CORE TRANSFORM DESIGN FOR HIGH EFFICIENCY VIDEO CODING (HEVC)

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Core Transform in HEVC

- HEVC -- High Efficiency Video Coding
  - Emerging video coding standard developed by JCT-VC of ITU-T/VCEG and ISO/IEC/MPEG.
  - Focused on HD and ultra HD videos
  - Coding unit size up to $2^K \times 2^K$ (K set in SPS)
  - Transform size scaled accordingly
    - 16×16 and 32×32 for large homogeneous regions
    - 4×4 and 8×8 for detail-rich regions
- Highly desired features in integer transform design
  - High energy compaction capability
  - Equal L^2 norms of basis vectors
  - Orthogonal
  - Flexibility in implementation (matrix multiplication and fast algorithm)
  - 16-bit integer arithmetic

Factorizable Transform Matrices

- Even-Odd Part Decomposition
  - Order-2*N* DCT matrix $\mathbf{T}_{DCT}^{(2N)}$

$$\mathbf{T}_{DCT}^{(2N)} = \begin{bmatrix} \frac{1}{\sqrt{2}}\mathbf{T}_{DCT}^{(N)} & 0 \\ 0 & \mathbf{P}_{DCT}^{(N)} \end{bmatrix} \begin{bmatrix} \mathbf{I}_N & \mathbf{J}_N \\ \mathbf{I}_N & -\mathbf{J}_N \end{bmatrix}$$

  - Proposed order-2*N* integer transform matrix $\mathbf{T}_{2N}$

$$\mathbf{T}_{2N} = \begin{bmatrix} s_N \mathbf{T}_N & 0 \\ 0 & \mathbf{P}_N \end{bmatrix} \begin{bmatrix} \mathbf{I}_N & \mathbf{J}_N \\ \mathbf{I}_N & -\mathbf{J}_N \end{bmatrix}$$

$$\mathbf{T}_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

Factorizable Transform Matrices (Order-8)

- Odd Part of Order-8 DCT $\mathbf{P}_{DCT}^{(4)}$

$$\mathbf{P}_{DCT}^{(4)} = \begin{bmatrix} A_4 & B_4 & C_4 & D_4 \\ B_4 & -D_4 & -A_4 & -C_4 \\ C_4 & -A_4 & D_4 & B_4 \\ D_4 & -C_4 & B_4 & -A_4 \end{bmatrix} = \begin{bmatrix} \frac{1}{\sqrt{2}}(B_4+C_4) & \frac{1}{\sqrt{2}}(A_4+D_4) & \frac{1}{\sqrt{2}}(A_4-D_4) & \frac{1}{\sqrt{2}}(B_4-C_4) \\ B_4 & -D_4 & -A_4 & -C_4 \\ C_4 & -A_4 & D_4 & B_4 \\ \frac{1}{\sqrt{2}}(B_4-C_4) & -\frac{1}{\sqrt{2}}(A_4-D_4) & \frac{1}{\sqrt{2}}(A_4+D_4) & -\frac{1}{\sqrt{2}}(B_4+C_4) \end{bmatrix}$$

- Elements' magnitudes

$$[A_4, B_4, C_4, D_4] = \left[\frac{1}{2}\cos\left(\frac{\pi}{16}\right) \quad \frac{1}{2}\cos\left(\frac{3\pi}{16}\right) \quad \frac{1}{2}\cos\left(\frac{5\pi}{16}\right) \quad \frac{1}{2}\cos\left(\frac{7\pi}{16}\right)\right]$$

[1] C. Loeffler, A. Ligtenberg, and G. S. Moschytz, "Practical fast 1-D DCT algorithms with 11 multiplications," in *Proc. IEEE Int. Conf. Acoust. Speech Signal Process.*, vol. 2. May 1989, pp. 988–991.

Factorizable Transform Matrices (Order-8)

- Odd part of the Proposed Order-8 Integer Transform

$$\mathbf{P}_4 = \begin{bmatrix} h_4e_4(b_4+c_4) & h_4f_4(a_4+d_4) & h_4f_4(a_4-d_4) & h_4e_4(b_4-c_4) \\ k_4j_4b_4 & -k_4i_4d_4 & -k_4i_4a_4 & -k_4j_4c_4 \\ k_4j_4c_4 & -k_4i_4a_4 & k_4i_4d_4 & k_4j_4b_4 \\ h_4e_4(b_4-c_4) & -h_4f_4(a_4-d_4) & h_4f_4(a_4+d_4) & -h_4e_4(b_4+c_4) \end{bmatrix}$$

$$= \begin{bmatrix} h_4 & 0 & 0 & h_4 \\ 0 & 0 & k_4 & 0 \\ 0 & k_4 & 0 & 0 \\ h_4 & 0 & 0 & -h_4 \end{bmatrix} \times \begin{bmatrix} e_4 & 0 & f_4 & 0 \\ 0 & -i_4 & 0 & j_4 \\ j_4 & 0 & -i_4 & 0 \\ 0 & f_4 & 0 & e_4 \end{bmatrix} \times \begin{bmatrix} a_4 & 0 & 0 & -b_4 \\ 0 & c_4 & -d_4 & 0 \\ 0 & d_4 & c_4 & 0 \\ b_4 & 0 & 0 & a_4 \end{bmatrix}$$

- **Elements' Relation 1**
  1. $(b_4+c_4)/(b_4-c_4) \approx a_4/d_4 \approx A_4/D_4$ and $(a_4+d_4)/(a_4-d_4) \approx b_4/c_4 \approx B_4/C_4$
  2. $(i_4a_4)/(j_4b_4) \approx (e_4(b_4+c_4))/(f_4(a_4+d_4)) \approx A_4/B_4$
  3. $h_4f_4(a_4+d_4) \approx k_4j_4b_4$ and $h_4e_4(b_4+c_4) \approx k_4i_4a_4$

Factorizable Transform Matrices (Order-16)

- Odd Part of Order-16 DCT $\mathbf{P}_{DCT}^{(8)}$

$$
\mathbf{P}_{DCT}^{(8)} = \begin{bmatrix}
A_8 & B_8 & C_8 & D_8 & E_8 & F_8 & G_8 & H_8 \\
B_8 & E_8 & H_8 & -F_8 & -C_8 & -A_8 & -D_8 & -G_8 \\
C_8 & H_8 & -D_8 & -B_8 & -G_8 & E_8 & A_8 & F_8 \\
D_8 & -F_8 & -B_8 & H_8 & A_8 & G_8 & -C_8 & -E_8 \\
E_8 & -C_8 & -G_8 & A_8 & -H_8 & -B_8 & F_8 & D_8 \\
F_8 & -A_8 & E_8 & G_8 & -B_8 & D_8 & H_8 & -C_8 \\
G_8 & -D_8 & A_8 & -C_8 & F_8 & H_8 & -E_8 & B_8 \\
H_8 & -G_8 & F_8 & -E_8 & D_8 & -C_8 & B_8 & -A_8
\end{bmatrix}
$$

$$
= \begin{bmatrix}
\frac{1}{\sqrt{2}}(D_8+E_8) & \frac{1}{\sqrt{2}}(C_8+F_8) & \frac{1}{\sqrt{2}}(B_8+G_8) & \frac{1}{\sqrt{2}}(A_8+H_8) & \frac{1}{\sqrt{2}}(A_8-H_8) & \frac{1}{\sqrt{2}}(B_8-G_8) & \frac{1}{\sqrt{2}}(C_8-F_8) & \frac{1}{\sqrt{2}}(D_8-E_8) \\
E_8I_8+D_8J_8 & -F_8I_8+C_8J_8 & B_8I_8-G_8J_8 & -A_8I_8-H_8J_8 & H_8I_8-A_8J_8 & -G_8I_8-B_8J_8 & -C_8I_8-F_8J_8 & D_8I_8-E_8J_8 \\
D_8I_8+E_8J_8 & -C_8I_8+F_8J_8 & G_8I_8-B_8J_8 & -H_8I_8-A_8J_8 & -A_8I_8+H_8J_8 & B_8I_8+G_8J_8 & F_8I_8+C_8J_8 & -E_8I_8+D_8J_8 \\
D_8 & -F_8 & -B_8 & H_8 & A_8 & G_8 & -C_8 & -E_8 \\
E_8 & -C_8 & -G_8 & A_8 & -H_8 & -B_8 & F_8 & D_8 \\
-E_8I_8+D_8J_8 & -F_8I_8-C_8J_8 & B_8I_8+G_8J_8 & A_8I_8-H_8J_8 & -H_8I_8-A_8J_8 & -G_8I_8+B_8J_8 & -C_8I_8+F_8J_8 & -D_8I_8-E_8J_8 \\
-D_8I_8+E_8J_8 & -C_8I_8-F_8J_8 & G_8I_8+B_8J_8 & H_8I_8-A_8J_8 & A_8I_8+H_8J_8 & B_8I_8-G_8J_8 & F_8I_8-C_8J_8 & E_8I_8+D_8J_8 \\
\frac{1}{\sqrt{2}}(D_8-E_8) & -\frac{1}{\sqrt{2}}(C_8-F_8) & \frac{1}{\sqrt{2}}(B_8-G_8) & -\frac{1}{\sqrt{2}}(A_8-H_8) & \frac{1}{\sqrt{2}}(A_8+H_8) & -\frac{1}{\sqrt{2}}(B_8+G_8) & \frac{1}{\sqrt{2}}(C_8+F_8) & -\frac{1}{\sqrt{2}}(D_8+E_8)
\end{bmatrix}
$$

$$
[A_8, B_8, C_8, \ldots, G_8, H_8] = \left[\frac{1}{\sqrt{8}}\cos\left(\frac{\pi}{32}\right) \quad \frac{1}{\sqrt{8}}\cos\left(\frac{3\pi}{32}\right) \quad \frac{1}{\sqrt{8}}\cos\left(\frac{5\pi}{32}\right) \quad \frac{1}{\sqrt{8}}\cos\left(\frac{7\pi}{32}\right) \quad \ldots\ldots \quad \frac{1}{\sqrt{8}}\cos\left(\frac{13\pi}{32}\right) \quad \frac{1}{\sqrt{8}}\cos\left(\frac{15\pi}{32}\right)\right]
$$

Factorizable Transform Matrices (Order-16)

- Odd part of the Proposed Order-16 Integer Transform

$$
\mathbf{P}_8 = \begin{bmatrix}
l_8(d_8+e_8) & l_8(c_8+f_8) & l_8(b_8+g_8) & l_8(a_8+h_8) & l_8(a_8-h_8) & l_8(b_8-g_8) & l_8(c_8-f_8) & l_8(d_8-e_8) \\
e_8 i_8 + d_8 j_8 & -f_8 i_8 + c_8 j_8 & b_8 i_8 - g_8 j_8 & -a_8 i_8 - h_8 j_8 & h_8 i_8 - a_8 j_8 & -g_8 i_8 - b_8 j_8 & -c_8 i_8 - f_8 j_8 & d_8 i_8 - e_8 j_8 \\
d_8 i_8 + e_8 j_8 & -c_8 i_8 + f_8 j_8 & g_8 i_8 - b_8 j_8 & -h_8 i_8 - a_8 j_8 & -a_8 i_8 + h_8 j_8 & b_8 i_8 + g_8 j_8 & f_8 i_8 + c_8 j_8 & -e_8 i_8 + d_8 j_8 \\
k_8 d_8 & -k_8 f_8 & -k_8 b_8 & k_8 h_8 & k_8 a_8 & k_8 g_8 & -k_8 c_8 & -k_8 e_8 \\
k_8 e_8 & -k_8 c_8 & -k_8 g_8 & k_8 a_8 & -k_8 h_8 & -k_8 b_8 & k_8 f_8 & k_8 d_8 \\
-e_8 i_8 + d_8 j_8 & -f_8 i_8 - c_8 j_8 & b_8 i_8 + g_8 j_8 & a_8 i_8 - h_8 j_8 & -h_8 i_8 - a_8 j_8 & -g_8 i_8 + b_8 j_8 & -c_8 i_8 + f_8 j_8 & -d_8 i_8 - e_8 j_8 \\
-d_8 i_8 + e_8 j_8 & -c_8 i_8 - f_8 j_8 & g_8 i_8 + b_8 j_8 & h_8 i_8 - a_8 j_8 & a_8 i_8 + h_8 j_8 & b_8 i_8 - g_8 j_8 & f_8 i_8 - c_8 j_8 & e_8 i_8 + d_8 j_8 \\
l_8(d_8-e_8) & -l_8(c_8-f_8) & l_8(b_8-g_8) & -l_8(a_8-h_8) & l_8(a_8+h_8) & -l_8(b_8+g_8) & l_8(c_8+f_8) & -l_8(d_8+e_8)
\end{bmatrix}
$$

$$
\begin{bmatrix}
0 & 0 & 0 & l_8 & -l_8 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -j_8 & i_8 \\
i_8 & j_8 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & k_8 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & k_8 & 0 & 0 \\
j_8 & -i_8 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & i_8 & j_8 \\
0 & 0 & 0 & l_8 & l_8 & 0 & 0 & 0
\end{bmatrix}
\times
\begin{bmatrix}
-1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & -1 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\times
\begin{bmatrix}
-1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -1 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 1
\end{bmatrix}
\times
\begin{bmatrix}
d_8 & 0 & 0 & 0 & 0 & 0 & 0 & -e_8 \\
0 & f_8 & 0 & 0 & 0 & 0 & c_8 & 0 \\
0 & 0 & b_8 & 0 & 0 & -g_8 & 0 & 0 \\
0 & 0 & 0 & h_8 & a_8 & 0 & 0 & 0 \\
0 & 0 & 0 & -a_8 & h_8 & 0 & 0 & 0 \\
0 & 0 & g_8 & 0 & 0 & b_8 & 0 & 0 \\
0 & -c_8 & 0 & 0 & 0 & 0 & f_8 & 0 \\
e_8 & 0 & 0 & 0 & 0 & 0 & 0 & d_8
\end{bmatrix}
$$

- **Elements' Relation 2**
  1. $a_8 : b_8 : c_8 : d_8 : e_8 : f_8 : g_8 : h_8 \approx A_8 : B_8 : C_8 : D_8 : E_8 : F_8 : G_8 : H_8$
  2. $i_8 : j_8 : k_8 : l_8 \approx \cos\left(\frac{3\pi}{8}\right) : \sin\left(-\frac{3\pi}{8}\right) : 1 : \frac{1}{\sqrt{2}}$

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Factorizable Transform Matrices (Order-32)

- Odd Part of Order-32 DCT $\mathbf{P}_{DCT}^{(16)}$
  - Factorization proposed by Chen *et al*. cause high latency

$$\mathbf{P}_{DCT}^{(16)} = \mathbf{R}_7 \times \mathbf{R}_6 \times \mathbf{R}_5 \times \mathbf{R}_4 \times \mathbf{R}_3 \times \mathbf{R}_2 \times \mathbf{R}_1$$

- Odd Part of the Proposed Order-32 Integer Transform

$$\mathbf{P}_{16} = \mathbf{W} \times \mathbf{M}_4 \times \mathbf{M}_3 \times \mathbf{M}_2 \times \mathbf{M}_1$$

  - $\mathbf{M}_3, \mathbf{M}_1$ approximate $\mathbf{R}_3, \mathbf{R}_1$
  - $\mathbf{R}_4, \mathbf{R}_2$ are binary matrices and the same as $\mathbf{M}_4, \mathbf{M}_2$
  - $\mathbf{W}$ approximate $\mathbf{R}_7 \times \mathbf{R}_6 \times \mathbf{R}_5$

[2] W. H. Chen, C. H. Smith, and S. C. Fralick, “A fast computational algorithm for the discrete cosine transform”, *IEEE Trans. Commun.*, vol. 25, no. 9, pp.1004-1009, Sept. 1977.

Factorizable Transform Matrices (Order-32)

$$\mathbf{M}_1 = \begin{bmatrix}
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&x_0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&x_0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&x_0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&x_0&0&0&0\\
0&0&0&0&x_1&0&0&0&0&0&0&-x_1&0&0&0&0\\
0&0&0&0&0&x_1&0&0&0&0&-x_1&0&0&0&0&0\\
0&0&0&0&0&0&x_1&0&0&-x_1&0&0&0&0&0&0\\
0&0&0&0&0&0&0&x_1&-x_1&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&x_1&x_1&0&0&0&0&0&0&0\\
0&0&0&0&0&0&x_1&0&0&x_1&0&0&0&0&0&0\\
0&0&0&0&0&x_1&0&0&0&0&x_1&0&0&0&0&0\\
0&0&0&0&x_1&0&0&0&0&0&0&x_1&0&0&0&0\\
0&0&0&x_0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&x_0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&x_0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
x_0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0
\end{bmatrix}$$

$$\mathbf{M}_3 = \begin{bmatrix}
y_0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&y_0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&-y_2&0&0&0&0&0&0&0&0&0&0&y_1&0&0\\
0&0&0&-y_2&0&0&0&0&0&0&0&0&y_1&0&0&0\\
0&0&0&0&-y_1&0&0&0&0&0&0&-y_2&0&0&0&0\\
0&0&0&0&0&-y_1&0&0&0&0&-y_2&0&0&0&0&0\\
0&0&0&0&0&0&y_0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&y_0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&y_0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&y_0&0&0&0&0&0&0\\
0&0&0&0&0&-y_2&0&0&0&0&y_1&0&0&0&0&0\\
0&0&0&0&-y_2&0&0&0&0&0&0&y_1&0&0&0&0\\
0&0&0&y_1&0&0&0&0&0&0&0&0&y_2&0&0&0\\
0&0&y_1&0&0&0&0&0&0&0&0&0&0&y_2&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&y_0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&y_0
\end{bmatrix}$$

- **Elements' Relation 3**
  1. $x_0 : x_1 \approx \sqrt{2} : 1$
  2. $y_0 : y_1 : y_2 \approx 1 : \sin\left(\frac{\pi}{8}\right) : \cos\left(\frac{\pi}{8}\right)$

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Factorizable Transform Matrices (Order-32)

- Odd Part of the Proposed Order-32 Integer Transform

$$\mathbf{P}_{16} = \mathbf{W} \times \mathbf{M}_4 \times \mathbf{M}_3 \times \mathbf{M}_2 \times \mathbf{M}_1$$

$$\mathbf{W} = \mathbf{Z} \times \mathbf{X} \times \mathbf{Y}$$

  - $\mathbf{Z}, \mathbf{Y}$ are binary matrices with only one non-zero element in each row/column, used for re-ordering.
  - $\mathbf{X}$ is the only effective matrix in $\mathbf{W}$.

$$\mathbf{X} = \begin{bmatrix} \mathbf{X}_1 & 0 & 0 & 0 \\ 0 & \mathbf{X}_2 & 0 & 0 \\ 0 & 0 & \mathbf{X}_3 & 0 \\ 0 & 0 & 0 & \mathbf{X}_4 \end{bmatrix}$$

$$\mathbf{X}_1 = \begin{bmatrix} p_0 & p_1 & p_2 & p_3 \\ p_4 & p_5 & -p_6 & p_7 \\ -p_7 & -p_6 & -p_5 & p_4 \\ -p_3 & p_2 & -p_1 & p_0 \end{bmatrix} \quad \mathbf{X}_2 = \begin{bmatrix} q_0 & q_1 & q_2 & q_3 \\ -q_4 & q_5 & q_6 & -q_7 \\ -q_7 & -q_6 & q_5 & q_4 \\ q_3 & -q_2 & q_1 & -q_0 \end{bmatrix} \quad \mathbf{X}_3 = \begin{bmatrix} r_0 & r_1 & r_2 & r_3 \\ r_4 & r_5 & -r_6 & r_7 \\ -r_7 & -r_6 & -r_5 & r_4 \\ -r_3 & r_2 & -r_1 & r_0 \end{bmatrix} \quad \mathbf{X}_4 = \begin{bmatrix} v_0 & v_1 & v_2 & -v_3 \\ -v_4 & v_5 & v_6 & -v_7 \\ -v_7 & -v_6 & v_5 & v_4 \\ -v_3 & -v_2 & v_1 & -v_0 \end{bmatrix}$$

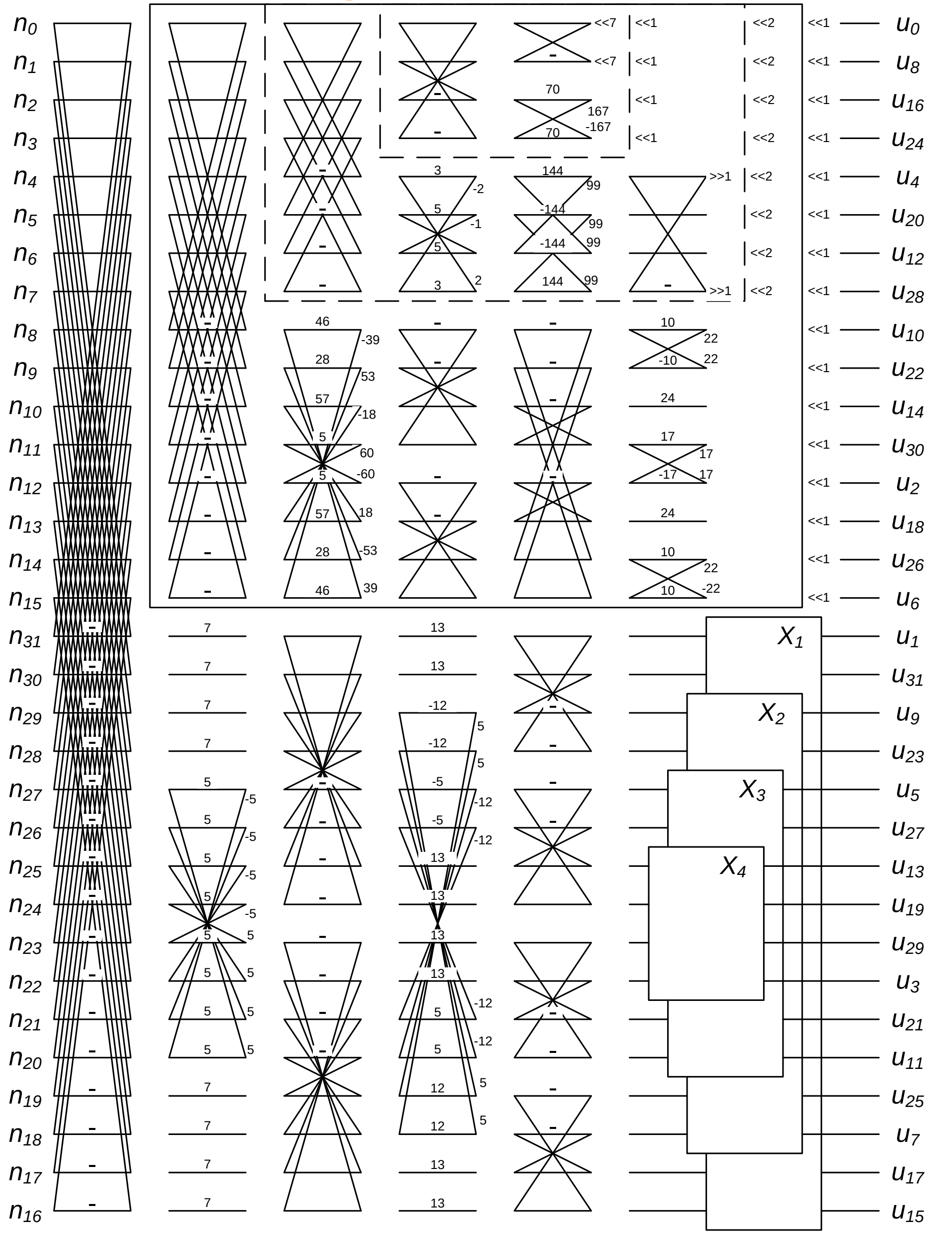
Core Transform Design Proposed for HEVC

- Use the proposed general transform matrices
- Brute-force search for the matrix elements based on
  - Element relations
  - Almost equal L^2 norms of the basis vectors
  - Negligible deviation from DCT [3]
  - Negligible transform error introduced by non-orthogonality [4]

Order-4	a_2, b_2	167	70						
Order-8	$a_4, b_4, c_4, d_4, e_4, f_4, i_4, j_4, h_4, k_4$	3	2	5	1	144	99	72	99
Order-16	$a_8, b_8, c_8, d_8, e_8, f_8, g_8, h_8$	60	57	53	46	39	28	18	5
	i_8, j_8, k_8, l_8	10	-22	24	17				
Order-32	x_0, x_1	7	5						
	y_0, y_1, y_2	13	5	12					
	$p_0, p_1, p_2, p_3, p_4, p_5, p_6, p_7$	1	5	31	32	23	19	26	21
	$q_0, q_1, q_2, q_3, q_4, q_5, q_6, q_7$	31	13	28	8	16	30	11	27
	$r_0, r_1, r_2, r_3, r_4, r_5, r_6, r_7$	8	21	23	31	27	2	32	16
	$v_0, v_1, v_2, v_3, v_4, v_5, v_6, v_7$	30	19	25	10	29	31	5	13
S_N	s_2, s_4, s_8, s_{16}	128	2	4	2				

[3] M. Wien and S. Sun, "ICT comparison for adaptive block transforms," document VCEG-L12, ITU-T SG16/Q6, Jan. 2001.
[4] J. Dong, K. N. Ngan, C. K. Fong, and W. K. Cham, "2D order-16 integer transforms for HD video coding," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 19, no. 10, pp. 1463–1474, Oct. 2009.

Core Transform Design Proposed for HEVC



Experimental Results

- Integrated into HM4.0 using 16-bit integer arithmetic
- Tested under common test condition for and special test condition of CE10
- Compared with other core transform designs in CE10
- Rate-Distortion Performance: less than 1% BD-rate difference under various test settings and *QP*s

[5] A. Fuldseth, G. Bjøntegaard, and M. Budagavi, "CE10: core transform design for HEVC," document JCTVC-G495, Joint Collaborative Team on Video Coding, Nov. 2011.
[6] R. Joshi, J. Sole, and M. Karczewicz, "CE10: Scaled integer transforms supporting recursive factorization structure," document JCTVC-G579, Joint Collaborative Team on Video Coding, Nov. 2011.
[7] E. Alshina *et al.*, "CE10: full factorization core transforms for HEVC," document JCTVC-G737, Joint Collaborative Team on Video Coding, Nov. 2011.

Experimental Results

- Features offered by each core transform design

	Small DCT distortion	Full factorization	No scaling process	Negligible transform error	Flexible implementation
Cisco's	√		√	√	√
Qualcomm's	√	√		√	
Samsung's	√	√	√	√	√
Proposed	√	√	√	√	√

- Numbers of arithmetic operations for *N*-point 1-D transform

		Cisco's	Qualcomm's	Samsung's	Proposed
4-point	+	8	9	9	9
	×	6	3	3	3
8-point	+	28	26	29	31
	×	22	12	11	11
16-point	+	100	72	81	93
	×	86	36	31	21
32-point	+	372	186	229	279
	×	342	92	87	56

Conclusion

- Propose the core transform design for HEVC
  - Factorizable general transform matrices
  - Matrix elements
- Features offered
  - High energy compaction capability
  - No scaling process
  - Negligible transform error introduced by non-orthogonality
  - Flexible implementations
  - 16-bit integer arithmetic
- R-D performance
  - Less than 1% BD-rate difference under various test settings