LOSSLESS COMPRESSION OF MEDICAL IMAGES BASED ON HEVC INTRA CODING

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ABSTRACT

The recent introduction of the High Efficiency Video Coding (HEVC) standard provides opportunities to improve medical image compression in picture archiving and communications systems. In this paper, we propose improvements to the HEVC intra coding process for lossless compression of grayscale anatomical medical images, which are characterized by their large amount of edges. Specifically, we propose alternative angular and planar prediction modes that are based on sample-wise differential pulse code modulation (DPCM) with an increased range of directionalities. We also propose an implementation of the DPCM decoding process that maintains the block-wise coding structure of HEVC. Evaluation results on various medical images show that the proposed DPCM modes efficiently predict the large amount of edges in these images achieving bit-rate savings of up to 15%.

Index Terms— HEVC intra coding, medical images, lossless compression

1. INTRODUCTION

Lossless compression has been long recognized by the medical and information technology communities as the most appropriate solution to reduce the storage and transmission resources associated with medical images, while guaranteeing their perfect reconstruction [1]. With the widespread use of picture archiving and communications systems (PACS), it is advisable that any compression solution adhere to the Digital Imaging and Communications in Medicine (DICOM) standard [2]. To this end, a number of important proposals based on DICOM-compliant compression methods, such as JPEG2000 and H.264/AVC, have been previously made [3-7]. For example, [3] introduces the use of JPEG2000 and JPIP (JPEG2000 Interactive Protocol) for remote access and visualization of 3D medical images. The work in [4] presents a method for compression of digital mammography using the region of interest coding and scalability properties of JPEG2000; and in [5-7] the authors tailor the H.264/AVC standard for lossless compression of 3D and 4D medical images based on the observation that slices of these high-dimensional data may be treated as frames of video sequences.

The recent introduction of the High Efficiency Video Coding (HEVC) standard [8-10] opens new possibilities for improved lossless compression of medical imaging data in PACS. HEVC has already shown to provide significant improvements in coding efficiency of video sequences compared to its predecessor H.264/AVC, achieving bit-rate reductions in the range of 50% for equal perceptual quality [9,10]. Similarly to H.264/AVC, HEVC features two coding modes, inter-picture and intra-picture coding. In inter-picture coding, frames are coded on a block-by-block basis by using temporally predictive coding with motion compensation and estimation. In intra-picture coding, frames are coded on a block-by-block basis by using spatial data prediction within the same frame. Intra-picture coding (hereafter referred to as intra coding) is particularly suitable for medical images, as it allows compressing not only 2D, but also 3D imaging data, which is useful to randomly access any slice without decoding the entire 3D data set.

In this paper, we focus on the HEVC intra coding process as a compression method with great potential to be adopted by DICOM. We specifically concentrate on lossless compression of grayscale anatomical medical images, such as slices of magnetic resonance imaging (MRI), computed tomography (CT), and X-ray angiography (angio) sequences, since these data are known to be challenging to compress due to their high number of edges. To this end, we tailor the HEVC intra coding process to accurately predict edge information by performing intra prediction using sample-wise differential pulse code modulation (DPCM) with an increased range of directionalities. In order to maintain the block-wise coding structure of HEVC, we also propose an implementation of the DPCM intra coding process that is amenable for parallelization at the decoder.

Performance evaluations on various MRI, CT and X-ray angio sequences show that our proposed intra coding process achieves higher lossless compression ratios when compared to current HEVC intra coding, and competitive performance when compared to two DICOM-compliant methods, JPEG-LS and JPEG2000.

The rest of the paper is organized as follows. We briefly review HEVC intra coding in Section 2. We describe our proposed DPCM intra coding process and discuss how it relates to prior work in Section 3. Performance evaluations are presented in Section 4. Section 5 concludes this paper.

2. HEVC INTRA CODING

The main goal of intra coding in HEVC is to reduce the energy of video frames by predicting each on a block-by-block basis using only information contained within the same frame. Energy reductions are achieved by computing the residual signal, which is the difference between the original frame and its prediction. In the case of lossless compression, any processing that affects the perfect reconstruction of the frame is bypassed and the residual signal is fed directly to the entropy coder [10].

HEVC intra coding features a set of angular prediction modes to model 33 different directional patterns; a DC and planar prediction mode to generate smooth surfaces, and adaptive filtering of reference samples and block boundaries to avoid the introduction of artificial edges in the residual signal [10]. Fig. 1(a) illustrates the prediction directions associated with the angular modes in HEVC.

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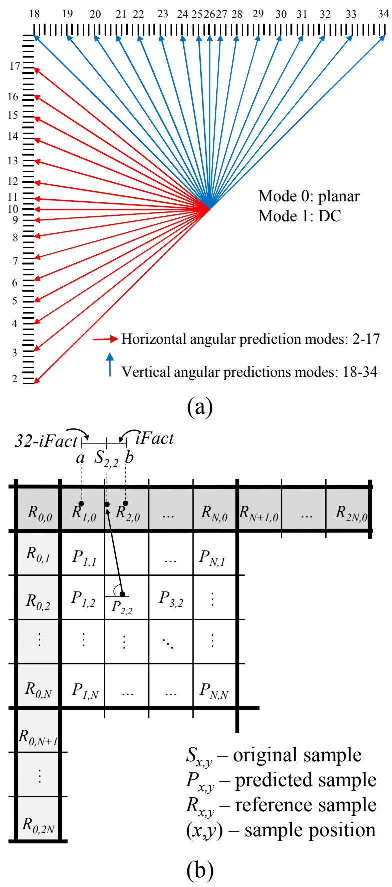

Fig. 1. (a) Intra prediction modes in HEVC. Angular modes are classified into two groups: vertical and horizontal. (b) Example of the prediction principle using interpolation at 1/32 pixel accuracy. *iFact* is the distance between sample $S_{x,y}$ and reference sample b. Reference samples used for prediction are: $\{R_{0,1}, R_{0,2},\ldots, R_{0,2N}\}$ – located to the left of the current block and $\{R_{0,0}, R_{1,0},\ldots, R_{2N,0}\}$ – located above of the current block.

The basic prediction principle for all angular modes is exemplified in Fig. 1(b). Each predicted sample $P_{x,y}$ is obtained by projecting its location (x,y) to the reference row or column applying the selected prediction direction and interpolating a value for the sample at 1/32 pixel accuracy, so that $P_{x,y} = ((32-iFact)*a + iFact*b + 16) >> 5$, where a and b are reference samples, >> denotes a bit shift operation to the right, and *iFact* is the distance measured between the original sample $S_{x,y}$ and b. All prediction modes in HEVC use the same set of reference samples from above and to the left of the current block, as shown in Fig. 1(b).

The angular modes in HEVC intra coding are designed based on the observation that in most natural imagery, horizontal and vertical patterns occur more frequently than patterns with other directionalities [10]. To this end, the density of modes close to horizontal and vertical directions is higher than that of modes close to diagonal directions. In the case of anatomical medical images, patterns with other directionalities also occur frequently due mainly to the high number of edges [11]. As a consequence, smooth regions tend to be less frequent in these images making it less efficient to predict the data using blocks with prediction values that are generated using only a limited number of reference samples. Based on this observation, we propose alternative prediction modes that employ sample-wise DPCM with an increased range of directionalities. The objective is to better predict edge information by exploiting data correlations at a pixel level.

3. PROPOSED DPCM INTRA CODING

Intra coding based on DPCM is first introduced in [12] for all intra prediction modes of H.264/AVC that employ a single sample as predictor. Later, the work in [13] proposes the use of DPCM for the HEVC angular modes maintaining the same range of directionalities but altering the block-wise coding structure of the standard. In [14], prediction based on the LOCO-I algorithm is introduced as a post-processing step on the residual signal computed by the original HEVC intra coding process. This post-processing step, however, adds an extra coding step to the pipeline and alters the block-wise coding structure of HEVC. In this work, we apply DPCM to all modes in HEVC intra coding without altering the block-wise coding structure. Specifically, we tailor the prediction modes to grayscale anatomical medical images by increasing the range of available directionalities for angular prediction and by employing a single mode in lieu of the current DC and planar mode.

Figure 2(a)-(b) illustrates the prediction directions associated with our proposed DPCM angular modes, while Fig. 2(c) depicts the prediction principle. Table 1 summarizes the corresponding prediction operations. Note that the proposed modes have 1/4 pixel accuracy and cover a wider range of directions including angles smaller than $\pi/4$ rad. For each sample $S_{x,y}$, the corresponding prediction sample $P_{x,y}$ is computed by using a set of the neighboring samples located at positions $\{a, b, c, d, e, f, g, h, i\}$, according to the prediction mode used. For example, for proposed mode 23 [see Table 1 and Fig. 2(c)], predicted sample $P_{2,2}$ is calculated using neighboring samples at positions $\{e, f\}$ as $P_{2,2} = (e + 3f) >> 2$, with $e = S_{1,1}$ and $f = S_{2,1}$. Note that unlike the current HEVC intra coding process, the proposed modes result in a constant density of modes in all directions. This allows us exploiting correlations among neighboring pixels equally in all directions and account for the observation that grayscale anatomical medical images frequently depict patterns in various directions other than horizontal and vertical.

For the DC and planar modes, we propose using a single DPCM DC mode that computes the average of neighboring samples at positions $\{c, f\}$ to predict the current sample $S_{x,y}$, as illustrated in Fig. 3. This can be regarded as an alternative way of doing planar prediction at a sample level.

3.1. Parallelization of proposed modes

The proposed DPCM modes may alter the block-wise coding structure of HEVC since the decoder now requires that samples be decoded sequentially and be readily available for the prediction and reconstruction of subsequent samples. To solve this issue, we propose implementing all proposed modes at the decoder as a spatial residual transform that only depends on the residual samples and the reference samples from above and to the left of the current block. To illustrate this, let us take proposed modes 6-10, which depend on neighboring samples at positions $\{b,c\}$ for prediction. For a 4×4 block, samples $S_{1,1}$ and $S_{2,1}$ may be reconstructed at the decoder as:

$$S_{1,1} = r_{1,1} + P_{1,1} \tag{1}$$

$$S_{2,1} = r_{2,1} + P_{2,1} \tag{2}$$

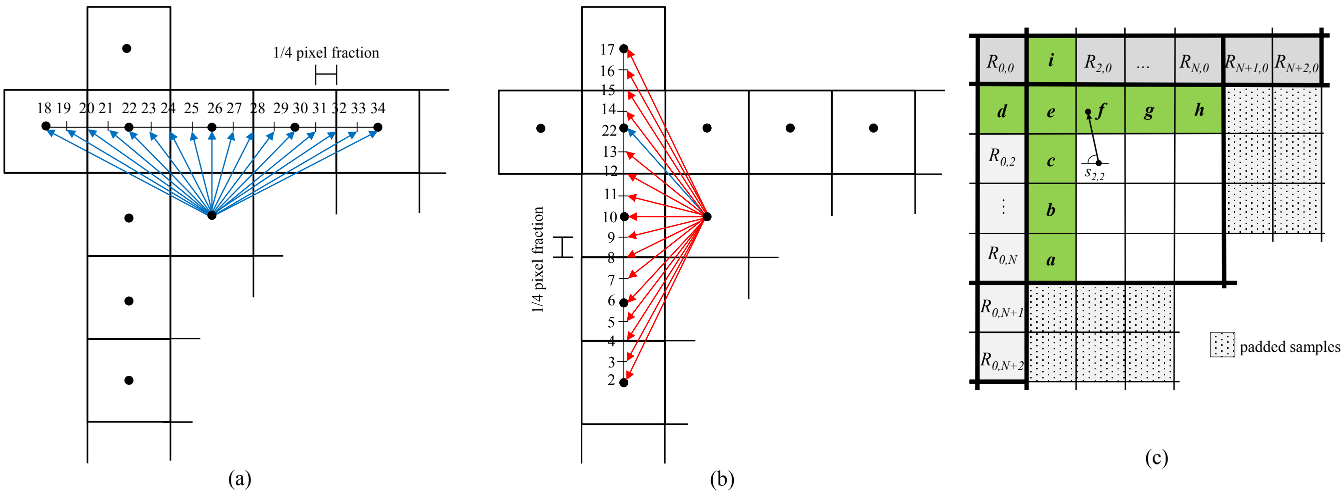

Fig. 2. Prediction directions associated with the proposed DPCM angular modes, classified as (a) vertical and (b) horizontal modes. (c) Prediction principle of the proposed DPCM angular modes. Neighboring reference samples that are unavailable for prediction, e.g., samples in neighboring blocks yet to be coded, are padded with boundary samples of the current block.

Table 1. Prediction operation for the proposed angular modes

Mode	Prediction operation	Mode	Prediction operation
Vertical angular modes			
2	$P_{x,y} = a$	10	$P_{x,y} = c$
3	$P_{x,y} = (3a + b) >> 2$	11	$P_{x,y} = (3c + e) >> 2$
4	$P_{x,y} = (a + b) >> 1$	12	$P_{x,y} = (c + e) >> 1$
5	$P_{x,y} = (a + 3b) >> 2$	13	$P_{x,y} = (c+ 3e) >> 2$
6	$P_{x,y} = b$	14	$P_{x,y} = (3e + i) >> 2$
7	$P_{x,y} = (3b + c) >> 2$	15	$P_{x,y} = (e + i) >> 1$
8	$P_{x,y} = (b + c) >> 1$	16	$P_{x,y} = (e + 3i) >> 1$
9	$P_{x,y} = (b + 3c) >> 2$	17	$P_{x,y} = i$
Horizontal angular modes			
18	$P_{x,y} = d$	26	$P_{x,y} = f$
19	$P_{x,y} = (3d + e) >> 2$	27	$P_{x,y} = (3f+ g) >> 2$
20	$P_{x,y} = (d + e) >> 1$	28	$P_{x,y} = (f+ g) >> 1$
21	$P_{x,y} = (d + 3e) >> 2$	29	$P_{x,y} = (f+ 3g) >> 2$
22	$P_{x,y} = e$	30	$P_{x,y} = g$
23	$P_{x,y} = (3e + f) >> 2$	31	$P_{x,y} = (3g + h) >> 2$
24	$P_{x,y} = (e + f) >> 1$	32	$P_{x,y} = (g + h) >> 1$
25	$P_{x,y} = (e + 3f) >> 2$	33	$P_{x,y} = (g + 3h) >> 2$
		34	$P_{x,y} = h$

where $r_{x,y}$ denotes the residual sample at position (x,y). Let us now define predicted samples $P_{1,1}$ and $P_{2,1}$ in terms of the reference samples $\{R_{0,1}, R_{0,2},\ldots, R_{0,2N}\}$ located to the left and the reference samples $\{R_{0,0}, R_{1,0},\ldots, R_{2N,0}\}$ located above of the current block. Let us also use a set of weights to denote the contribution of each reference sample to the predicted sample, so that $P_{1,1} = w_bR_{0,2} + w_cR_{0,1}$ and $P_{2,1} = w_bS_{1,2} + w_cS_{1,1}$, where $S_{1,1}$ is as given in Eq. (1), $S_{1,2} = r_{1,2} + w_bR_{0,3} + w_cR_{0,2}$ and w_b and w_c are the weights applied to the reference samples at positions b and c, respectively. Equations (1)-(2) may then be expressed as:

$$S_{1,1} = r_{1,1} + w_bR_{0,2} + w_cR_{0,1} \tag{3}$$

$$S_{2,1} = r_{2,1} + w_br_{1,2} + w_cr_{1,1} + w_b^2R_{0,3} + 2w_bw_cR_{0,2} + w_c^2R_{0,1} \tag{4}$$

The reconstruction of samples $S_{1,1}$ and $S_{2,1}$ now depends only on residual and reference samples, which are readily available for any block when a block-wise decoding structure is followed. Following the same reasoning leading to Eq. (3)-(4), the rest of the

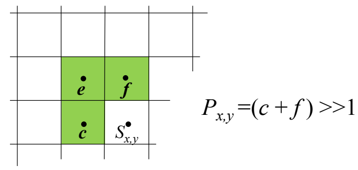

Fig. 3. Proposed DPCM DC mode and the corresponding prediction operation.

samples in the first row of a 4×4 block may be reconstructed using the following matrix equation:

$$\begin{aligned}
\begin{bmatrix} S_{1,1} \\ S_{2,1} \\ S_{3,1} \\ S_{4,1} \end{bmatrix} &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ w_c & 1 & 0 & 0 \\ w_c^2 & w_c & 1 & 0 \\ w_c^3 & w_c^2 & w_c & 1 \end{bmatrix} \begin{bmatrix} r_{1,1} \\ r_{2,1} \\ r_{3,1} \\ r_{4,1} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & w_b & 0 & 0 \\ 0 & 2w_bw_c & w_b & 0 \\ 0 & w_bw_c^2 & 2w_bw_c & w_b \end{bmatrix} \begin{bmatrix} 0 \\ r_{1,2} \\ r_{2,2} \\ r_{3,2} \end{bmatrix} \\
&+ \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & w_b^2 & 0 \\ 0 & 0 & w_b^2w_c & w_b^2 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ r_{1,3} \\ r_{2,3} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & w_b^3 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ r_{1,4} \end{bmatrix} + R_{0,1} \begin{bmatrix} w_c \\ w_c^2 \\ w_c^3 \\ w_c^4 \end{bmatrix} \\
&+ R_{0,2} \begin{bmatrix} w_b \\ 2w_bw_c \\ 3w_bw_c^2 \\ 2w_bw_c^3 \end{bmatrix} + R_{0,3} \begin{bmatrix} 0 \\ w_b^2 \\ 3w_b^2w_c \\ 2w_b^2w_c^2 \end{bmatrix} + R_{0,4} \begin{bmatrix} 0 \\ 0 \\ w_b^2 \\ 2w_b^3w_c \end{bmatrix} + R_{0,5} \begin{bmatrix} 0 \\ 0 \\ 0 \\ w_b^3 \end{bmatrix}
\end{aligned} \tag{5}$$

The matrix in (5) constitutes a general expression for the reconstruction of the first row of a 4×4 block for all modes that depend on neighboring samples at position b or c, or both. For example, if we set $w_b = 0$ and $w_c = 1$, (5) constitutes the expression for proposed mode 10 (directly horizontal). Similar expressions may be obtained for the reconstruction of the remaining rows of a 4×4 block and thus, for any N×N block.

Although the implementation of the proposed DPCM modes requires modifications to the originally codec, they can be fully parallelized at the decoder by implementing the decoding process using a matrix representation like the one in (5). Additionally, this

Table 2. Lossless compression ratios for the test data set; bpp savings are reported in % within parenthesis, with respect to HEVC intra coding.

Modality (slices:pixels per slice:bpp)	**Compression method**				
	Proposed DPCM	Method in [13]	HEVC intra coding	J2K	JPEG-LS
1.MRI (11:512×512:8)	**2.57 (15.24%)**	2.47 (10.76%)	2.23	2.87	2.81
2.MRI (50:512×512:8)	**5.13 (4.69%)**	5.02 (2.44%)	4.90	5.03	5.38
3.MRI (100:256×256:8)	**2.43 (4.74%)**	2.37 (2.15%)	2.32	2.31	2.42
4.CT (596:512×512:12)	**2.42 (6.60%)**	2.33 (2.64%)	2.27	2.57	2.58
5.CT (637:512×512:12)	**2.43 (8.96%)**	2.34 (4.93%)	2.23	2.71	2.65
6.CT (82:512×512:12)	**2.87 (7.89%)**	2.78 (4.51%)	2.66	3.01	3.00
7.Angio (151:512×512:12)	**2.35 (3.98%)**	2.31 (2.21%)	2.26	2.51	2.53
8.Angio (186:512×512:12)	**2.32 (4.03%)**	2.28 (2.24%)	2.23	2.49	2.51
9.Angio (271:512×512:12)	**2.16 (0.93%)**	2.15 (0.46%)	2.14	2.34	2.36

matrix implementation allows maintaining the block-wise decoding structure of HEVC. It is important to note that the operations associated with this matrix implementation can be simplified to additions and multiplications using bit-shifts, which reduces its computational complexity. For example, for proposed mode 8, sample $S_{2,1}$ in (5) is computed as $S_{2,1} = r_{2,1} + w_b r_{1,2} + w_c r_{1,1} + (w_b w_b)R_{0,3} + (2w_b w_c)R_{0,2} + (w_c w_c)R_{0,1}$ with $w_b = ½$ and $w_c = ½$, which can be implemented as $S_{2,1} = r_{2,1} + r_{1,2}{>>}1 + r_{1,1}{>>}1 + R_{0,3}{>>}2 + R_{0,2}{>>}1 + R_{0,1}{>>}2$.

4. EXPERIMENTAL RESULTS

The coding efficiency of the proposed DPCM modes is tested on several slices of MRI, CT and X-ray angio sequences, whose characteristics are summarized in Table 2, column 1. Sequences 1 and 2 comprise MRI slices of the sagittal view of a human spinal cord and knee, respectively. Sequence 3 comprises MRI slices of the axial view of a human brain. Sequences 4-6 comprise CT slices of the axial view of a human thorax, while sequences 7-9 comprise X-ray slices of a vascular study of a human heart.

The proposed modes are implemented in all block sizes with a maximum size of 32×32. Experiments are performed using the HM11.0 software [15] with the Main-Still-Picture profile in lossless mode, i.e., only intra coding is employed and the transform and quantization processes are bypassed. In order to comply with this profile, all slices are coded in the YUV 4:2:0 format by adding a zero-valued sub-sampled chroma component. These chroma components are not included in the final bit-rate calculations. We compare the proposed DPCM modes to HEVC intra coding, the modes proposed in [13] and two DICOM-compliant methods, JPEG2000 (J2K) and JPEG-LS. For JPEG2000, we employ the BOI [16] implementation with 5 levels of 5/3 reversible spatial wavelet transform and code-blocks of size 64×64. For JPEG-LS, we employ the HP implementation [17] with a 64 reset interval.

Lossless compression ratios tabulated in Table 2 show that our proposed DPCM modes achieve bit-rate savings of up to 15.24% for MRI sequences and up to 8.96% for CT sequences, compared to current HEVC intra coding. Compared to the modes proposed in [13], which are also based on DPCM, our modes further reduce the bit-rate by up to 4.5%, confirming the advantages of a using an increased range of directionalities with a constant density of modes in all directions. The proposed modes achieve competitive results compared to J2K and JPEG-LS

Fig. 4. Sample slice of test sequence 1. Notice the large number of edges and well defined structures.

For the X-ray angio sequences, the average coding improvements achieved by our proposed modes and those in [13] are only 3.00 % and 1.64%, respectively. These particular sequences feature a large amount of noise with frequent variations in intensity among neighboring pixels, making them hard to compress [18]. Overall, the proposed modes provide the best coding improvement for the CT sequences, which are 12 bpp data. This may be attributed to the fact that the entropy coder of HEVC is very efficient for low-energy residual signals. In the case of 8 bpp data (e.g., the MRI sequences) the residual signals produced by HEVC intra coding have in general low energy and thus, limited improvements may be achieved by the entropy coder when our proposed modes are applied. On the other hand, for 12 bbp data, the further energy reductions on the residual signal achieved by our proposed modes result on an improved performance at the entropy coder. Interesting to note is the fact that the best coding improvements are achieved for test sequence 1. A sample slice of this sequence is depicted in Fig. 4. Notice the large number of edges and well defined structures. It is expected that sample-wise DPCM prediction outperforms block-based prediction for images like this one, as edges are best predicted by exploiting correlations among neighboring pixels.

5. CONCLUSIONS

In this paper, we focused on the HEVC intra coding process as a potential compression method to be included in DICOM. Specifically, we proposed intra prediction modes for coding grayscale anatomical medical images with several edges. The proposed modes, which are based on sample-wise DPCM prediction, feature an increased range of directionalities, which allows exploiting correlation among neighboring pixels and accurately predict edge information. We also proposed an implementation of the DPCM decoding process that is amenable for parallelization and thus, maintains the block-wise coding structure of HEVC. Performance evaluations showed that the proposed modes attain bit-rate savings of up to 15% over current HEVC intra coding.

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