Transactions Letters

Improving Lossless Intra Coding of H.264/AVC by Pixel-Wise Spatial Interleave Prediction

Li Song, *Member, IEEE,* Zhengyi Luo, and Cong Xiong

***Abstract*—H.264/AVC adopts many directional spatial prediction models in block-based manner that neighboring pixels on the left and top sides yield prediction for the pixels in a data block to be encoded. However, such models may adapt poorly to the rich textures inside blocks of video signal. In this letter, a new lossless intra coding method based on pixel-wise interleave prediction is presented to enhance the compression performance of H.264/AVC. In our scheme, pixels are coded alternately with interleave prediction, which makes full use of reconstructed pixels to predict later ones in bidirectional or multidirectional manner. Extensive experiments demonstrate that compared to the H.264/AVC standard, our scheme has higher compression ratio, especially for sequences of high resolution. In addition, the scheme can be regarded as a frame-level coding mode and can be easily integrated into the H.264/AVC framework.**

***Index Terms*—H.264/AVC, interleave prediction, intra coding, lossless.**

I. Introduction

Developed jointly by ITU-T and ISO/IEC, the H.264/AVC standard [1] is a state-of-the-art video coding standard. Recent comparisons reveal that H.264/AVC also has a strong potential on individually coded pictures [2], which mainly comes from its powerful intra prediction capabilities and makes it a good alternative to JPEG [3] and JPEG2000 [4]. The intra coding algorithm of H.264/AVC removes spatial redundancies between adjacent blocks by predicting a block from its spatially adjacent causal neighbors. A choice of coarse and fine intra prediction is allowed on a block-by-block basis.

Recently, as demands for medical images or professional content-authoring applications increase rapidly, lossless compression has become a topic of interest. Accordingly, to provide an alternative to JPEG-LS (lossless) [5] and JPEG2000 lossless, the H.264/AVC FRExt introduces efficient lossless coding methods into the coding framework of H.264/AVC [6], which inherits the directional prediction modes and context adaptive entropy coding but with transform and quantization bypassed out of the consideration of lossless compression [7].

As in lossy intra coding pixels on the left and top sides are used as prediction for the pixels in a block, originally the block-based prediction model was also employed by the lossless intra coding of H.264/AVC. But considering the model adapts poorly to blocks with rich textures, improvement has been made to reduce bit rates further in the lossless scenario. Because in lossless intra coding, pixels can be reconstructed exactly and pixels immediately neighboring the pixel to be coded are typically better predictors, Lee *et al.* [8]–[10] proposed to refine the horizontal and vertical prediction modes so that pixels immediately on the left or top side can be used as prediction. The proposed horizontal and vertical prediction modes of sample-by-sample (SbS) differential pulse-code modulation (DPCM) improve the coding efficiency obviously and have been adopted in the latest standard. Wei *et al.* [11] also proposed an interpolation method to enhance the prediction modes of lossless intra coding. With the interpolations applied, the DPCM concept can be extended to the other directional prediction modes at the expense of increased complexity. Besides, for higher compression ratio, recursive prediction and block-matching prediction can also be utilized [12] at the expense of high complexity, and context-adaptive variable-length coding may be redesigned to cater for the prediction residuals of lossless intra coding as well [13]–[15].

As far as we know, representative improvement focuses mainly on the refinement of existing unidirectional intra prediction modes. Inspired by the bidirectional interframe prediction of video coding, in this letter, a novel improvement option of pixel-wise spatial interleave prediction is contributed to enhance the compression performance of H.264/AVC lossless intra coding. First, a frame is down-sampled into four sub-images of 1/4 size. Then the four sub-images are encoded, respectively, using different mode sets, where available surrounding pixels are made full use of to perform multidirectional spatial prediction. Our scheme can be regarded as a frame-level coding mode and necessitates only minor modification when integrated into the H.264/AVC framework. What is more, the scheme can be applied jointly with many previous methods, and its coding style with downsampling has

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L. Song and Z. Luo are with the Institute of Image Communication and Information Processing, Shanghai Jiao Tong University, Shanghai 200240, China (e-mail: song_li@sjtu.edu.cn; llzzyynjupt@sjtu.edu.cn).

C. Xiong is with the AMD Shanghai Research and Development Center, Shanghai 201203, China (e-mail: congxiong@hotmail.com).

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$P_{-1,-1}$	$P_{0,-1}$	$P_{1,-1}$	$P_{2,-1}$	$P_{3,-1}$
$P_{-1,0}$	$P_{0,0}$	$P_{1,0}$	$P_{2,0}$	$P_{3,0}$
$P_{-1,1}$	$P_{0,1}$	$P_{1,1}$	$P_{2,1}$	$P_{3,1}$
$P_{-1,2}$	$P_{0,2}$	$P_{1,2}$	$P_{2,2}$	$P_{2,3}$
$P_{-1,3}$	$P_{0,3}$	$P_{1,3}$	$P_{2,3}$	$P_{3,3}$

Fig. 1. 4×4 luma block and its neighboring pixels.

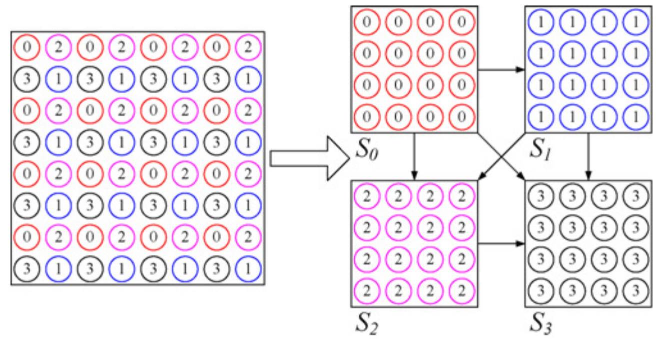

Fig. 2. Illustration of the interleave prediction.

the natural virtue of scalability, which is friendly to many practical applications.

The remainder of this letter is organized as follows. In Section II, the lossless intra coding of H.264/AVC is briefly reviewed. Section III describes the proposed pixel-wise spatial interleave prediction in detail. Experimental results validating the effectiveness of our scheme are shown in Section IV, and Section V draws the conclusion.

II. Lossless Intra Coding of H.264/AVC

H.264/AVC removes spatial redundancies by means of intra prediction, where prediction values can be obtained based on pixels of neighboring blocks. As far as the common 4:2:0 sequences are concerned, luminance (luma) can be encoded in 4×4, 8×8, or 16×16 blocks and chrominance (chroma) can be encoded in 8×8 blocks. For the 4×4 or 8×8 luma blocks, nine prediction modes are available. While for the 16×16 luma blocks or 8×8 chroma blocks, only four modes may be used.

When lossless intra coding was introduced into H.264/AVC, originally those previous prediction modes were inherited intactly. But as pixels can be reconstructed exactly in lossless coding and immediately neighboring pixels typically predict better than those in neighboring blocks, later improvement SbS DPCM [10] has been adopted to refine the horizontal and vertical prediction modes. Take a 4×4 luma block as shown in Fig. 1 for example. If the vertical prediction is used, the prediction value for $p_{i,j}$ will be

$$Pred\,[i, j] = p_{i,j-1} \quad (0 \le i \le 3,\ 0 \le j \le 3) \tag{1}$$

while if the horizontal prediction is used, the prediction value will be

$$Pred\,\left[i, j\right] = p_{i-1,j} \quad (0 \le i \le 3,\ 0 \le j \le 3)\,. \tag{2}$$

Similar improvement also applies to the vertical and horizontal prediction modes of other blocks.

From (1) and (2) we can see that the improvement uses pixels in only one direction to predict later ones. In the next section, we will propose a novel improvement option, which makes multidirectional prediction possible in intra coding. Meanwhile, it can also be applied jointly with existing improvement methods.

III. Proposed Interleave Prediction for Lossless Intra Coding

In the field of video coding, it is widely recognized that bidirectional prediction removes more redundancies. Higher compression ratio can be expected if bidirectional prediction is applied to lossless intra coding. But in the existing framework of H.264/AVC, only modes of unidirectional intra prediction are utilized. In order to apply bidirectional prediction to lossless intra coding, we propose the interleave prediction algorithm as follows.

A. Multidirectional Interleave Prediction

The flowchart of our algorithm is shown in Fig. 2. Let W and H denote the width and height of the original image S, respectively. We first down-sample S into four sub-images $S_k\,(k = 0 \sim 3)$, whose pixels are later referred to by $S_k\left[i, j\right]$ $\left(0 \le i \le W/2,\ 0 \le j \le H/2,\ 0 \le k \le 3\right)$, then encode them in the order of $S_0 \to S_1 \to S_2 \to S_3$. Specifically, encoding is performed in four passes, with one pass for each sub-image.

1) *First Pass:* In the first pass, S_0 is encoded as normal H.264/AVC processing, where previous improvement, e.g., SbS DPCM, is proved to be still effective by experiments and can be applied as before. Though prediction performance may be degraded due to the absence of original immediately neighboring pixels, this deliberate design will benefit prediction in the subsequent passes as shown later.

2) *Second Pass:* In the second pass, the reconstructed S_0 from the first pass is used to predict the diagonally adjacent sub-image S_1. As shown in Fig. 3(a), where the hollow circles mean the pixels being encoded in S_1 and the solid ones mean those already encoded in S_0, the reference pixels from the first pass are available on the top left, top right, bottom left, and bottom right sides. Therefore, to some sense S_1 has circumambient contexts, which benefit prediction obviously. Intuitively, surrounding pixels from S_0 correlate well with the current pixel in S_1 and good prediction can be obtained via appropriate combination. To find the suitable combination coefficients, we treat the prediction from S_0 as equivalent interframe prediction for S_1. And we resort to the six-tap Wiener interpolation filter in H.264/AVC [16] to attenuate the aliasing during the interpolative prediction. Specifically, a mode set including three prediction modes are designed for S_1-hybrid mode (Mode 0), horizontal mode (Mode 1), and

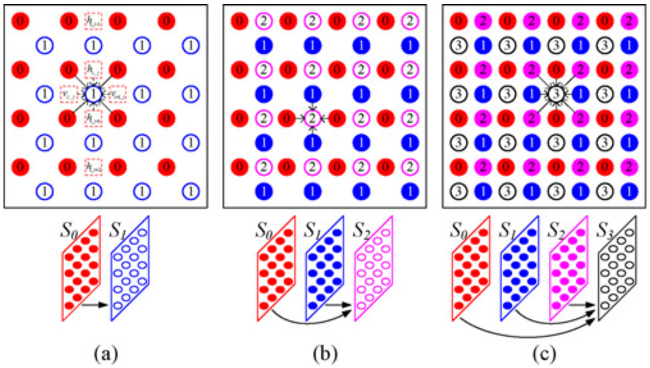

Fig. 3. Prediction contexts for (a) S_1, (b) S_2, and (c) S_3.

vertical mode (Mode 2). If we define

$$P_h[i,j] = S_0[i-2,j] - 5S_0[i-1,j] + 20S_0[i,j] + 20S_0[i+1,j] - 5S_0[i+2,j] + S_0[i+3,j] \tag{3}$$

and

$$P_v[i,j] = S_0[i,j-2] - 5S_0[i,j-1] + 20S_0[i,j] + 20S_0[i,j+1] - 5S_0[i,j+2] + S_0[i,j+3] \tag{4}$$

then the prediction values for $S_1[i,j]$ in each mode can be shown in (5)–(7), where $Clip(\bullet)$ is used to clamp a number to the valid range of the pixel value.

a) *Mode* 0

$$Pred_{HB}[i,j] = Clip((P_h[i,j-2] - 5P_h[i,j-1] + 20P_h[i,j] + 20P_h[i,j+1] - 5P_h[i,j+2] + P_h[i,j+3] + 512) \gg 10). \tag{5}$$

b) *Mode* 1

$$Pred_H[i,j] = Clip((P_h[i,j] + P_h[i,j+1] + 32) \gg 6). \tag{6}$$

c) *Mode* 2

$$Pred_V[i,j] = Clip((P_v[i,j] + P_v[i+1,j] + 32) \gg 6). \tag{7}$$

In the horizontal mode (Mode 1), first horizontal interpolation is carried out for the half pixel positions $h_{i,j}$ and $h_{i,j+1}$ as shown in Fig. 3(a), then the prediction value for the current pixel in S_1 is derived by averaging the two intermediate values. Similarly, in the vertical mode (Mode 2), vertical interpolation is first carried out for $v_{i,j}$ and $v_{i+1,j}$, then the prediction value is derived by averaging the two intermediate values. In the hybrid mode (Mode 0), the prediction value is derived by diagonal half pixel interpolation, which is conducted by further interpolation of the horizontal intermediate values.

3) *Third Pass:* In this pass, reconstructed pixels from S_0 and S_1 are used to predict S_2. As shown in Fig. 3(b), pixels in S_2 have reference on the top, left, bottom, and right sides. Similar to the second pass, we design a mode set including three prediction modes for S_2-hybrid mode (Mode 0), horizontal mode (Mode 1), and vertical mode (Mode 2). The horizontal and vertical modes, based on the same Wiener filter as before, use reference pixels from S_0 and S_1, respectively, while the hybrid mode performs weighted prediction from both S_0 and S_1. If we have

$$P_h[i,j] = S_0[i-2,j] - 5S_0[i-1,j] + 20S_0[i,j] + 20S_0[i+1,j] - 5S_0[i+2,j] + S_0[i+3,j] \tag{8}$$

and

$$P_v[i,j] = S_1[i,j-2] - 5S_1[i,j-1] + 20S_1[i,j] + 20S_1[i,j+1] - 5S_1[i,j+2] + S_1[i,j+3] \tag{9}$$

then the prediction values for $S_2[i,j]$ in each mode can be represented in (10)–(12).

a) *Mode* 0

$$Pred_{HB}[i,j] = Clip((P_h[i,j] + P_v[i,j-1] + 32) \gg 6). \tag{10}$$

b) *Mode* 1

$$Pred_H[i,j] = Clip((P_h[i,j] + 16) \gg 5). \tag{11}$$

c) *Mode* 2

$$Pred_V[i,j] = Clip((P_v[i,j-1] + 16) \gg 5). \tag{12}$$

In the horizontal mode (Mode 1), the prediction value is derived by horizontal half pixel interpolation of S_0 as shown in Fig. 3(b). In the vertical mode (Mode 2), the prediction value is derived by vertical half pixel interpolation of S_1. In the hybrid mode (Mode 0), the prediction value is derived by averaging the above two half pixel interpolation values.

4) *Fourth Pass:* The last sub-image S_3 is encoded in this pass. As shown in Fig. 3(c), pixels from S_0, S_1, and S_2 in eight directions are all available for reference. Though many different modes may be designed to adapt to local variance, in view of complexity we only adopt three modes—Gaussian average mode (Mode 0), horizontal mode (Mode 1), and vertical mode (Mode 2). The Gaussian average mode uses a Gaussian-like filter, while the horizontal and vertical modes use the same Wiener filter as before. If we define

$$P_{ga}[i,j] = 2S_0[i,j] + 2S_0[i,j+1] + 2S_1[i,j] + 2S_1[i-1,j] - S_2[i,j] - S_2[i-1,j] - S_2[i-1,j+1] - S_2[i,j+1] \tag{13}$$

$$P_h[i,j] = S_1[i-2,j] - 5S_1[i-1,j] + 20S_1[i,j] + 20S_1[i+1,j] - 5S_1[i+2,j] + S_1[i+3,j] \tag{14}$$

and

$$P_v[i,j] = S_0[i,j-2] - 5S_0[i,j-1] + 20S_0[i,j] + 20S_0[i,j+1] - 5S_0[i,j+2] + S_0[i,j+3] \tag{15}$$

then the prediction values for $S_3[i,j]$ in each mode can be shown in (16)–(18).

TABLE I

COMPUTATION AMOUNTS OF THE PREDICTION MODES FOR EACH PIXEL OF SUB-IMAGES S_1, S_2, AND S_3

Operation	S_1			S_2			S_3		
	Mode 0	Mode 1	Mode 2	Mode 0	Mode 1	Mode 2	Mode 0	Mode 1	Mode 2
+ or −	36	12	12	12	6	6	8	6	6
×	28	8	8	8	4	4	4	4	4
>>	1	1	1	1	1	1	1	1	1

TABLE II

EXPERIMENTAL RESULTS FOR THE PROPOSED SCHEME

Format	Sequence	Resultant File Size (bytes)				Size Reduction Against H.264/AVC (%)	Encoding Time (s)	
		JPEG-LS	MJPEG2000	H.264/AVC	Our Method		H.264/AVC	Our Method
352 × 288	*Bus*	7 703 213	7 842 567	8 448 568	8 415 584	0.39	3.547	4.297
	Football	6 275 949	6 388 607	6 929 512	6 494 713	6.27	2.968	3.641
	Foreman	6 333 643	6 724 271	6 685 790	6 750 538	−0.97	2.922	3.718
	Mother and Daughter	5 017 559	5 218 716	5 431 374	5 141 242	5.34	2.485	3.218
	News	5 792 619	6 183 461	6 312 881	6 372 387	−0.94	2.812	3.625
	Silent	7 028 786	7 289 982	7 481 550	7 419 422	0.83	3.219	3.985
	Stefan	7 242 957	7 596 993	7 918 698	7 907 736	0.14	3.359	4.094
	Tempete	8 168 794	8 580 034	9 006 742	8 961 355	0.50	3.718	4.484
	Waterfall	8 568 847	8 357 701	9 332 164	8 661 939	7.18	3.797	4.407
704 × 576	*City*	26 142 157	26 898 684	28 529 281	27 669 329	3.01	13.375	14.906
	Crew	22 510 479	23 220 597	24 503 558	22 838 153	6.80	10.844	13.172
	Harbor	24 843 611	25 843 928	28 235 649	25 964 891	8.04	13.297	14.516
	Soccer	23 093 596	23 722 223	24 953 332	23 704 422	5.00	11.969	13.390
1280 × 720	*Cyclists*	40 545 156	42 405 000	42 858 417	41 171 389	3.94	21.172	26.750
	Night	52 526 288	55 195 935	57 996 693	56 187 212	3.12	26.063	31.781
	Optis	44 024 531	45 983 466	46 046 983	45 562 410	1.05	21.266	27.984
	Raven	40 773 533	42 832 923	47 168 848	41 414 902	12.20	23.407	27.172
	Sheriff	43 864 216	46 135 237	46 317 243	45 577 587	1.60	22.672	28.047
1920 × 1080	*Blue Sky*	104 119 884	105 088 667	112 959 418	104 211 078	7.74	51.297	63.360
	Pedestrian Area	99 620 712	99 696 252	103 213 499	100 801 164	2.34	51.860	62.016
	Riverbed	119 908 714	118 580 152	125 178 190	118 332 951	5.47	60.391	68.141
	Rush Hour	99 749 460	98 499 727	103 614 730	99 877 156	3.61	52.937	61.907
	Station	112 477 884	111 988 815	118 656 710	111 535 748	6.00	58.266	65.922
	Sunflower	95 764 477	94 354 192	105 320 546	95 926 260	8.92	57.406	61.453
	Tractor	117 600 171	117 945 523	124 529 894	117 464 776	5.67	59.422	67.593

a) *Mode* 0

$$Pred_{GA}\left[i, j\right] = Clip((P_{ga}\left[i, j\right] + 2) \gg 2). \tag{16}$$

b) *Mode* 1

$$Pred_{H}\left[i, j\right] = Clip((P_{h}\left[i-1, j\right] + 16) \gg 5). \tag{17}$$

c) *Mode* 2

$$Pred_{V}\left[i, j\right] = Clip((P_{v}\left[i, j\right] + 16) \gg 5). \tag{18}$$

In the horizontal mode (Mode 1), the prediction value is derived by horizontal half pixel interpolation of S_1 as shown in Fig. 3(c). In the vertical mode (Mode 2), the prediction value is derived by vertical half pixel interpolation of S_0. In the Gaussian average mode (Mode 0), the prediction value is derived by weighted averaging of the surrounding eight pixels.

B. Discussion

The proposed interleave prediction scheme aims to provide circumambient contexts for as many pixels as possible. Though the first sub-image acts as "seed" pixels at the expense of coding efficiency, obvious rewards can be obtained in future passes.

In addition to the prediction consideration, a brief complexity analysis of the interleave prediction is presented as follows. For one thing, our scheme needs extra downsampling preprocessing, which yet does not require much computation. For another, except for S_0, which is predicted as normal H.264/AVC processing, the newly designed prediction modes for S_1, S_2, and S_3 involve mainly addition (or subtraction), multiplication, and bit-wise right shift operations, whose computation amounts for each pixel are summarized in Table I. Considering only three prediction modes are adopted for S_1, S_2, and S_3, interleave prediction does not lead to a substantial increase in the complexity compared to H.264/AVC. Moreover, it should be noted that much "redundant" computation may be avoided from Table I. Specifically speaking, S_1's Mode 0 and Mode 1 along with S_2's Mode 0 and Mode 1 all require the horizontal half pixel interpolation of S_0; S_1's Mode 2 and S_3's Mode 2 both require the vertical half pixel interpolation of S_0; S_2's Mode 0 and Mode 2 both require the vertical half pixel interpolation of S_1. So if extra memory overhead is out of question, the interpolation intermediate values can be saved for later use, which may reduce the computation amounts further.

When the aforementioned prediction modes are applied to both luma and chroma blocks, clearly prediction values can be computed parallel for each pixel in the second, third, and fourth passes, which may reduce the computational complexity further in some cases. What is more, multi-resolution decompression is a natural byproduct of the four-pass scheme, which is friendly to many practical applications, e.g., for quick preview.

Last but not least, the proposed interleave prediction scheme can be regarded as a frame-level coding mode. Only flag bits are necessary for a frame to specify whether interleave prediction is applied. So our scheme necessitates only minor modification when integrated into the H.264/AVC framework.

IV. Experimental Results

The proposed scheme for the improvement of the H.264/AVC lossless intra coding is evaluated in the x264 rev602 [17]. To validate the effectiveness of our scheme, we perform experiments on representative 4:2:0 sequences, whose first 100 frames are lossless intra encoded with context-adaptive binary arithmetic coding applied.

Our scheme is compared to the latest H.264/AVC lossless intra coding, where luma is encoded in 4×4 or 16×16 partitions and chroma in 8×8 partitions as normal processing. In our scheme, S_0 is encoded in the same way as the above, while luma and chroma of S_1, S_2, and S_3, respectively, are encoded in 4×4 and 8×8 partitions for the time being, to which the newly designed multidirectional intra prediction modes are applied.

The experimental results for representative sequences are shown in Table II. From the results, we can see that compared to H.264/AVC, our scheme gives better compression for most of the sequences, and much higher compression can be observed for sequences of high resolution. Especially the compression ratio for sequences with rich textures, such as *Football*, *Waterfall*, *Harbor*, *Raven*, and *Sunflower*, is increased obviously. As in images of high resolution pixels often have a higher correlation with their surrounding neighbors, naturally our scheme of multidirectional prediction, whose performance depends highly on the correlation between pixels and their surrounding neighbors, performs better when applied to images of high resolution. The slight degradation for the *Foreman* and *News* sequences is due to the fact that their regular textures and large uniform areas can be well predicted by the multiple unidirectional prediction modes of H.264/AVC, which leaves few margins of improvement to the proposed multidirectional prediction. Besides, the low resolution of the *Foreman* and *News* sequences also goes against multidirectional prediction. But on the whole, multidirectional prediction can still make great gains for intra coding, which validates the effectiveness of the proposed pixel-wise spatial interleave prediction as well. Additionally, the resultant file sizes of JPEG-LS (based on JPEG-LS reference encoder v1.00 [18]) and motion JPEG2000 (based on OpenJPEG v1.4 [19]) are also shown in Table II. It can be seen that our scheme is comparable to these two standards for many sequences of high resolution.

To evaluate the computational complexity of our scheme, we have measured the encoding time of our scheme and the original encoder on a platform with 2.33 GHz CPU and 2 GB RAM. For fair comparison, in our scheme we do not employ extra memory to save the interpolation intermediate values for repeat use, and the measured encoding time is also tabulated in Table II. We can see that despite the repeat computation of the interpolation intermediate values, the encoding time of our scheme does not increase much in comparison to H.264/AVC, which enables the proposed multidirectional interleave prediction a promising frame-level intra coding mode.

V. Conclusion

In this letter, a novel improvement option for the H.264/AVC lossless coding was proposed, which uses pixel-wise interleave prediction to perform multidirectional intra prediction. The scheme was proved to make obvious coding gains for sequences of high resolution, and can be integrated into the H.264/AVC framework easily as a frame-level coding mode. Further, mode refinement and extension to lossy coding is underway.

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