 File Format)

The Configuration Record extends the sample description box ("moov", "trak", "mdia", "minf", "stbl", "stsd") with a "glbl" box which contains the ConfigurationRecord bitstream. See [ISO.14496-12.2015] 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.

4.1.3.3. In 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

4.1.3.4. In 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.

4.2. Frame

A frame consists of the keyframe field, parameters (if version <=1), and a sequence of independent slices.

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

4.3. Slice

```
pseudo-code                                                    | type
---------------------------------------------------------------|-----
Slice( ) {                                                     |
    if (version >= 3)                                          |
        SliceHeader( )                                         |
    SliceContent( )                                            |
    if (coder_type == 0)                                       |
        while (!byte_aligned())                                |
            padding                                            | u(1)
    if (version >= 3)                                          |
        SliceFooter( )                                         |
}                                                              |
```

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

4.4. Slice Header

```
pseudo-code                                                    | 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
    if (version >= 4) {                                        |
        reset_contexts                                         | br
        slice_coding_mode                                      | ur
   }                                                           |
}                                                              |
```

4.4.1. slice_x

"slice_x" indicates the x position on the slice raster formed by num_h_slices. Inferred to be 0 if not present.

4.4.2. slice_y

"slice_y" indicates the y position on the slice raster formed by num_v_slices. Inferred to be 0 if not present.

4.4.3. slice_width

"slice_width" indicates the width on the slice raster formed by num_h_slices. Inferred to be 1 if not present.

4.4.4. slice_height

"slice_height" indicates the height on the slice raster formed by num_v_slices. Inferred to be 1 if not present.

4.4.5. quant_table_set_index_count

"quant_table_set_index_count" is defined as 1 + ((chroma_planes || version <= 3) ? 1 : 0) + (alpha_plane ? 1 : 0).

4.4.6. 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. Inferred to be 0 if not present.

4.4.7. picture_structure

"picture_structure" specifies the picture structure. 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

4.4.8. sar_num

"sar_num" specifies the sample aspect ratio numerator. Inferred to be 0 if not present. MUST be 0 if sample aspect ratio is unknown.

4.4.9. sar_den

"sar_den" specifies the sample aspect ratio numerator. Inferred to be 0 if not present. MUST be 0 if sample aspect ratio is unknown.

4.4.10. reset_contexts

"reset_contexts" indicates if slice contexts must be reset. Inferred to be 0 if not present.

4.4.11. slice_coding_mode

"slice_coding_mode" indicates the slice coding mode. Inferred to be 0 if not present.

value	slice coding mode
0	normal Range Coding or VLC
1	raw PCM
Other	reserved for future use

4.5. Slice Content

```
pseudo-code                                                  | 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 )                                 |
    }                                                        |
}                                                            |
```

4.5.1. primary_color_count

"primary_color_count" is defined as 1 + (chroma_planes ? 2 : 0) + (alpha_plane ? 1 : 0).

4.5.2. plane_pixel_height

"plane_pixel_height[p]" is the height in pixels of plane p of the slice. "plane_pixel_height[0]" and "plane_pixel_height[1 + (chroma_planes ? 2 : 0)]" value is "slice_pixel_height". If "chroma_planes" is set to 1, "plane_pixel_height[1]" and "plane_pixel_height[2]" value is "ceil(slice_pixel_height / v_chroma_subsample)".

4.5.3. slice_pixel_height

"slice_pixel_height" is the height in pixels of the slice. Its value is "floor((slice_y + slice_height) * slice_pixel_height / num_v_slices) - slice_pixel_y".

4.5.4. slice_pixel_y

"slice_pixel_y" is the slice vertical position in pixels. Its value is "floor(slice_y * frame_pixel_height / num_v_slices)".

4.6. Line

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

4.6.1. plane_pixel_width

"plane_pixel_width[p]" is the width in pixels of plane p of the slice. "plane_pixel_width[0]" and "plane_pixel_width[1 + (chroma_planes ? 2 : 0)]" value is "slice_pixel_width". If "chroma_planes" is set to 1, "plane_pixel_width[1]" and "plane_pixel_width[2]" value is "ceil(slice_pixel_width / v_chroma_subsample)".

4.6.2. slice_pixel_width

"slice_pixel_width" is the width in pixels of the slice. Its value is "floor((slice_x + slice_width) * slice_pixel_width / num_h_slices) - slice_pixel_x".

4.6.3. slice_pixel_x

"slice_pixel_x" is the slice horizontal position in pixels. Its value is "floor(slice_x * frame_pixel_width / num_h_slices)".

4.7. Slice Footer

Note: slice footer is always byte aligned.

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

4.7.1. 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 this way parallel decoding as well as error resilience.

4.7.2. error_status

"error_status" specifies the error status.

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

4.7.3. slice_crc_parity

"slice_crc_parity" 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.

4.8. Parameters

```
pseudo-code                                                     | 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
    alpha_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
    }                                                           |
}                                                               |
```

4.8.1. version

"version" specifies the version of the bitstream. Each version is incompatible with others versions: decoders SHOULD reject a file due to unknown version. Decoders SHOULD reject a file with version <= 1 && ConfigurationRecordIsPresent == 1. Decoders SHOULD reject a file 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

* Version 2 was never enabled in the encoder thus version 2 files SHOULD NOT exist, and this document does not describe them to keep the text simpler.

4.8.2. micro_version

"micro_version" specifies the micro-version of the 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 a file 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

* were development versions which may be incompatible with the stable variants.

Meaning of micro_version for version 4 (note: at the time of writing of this specification, version 4 is not considered stable so the first stable version value is to be announced in the future):

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

* were development versions which may be incompatible with the stable variants.

4.8.3. 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

4.8.4. state_transition_delta

"state_transition_delta" specifies the Range coder custom state transition table. If state_transition_delta is not present in the bitstream, all Range coder custom state transition table elements are assumed to be 0.

4.8.5. colorspace_type

"colorspace_type" specifies the color space.

value	color space used
0	YCbCr
1	JPEG2000-RCT
Other	reserved for future use

4.8.6. chroma_planes

"chroma_planes" indicates if chroma (color) planes are present.

value	color space used
0	chroma planes are not present
1	chroma planes are present

4.8.7. bits_per_raw_sample

"bits_per_raw_sample" indicates the number of bits for each luma and chroma sample. Inferred to be 8 if not present.

value	bits for each luma and chroma sample
0	reserved*
Other	the actual bits for each luma and chroma sample

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

4.8.8. h_chroma_subsample

"h_chroma_subsample" indicates the subsample factor between luma and chroma width ("chroma_width = 2^(-log2_h_chroma_subsample) * luma_width").

4.8.9. v_chroma_subsample

"v_chroma_subsample" indicates the subsample factor between luma and chroma height ("chroma_height=2^(-log2_v_chroma_subsample) * luma_height").

4.8.10. alpha_plane

alpha_plane
indicates if a transparency plane is present.

value	color space used
0	transparency plane is not present
1	transparency plane is present

4.8.11. num_h_slices

"num_h_slices" indicates the number of horizontal elements of the slice raster. Inferred to be 1 if not present.

4.8.12. num_v_slices

"num_v_slices" indicates the number of vertical elements of the slice raster. Inferred to be 1 if not present.

4.8.13. quant_table_set_count

"quant_table_set_count" indicates the number of Quantization Table Sets. Inferred to be 1 if not present. MUST NOT be 0.

4.8.14. 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

4.8.15. initial_state_delta

"initial_state_delta" [i][j][k] indicates the initial Range coder state, it is encoded using k as context index and pred = j ? initial_states[i][j - 1][k] : 128 initial_state[i][j][k] = (pred + initial_state_delta[i][j][k]) & 255

4.8.16. ec

"ec" indicates the error detection/correction type.

value	error detection/correction type
0	32-bit CRC on the global header
1	32-bit CRC per slice and the global header
Other	reserved for future use

4.8.17. intra

"intra" indicates the relationship between frames. Inferred to be 0 if not present.

value	relationship
0	frames are independent or dependent (keyframes and non keyframes)
1	frames are independent (keyframes only)
Other	reserved for future use

4.9. Quantization Table Set

The Quantization Table Sets are stored by storing the number of equal entries -1 of the first half of the table (represented as "len - 1" in the pseudo-code 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.

example:

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

Stored values: 1, 3, 1

```
pseudo-code                                                    | 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 ] = ( scale + 1 ) / 2                     |
}                                                              |
```

MAX_CONTEXT_INPUTS is 5.

```
pseudo-code                                                    | type
---------------------------------------------------------------|-----
QuantizationTable(i, j, scale) {                               |
    v = 0                                                      |
    for( k = 0; k < 128; ) {                                   |
        len - 1                                                | ur
        for( a = 0; a < len; a++ ) {                           |
            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                                    |
}                                                              |
```

4.9.1. quant_tables

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

4.9.2. context_count

"context_count[i]" indicates the count of contexts for Quantization Table Set "i".

5. Restrictions

To ensure that fast multithreaded decoding is possible, starting 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, no slice overlapping).

For each Frame with keyframe value of 0, each slice MUST have the same value of slice_x, slice_y, slice_width, slice_height as a slice in the previous frame, except if reset_contexts is 1.

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, as outlined in [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. Although problems in encoders are typically rarer, the same applies to the encoder. 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 also to not check for integer overflows in pixel count computations, that is to allocate width * height without considering that the multiplication result may have overflowed the arithmetic types range.

The 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 encoders 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 as well as clangs address sanitizer [Address-Sanitizer], which track 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.

7. Appendixes

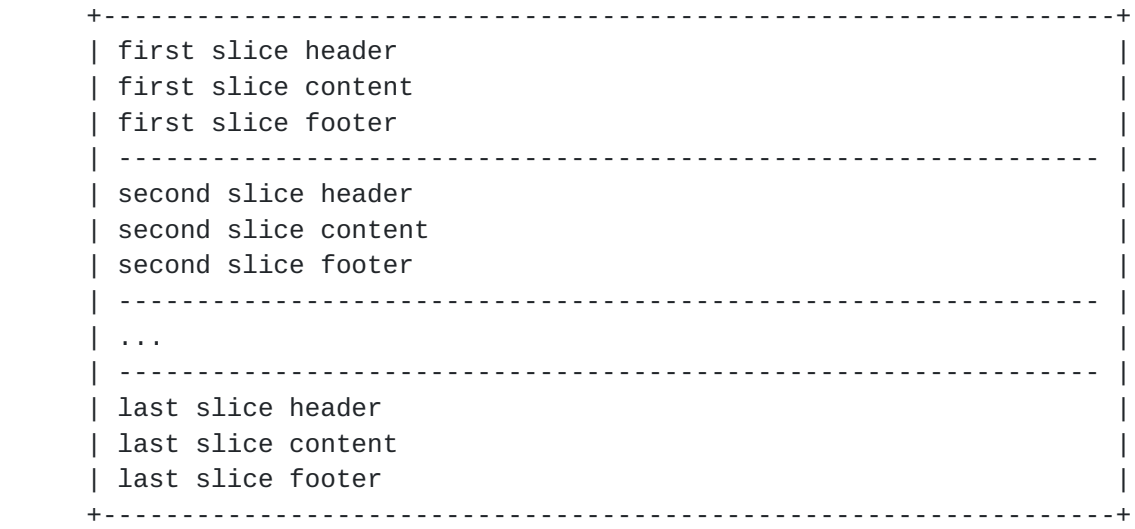
7.1. Decoder implementation suggestions

7.1.1. Multi-threading support and independence of slices

The 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 multi-threading 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 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 slices boundaries. A decoder MAY fallback on sequential order e.g. in case of corrupted frame (frame size unknown, slice_size of slices not coherent...) or if there is no possibility of seek into the stream.

Architecture overview of slices in a frame:



8. Changelog

See <https://github.com/FFmpeg/FFV1/commits/master>

9. ToDo

- mean,k estimation for the Golomb Rice codes

10. References

10.1. Normative References

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Authors' Addresses

Michael Niedermayer

Email: michael@niedermayer.cc

Dave Rice

Email: dave@dericed.com

Jerome Martinez

Email: jerome@mediaarea.net