Video Coding and HEVC

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Tutorial Agenda

Part I: Introduction to block based hybrid coding

Part II: Brief Overview of H.264/MPEG-4 AVC

Part III: **HEVC version 1 (and version 2)**

Part IV: Future Video Coding Development

Part I: Introduction to block-based hybrid video coding

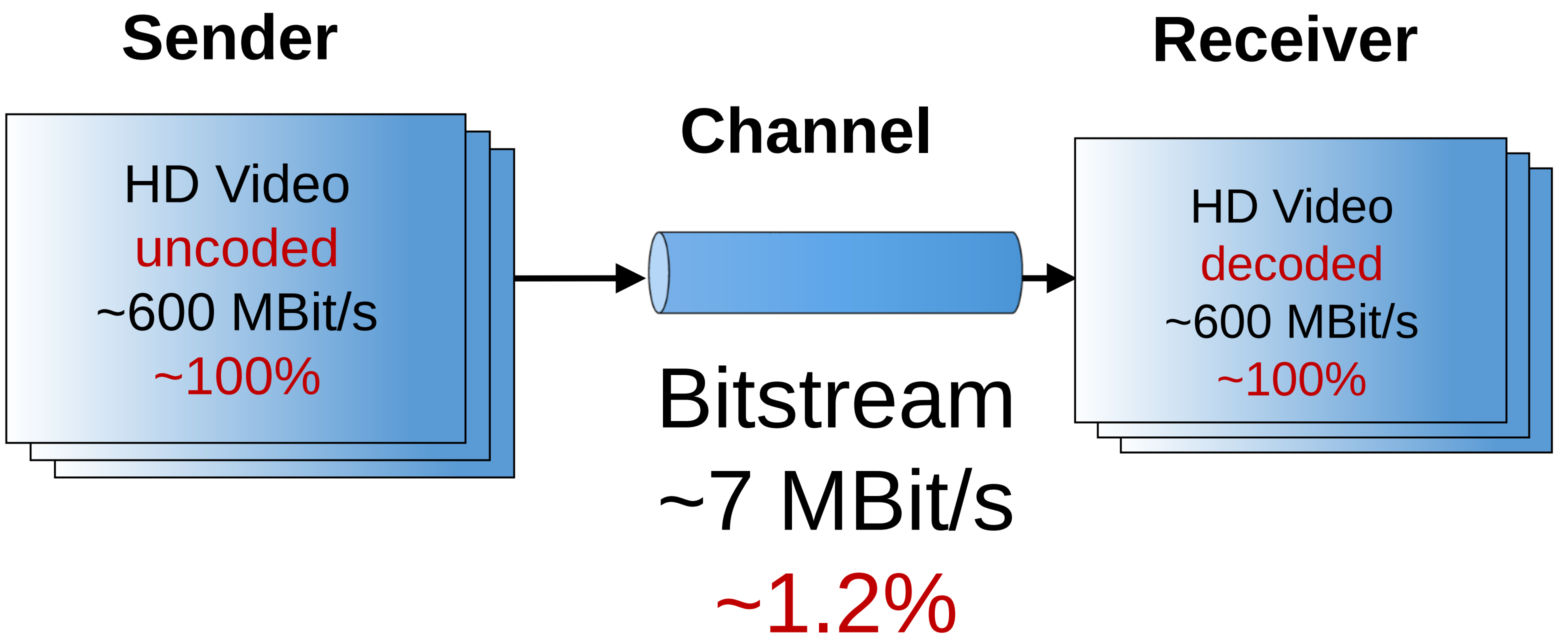
Video Compression Goal:

- Efficiently condense visual data, while
- Minimizing the loss of visual quality due to the compression.

Why do we need to compress video?

- To reduce the storage space;
- To reduce the transmission/delivery bit-rate...

Video Coding, Transmission, and Applications



[Grois2015]

Hybrid Video Coding (I)

Block based hybrid coding:

- Division into blocks
- Intra/Inter prediction
- Transform coding

[Grois2015]

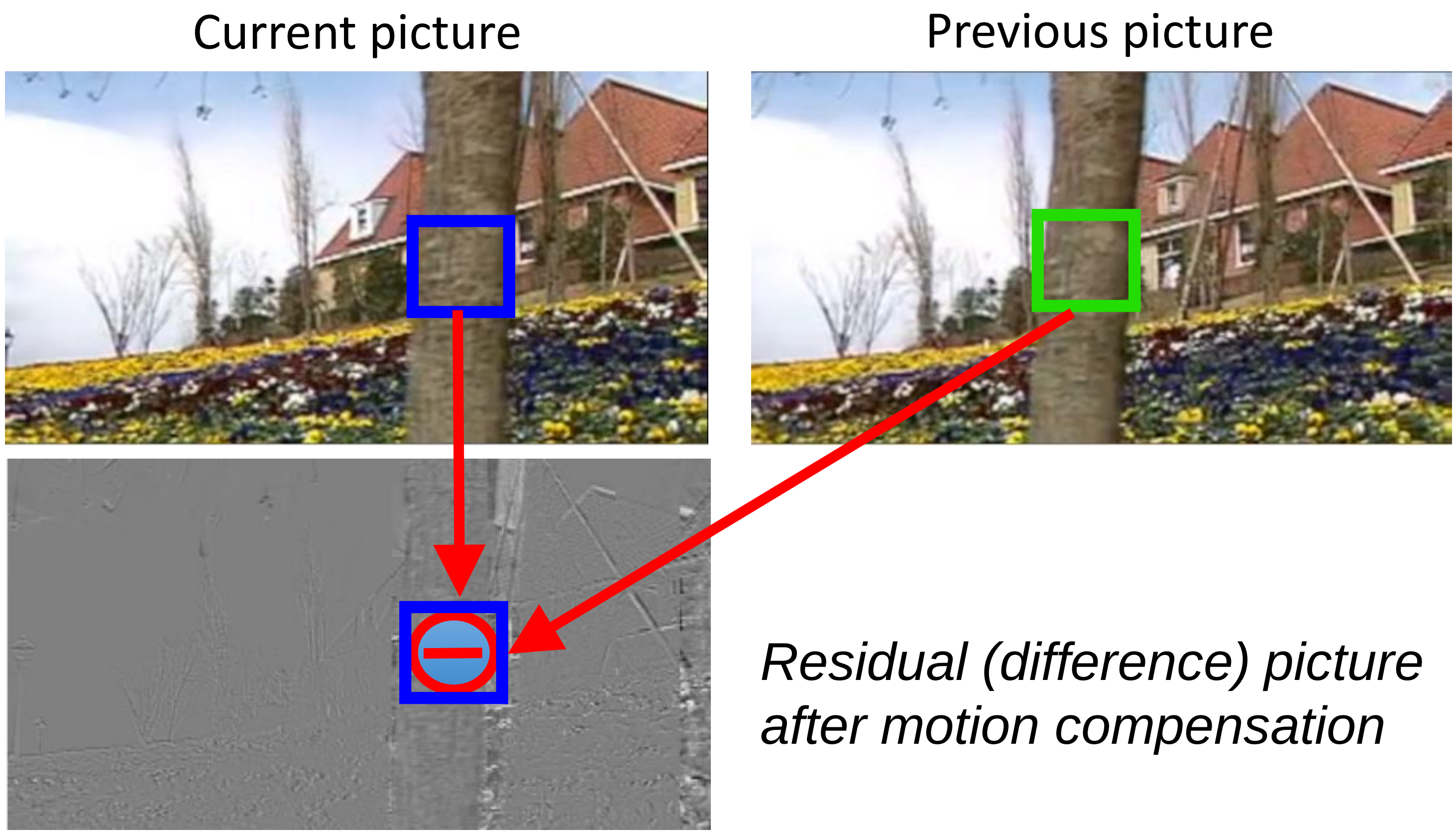
Hybrid Video Coding: Motion Compensation

Current picture

Previous picture

[Grois2015]

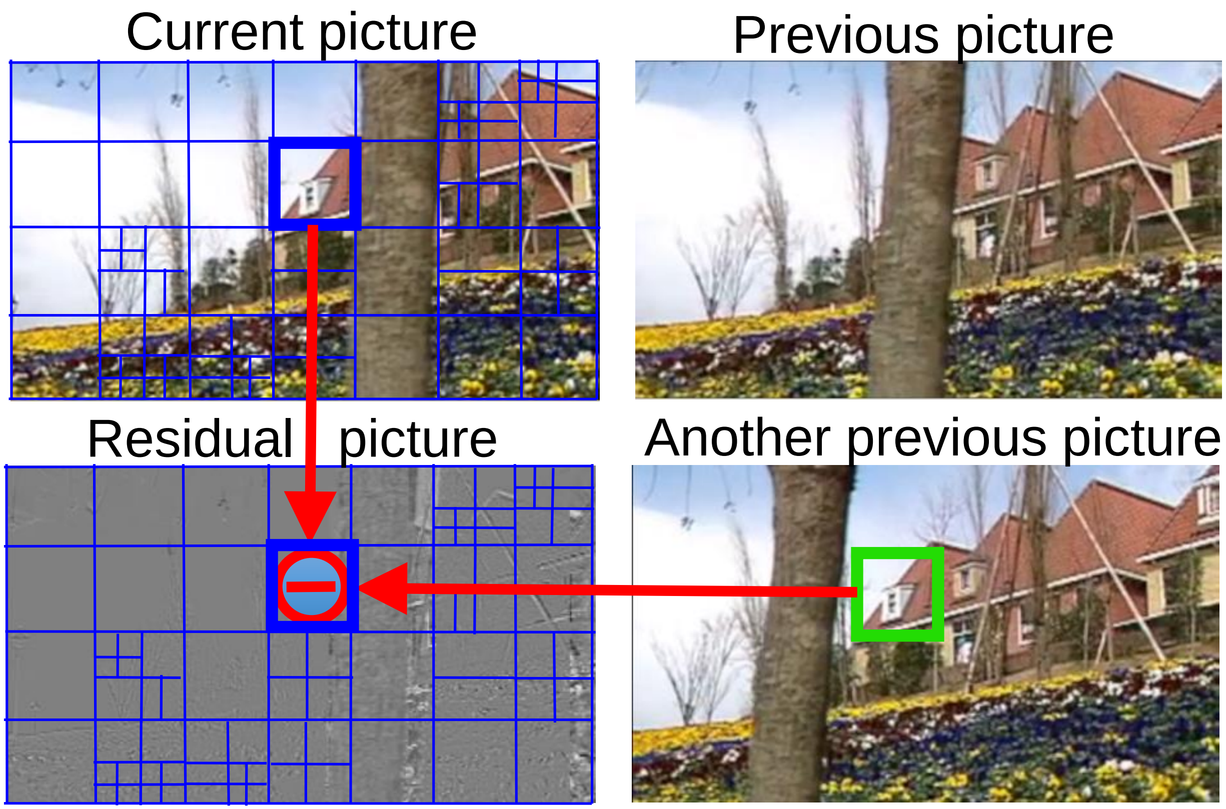
Hybrid Video Coding: Residual Processing



[Grois2015]

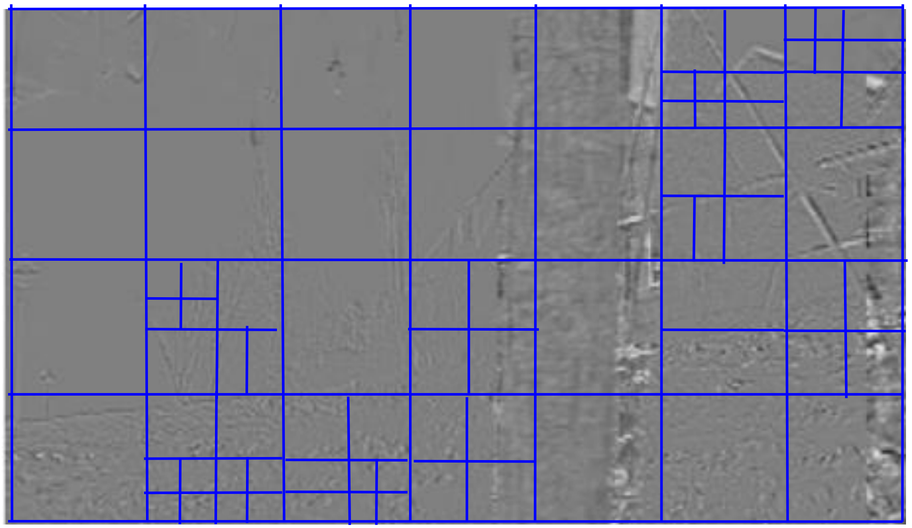
Hybrid Video Coding: Residual Processing

Things can be more complicated…



[Grois2015]

Transform and Quantization of the Residual Picture



- **Apply transform** (e.g., DCT) for converting the spatial domain pixels into transform domain coefficients;
- **Apply quantization** (e.g., scalar) for reducing a number of levels for transformed coefficients.

Goals:

- Adjust bit rate vs. fidelity;
- Remove subjectively irrelevant details.

[Grois2015]

Standardization organizations

Video Coding Experts Group (VCEG)

- Formally structured as Question 6 of ITU-T Study Group 16 (Q.6/SG16)
- Informal nickname, VCEG, originated in 1998
- History spans from the development of first standards for digital video coding (ITU-T H.120 and H.261) through recent development of HEVC (ITU-T H.265/MPEG-H Part 2) and its extensions
- Also responsible for still-picture coding in partnership with ISO/IEC JTC 1/SC 29/WG 1 (JPEG).

[Grois2015]

Standardization organizations

Moving Pictures Experts Group (MPEG)

- Formally ISO/IEC JTC 1/SC 29/WG 11 – Coding of moving pictures and audio (ISO/IEC Joint Technical Committee 1, Subcommittee 29, Working Group 11)
- Established in 1988
- Mission to develop standards for coded representation of digital audio and video and related data
- Several sub-groups:
  - Requirements
  - Systems
  - Video
  - Audio
  - 3D Graphics Compression
  - Test, Communication

[Grois2015]

H.264/MPEG-4 Advanced Video Coding (AVC)

H.264/MPEG-4 AVC Timeline

Aug. 1999

- First test model (TML-1) of H.26L in VCEG

Dec. 2001

- Formation of **Joint Video Team (JVT)** between **VCEG** and **MPEG**
- JVT Chairs: G. J. Sullivan, A. Luthra, and T. Wiegand

May 2003

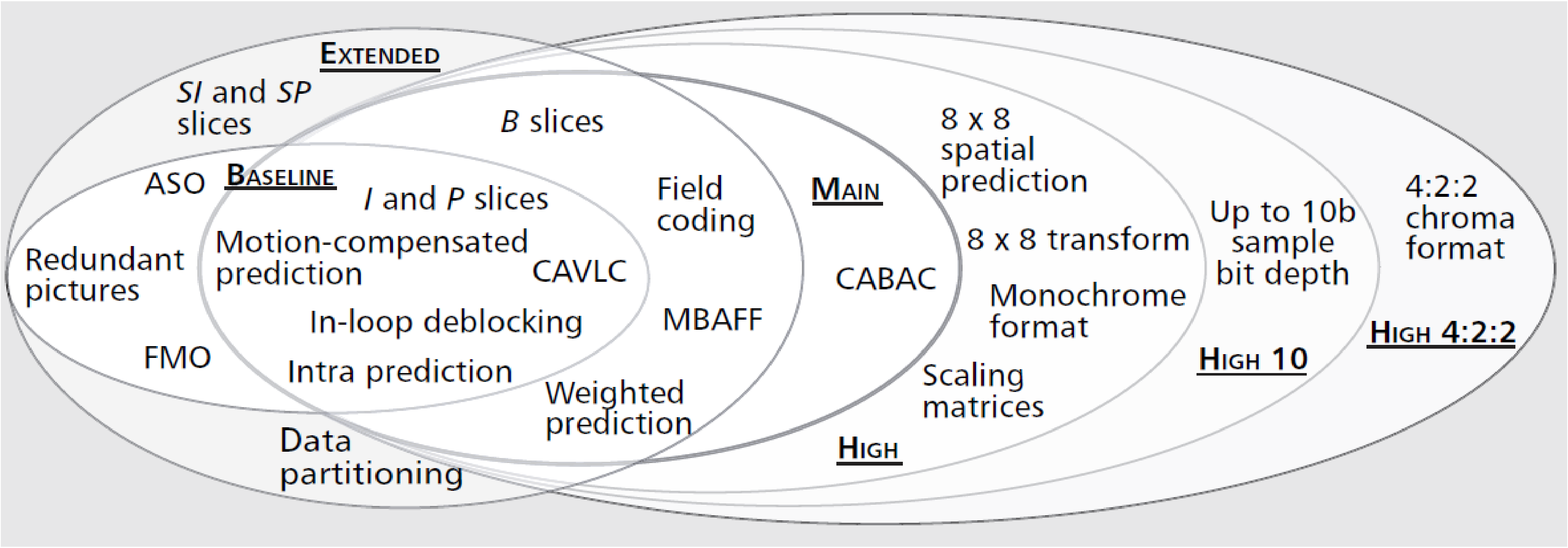
- ITU-T SG16 Recommendation H.264 approved
- International Standard ISO/IEC 14496-10

until April 2004

- Extensions Project: Fidelity range extensions (FRExt)

[Grois2015]

H.264/MPEG-4 AVC Common Profiles



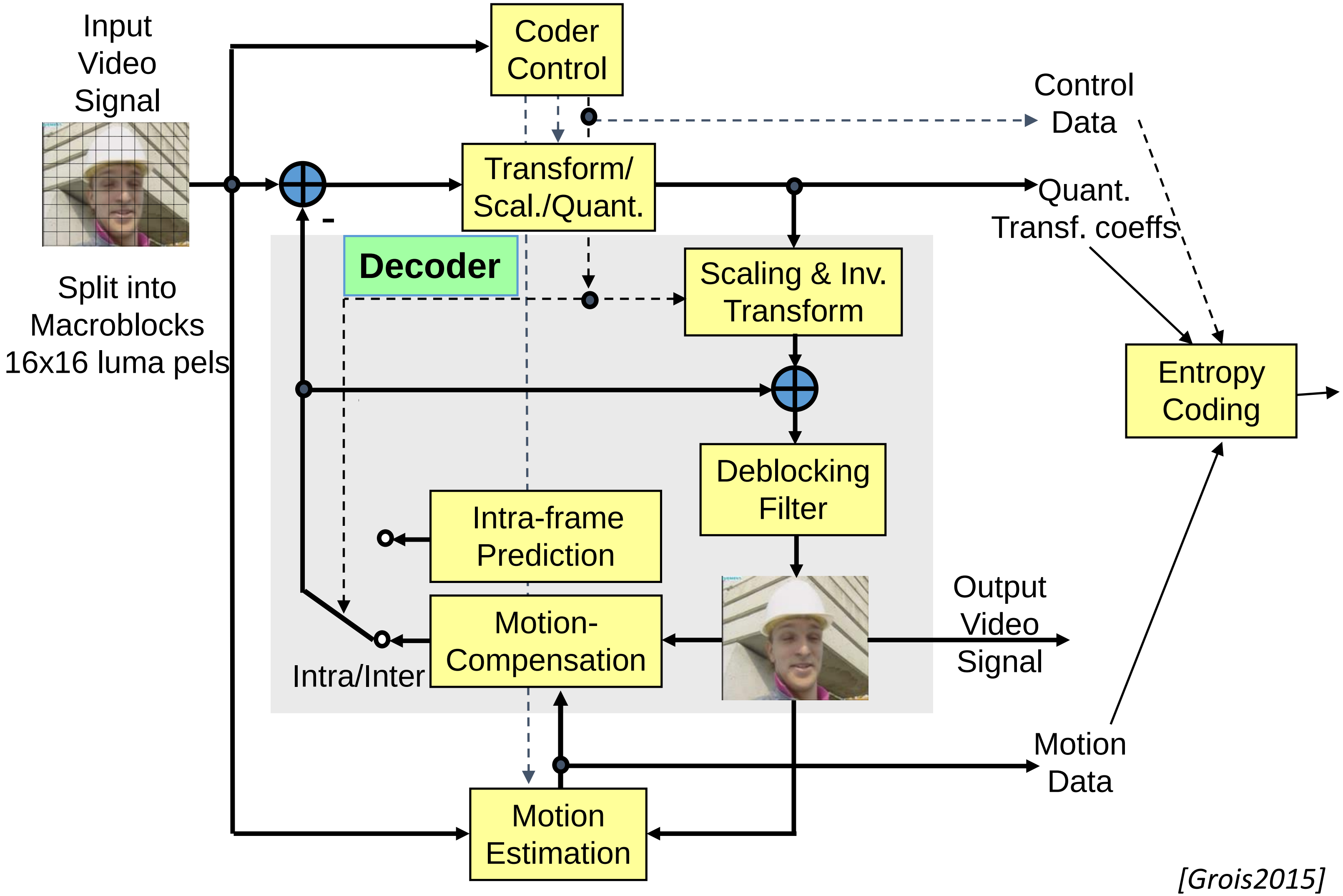
Marpe et al., IEEE Comm. Magazine, 2006

H.264/MPEG-4 AVC Summary

- Based on **hybrid video coding** and similar in its virtue to other standards but with several improvements.
- **Some new key aspects are:**
  - **Enhanced motion compensation;**
  - **Small blocks for transform coding;**
  - **Improved de-blocking filter;**
  - **Enhanced entropy coding.**
- Significant **bit-rate savings of about 50% compared** to H.262/MPEG-2 for the same perceptual quality (especially, for higher-latency applications allowing B pictures).

[Grois2015]

H.264/AVC Basic Coding Structure



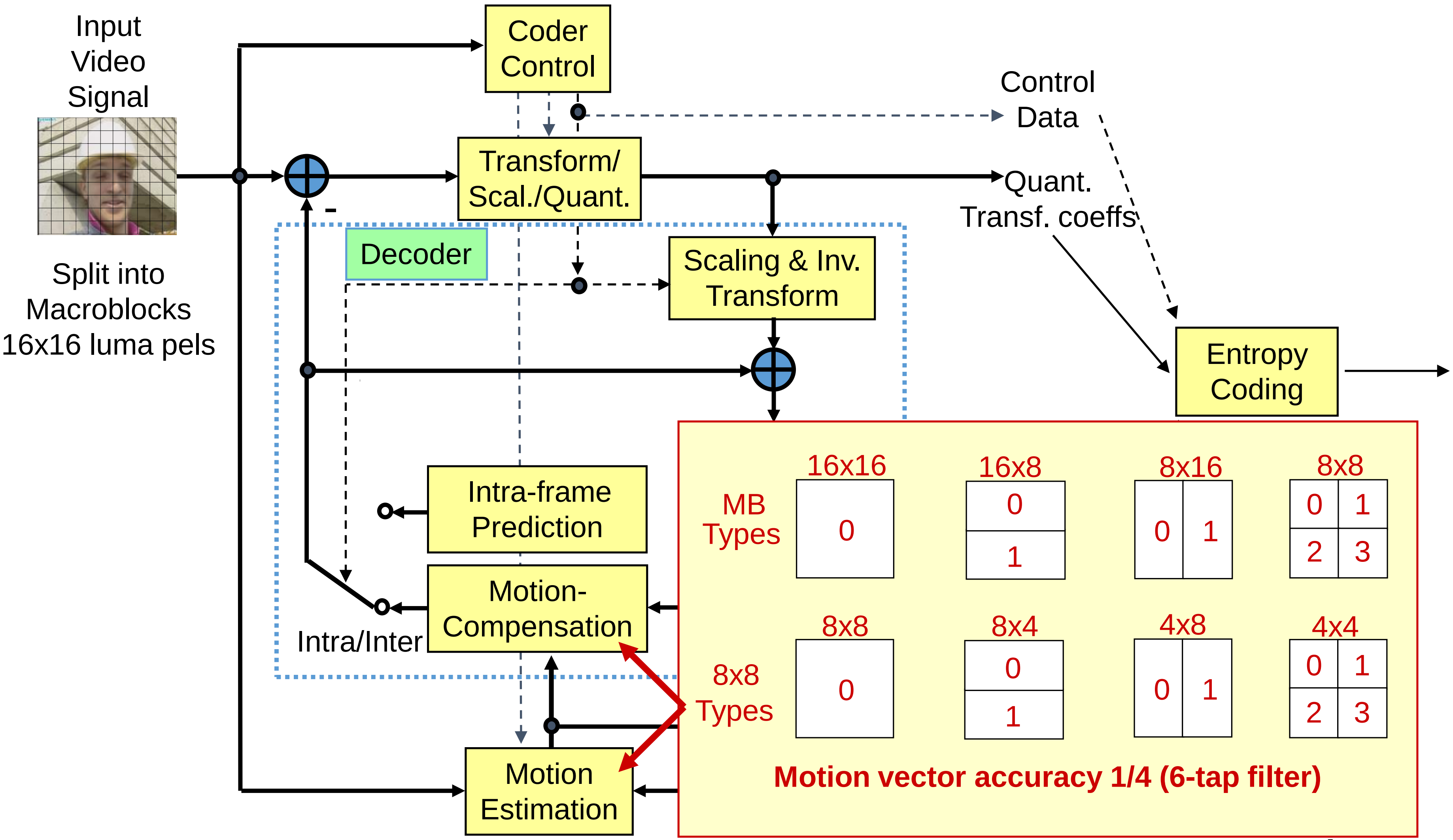
[Grois2015]

Common Elements with Previous Standards

- Macroblocks: 16x16 luma + 2 x 8x8 chroma samples;
- Input: Association of luma and chroma and conventional sub-sampling of chroma (4:2:0);
- Block motion displacement;
- Motion vectors over picture boundaries;
- Variable block-size motion;
- Block transforms;
- Scalar quantization;
- I, P, and B coding types.

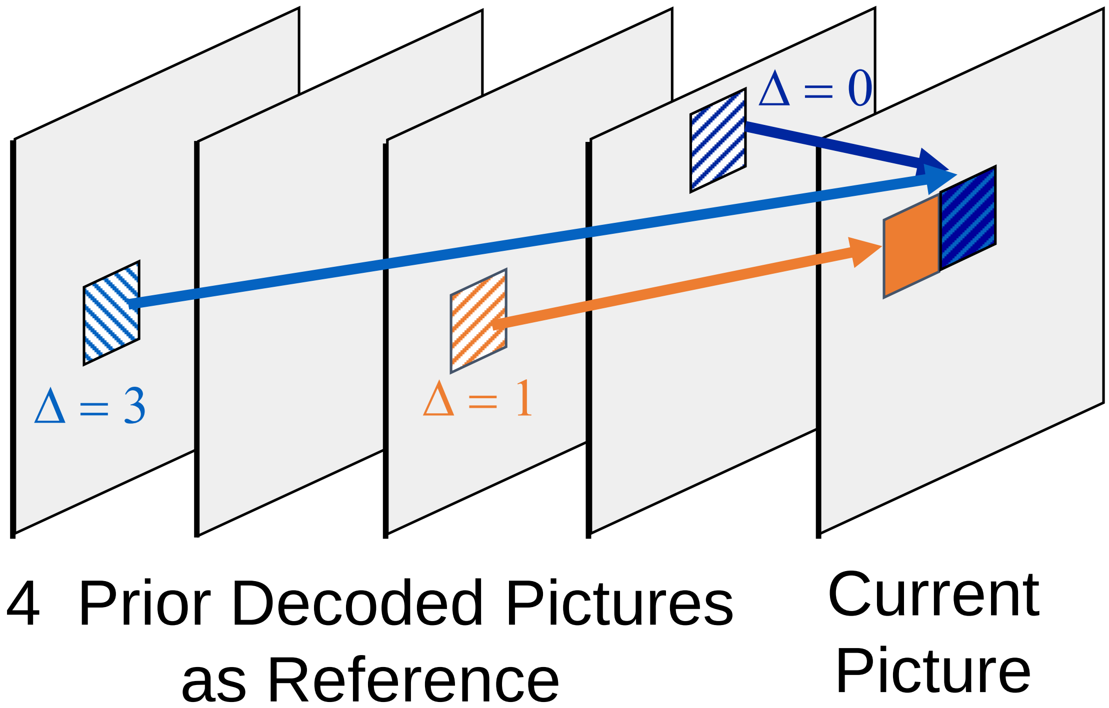
[Grois2015]

Macroblocks and partitions



[Grois2015]

Multiple Reference Frames and Generalized Bi-Predictive Frames



- **Extend motion vector by reference picture index Δ.**
- **Provide reference pictures at decoder side.**
- **In case of bi-predictive pictures: decode 2 sets of motion parameters.**

Can jointly exploit scene cuts, aliasing, uncovered background and other effects with one approach

[Grois2015]

Weighted Prediction

In addition to shifting in spatial position, and selecting from among multiple reference pictures, each region's prediction sample values can be:

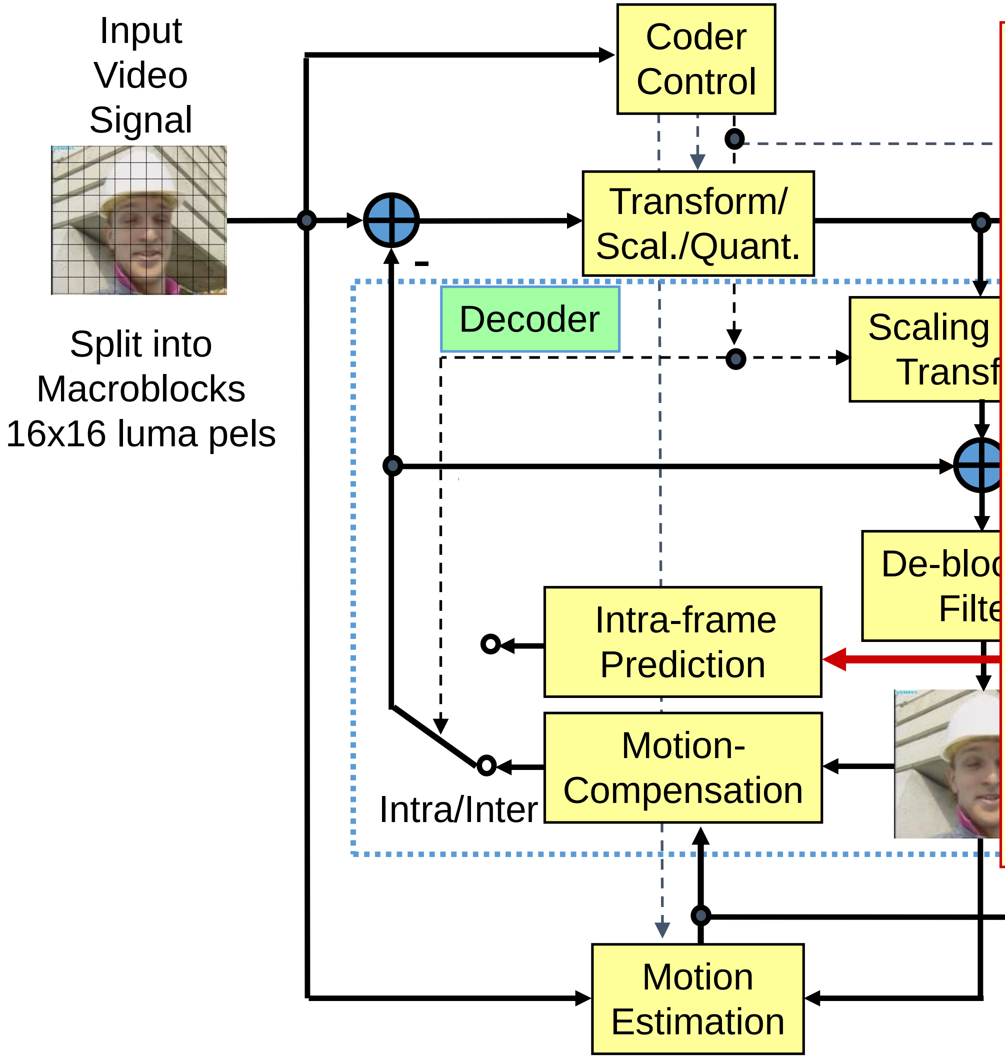
- Multiplied by a weight; and
- Given an additive offset.

Some key uses:

- Improved efficiency for B coding, e.g.: accelerating motion, multiple non-reference B temporally between reference pics.

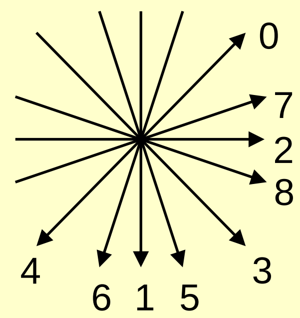
[Grois2015]

Intra Prediction



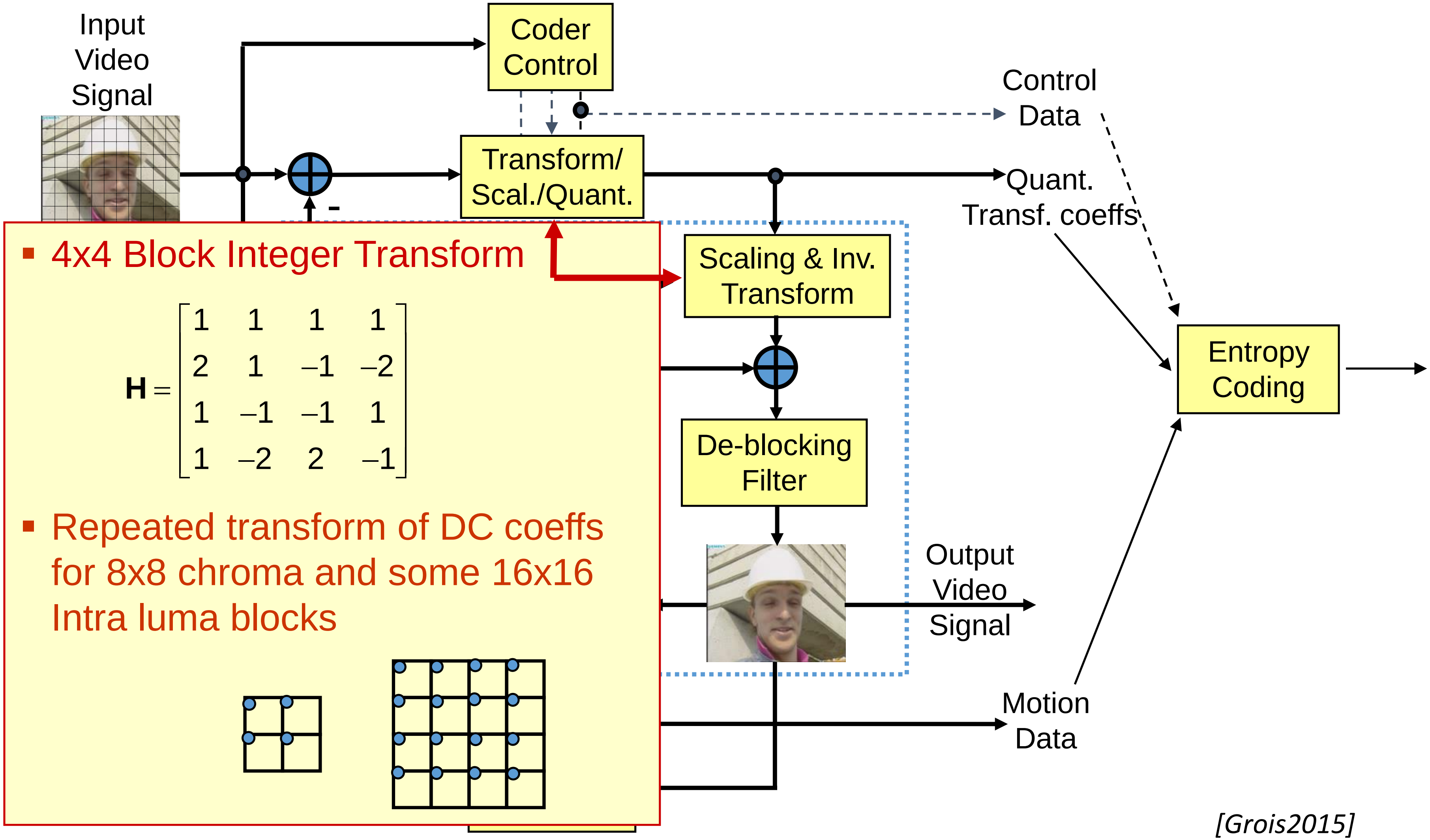
- Directional spatial prediction (9 types for luma, 1 chroma)

Q	A	B	C	D	E	F	G	H
I	a	b	c	d				
J	e	f	g	h				
K	i	j	k	l				
L	m	n	o	p				



[Grois2015]

Transform Coding



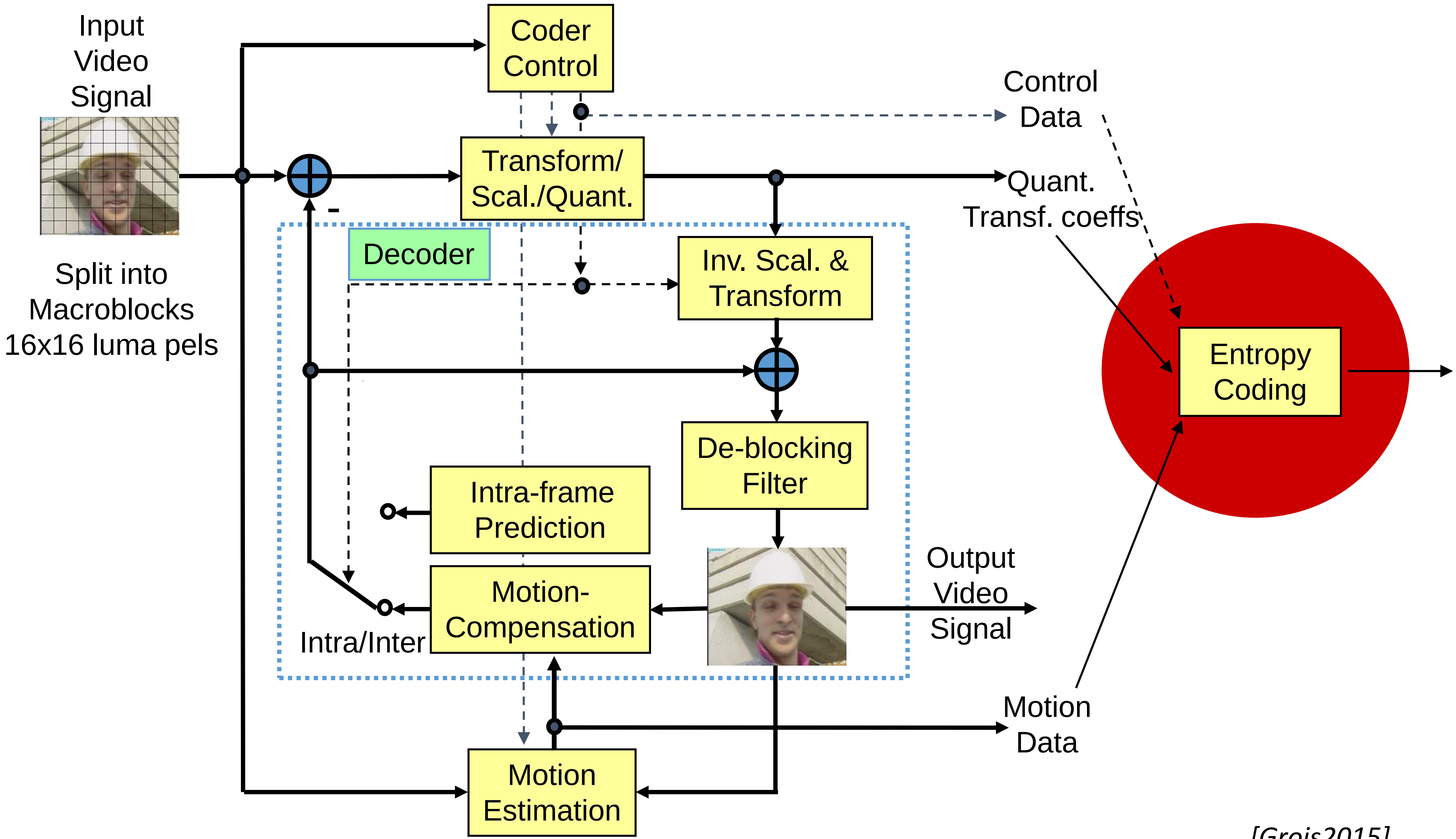
- 4x4 Block Integer Transform

$$\mathbf{H} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 2 & 1 & -1 & -2 \\ 1 & -1 & -1 & 1 \\ 1 & -2 & 2 & -1 \end{bmatrix}$$

- Repeated transform of DC coeffs for 8x8 chroma and some 16x16 Intra luma blocks

[Grois2015]

Entropy Coding



[Grois2015]

Binary Coding: CAVLC

Context-Adaptive Variable Length Coding (CAVLC)

- Exp-Golomb code for all symbols except for transform coefficients
- Context adaptive VLCs for coding of transform coefficients
  - No end-of-block, but number of coefficients is decoded;
  - Coefficients are scanned backwards;
  - Contexts are built dependent on transform coefficients.

[Grois2015]

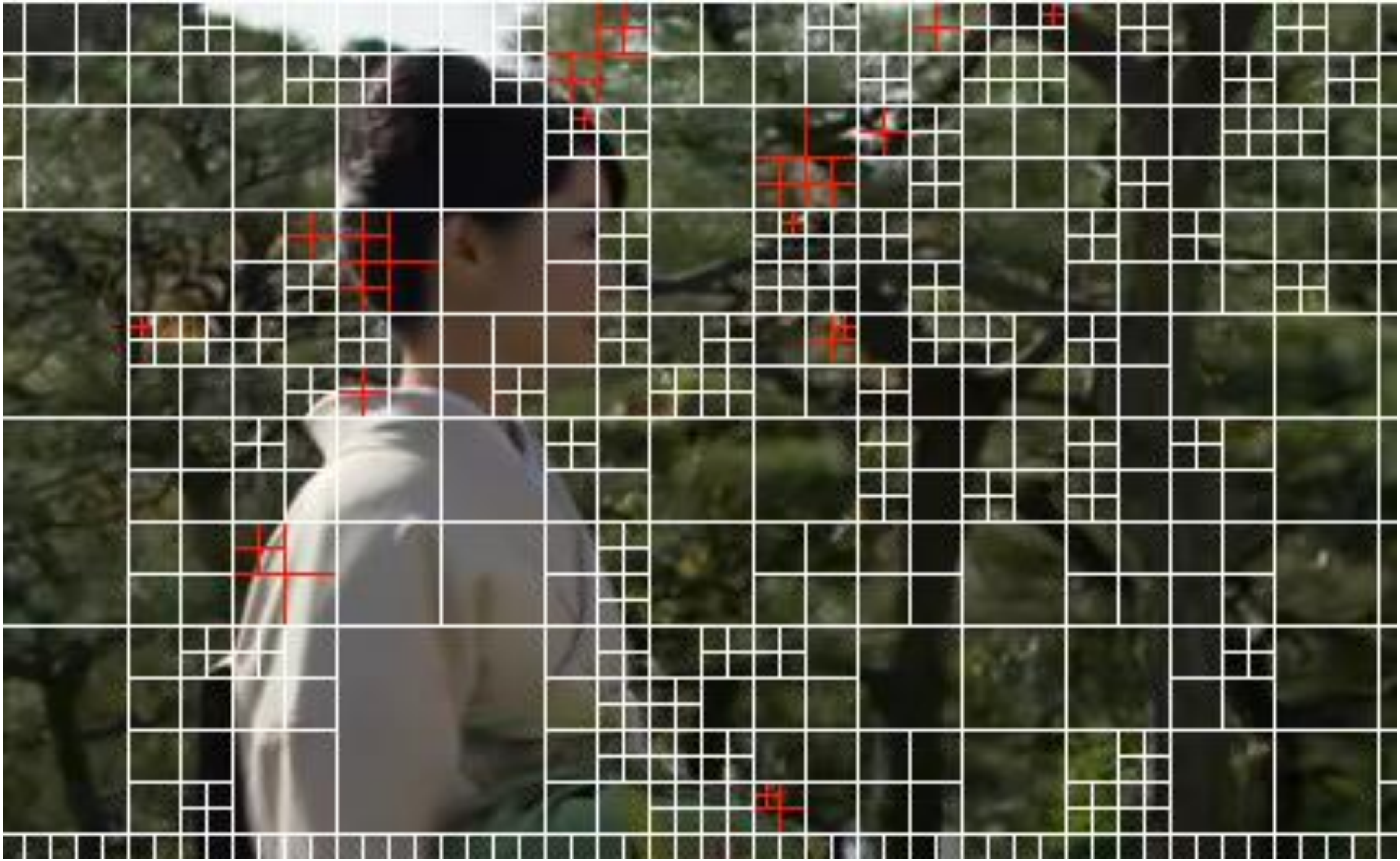
Binary Coding: CABAC

Context-based Adaptive Binary Arithmetic Coding (CABAC)

- Usage of adaptive probability models for most symbols;
- Exploiting symbol correlations by using contexts;
- Restriction to binary arithmetic coding:
  - Simple and fast adaptation mechanism;
  - Fast binary arithmetic codec based on table look-ups and shifts only.

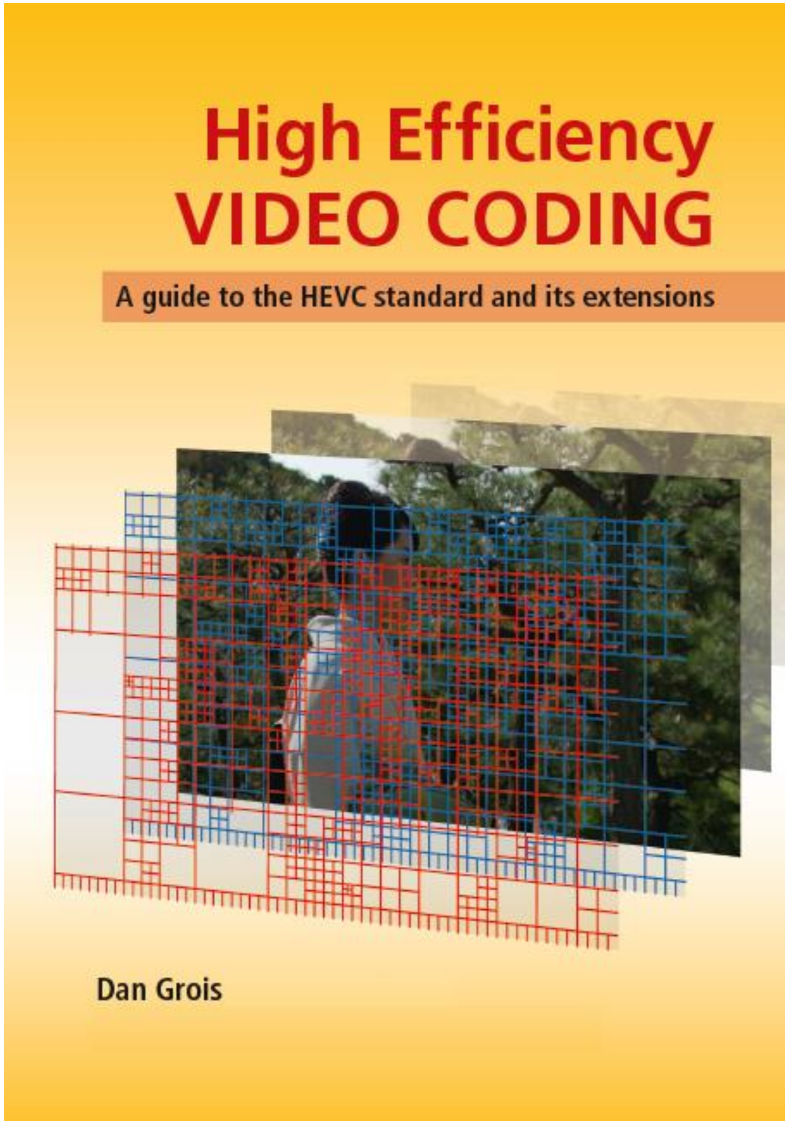
[Grois2015]

Part II: High Efficiency Video Coding Version 1



@ Prof. Masayuki Nakajima, Uppsala University

A Guide to the H.265/HEVC Standard and its Extensions



- **Cambridge University Press.**
- **Printed Fully In Color.**
- **Includes HEVC Extensions.**
- **Coming in 2019.**

Motivation for Improved Video Compression

History of Video Coding Standards

Jevons Paradox

"The efficiency with which a resource is used tends to increase (rather than decrease) the rate of consumption of that resource."

William Stanley Jevons

[Wikipedia, Bross2016]

Motivation for Improved Video Compression

- IP video traffic will be 82% of all consumer Internet traffic by 2021 *[Cisco2017].*

DOGTV

http://www.theexpgroup.com

CAT BOX TV

http://moneytipcentral.com

- For enabling High-Quality video services, efficient compression techniques are required, especially for 3840x2160 (4K) or 7680x4320 (8K) resolutions.

H.265/HEVC – Applications

- Internet streaming, download and play
- Real-time conversational services
- Broadcast
- Mobile streaming, conversational services and broadcast
- Content production and distribution
- Home and Digital Cinema
- Camcorders
- Medical imaging
- Remote video surveillance
- Storage media (e.g., disks, digital video tape recorder)
- Wireless display

HEVC and the JCT-VC Partnership

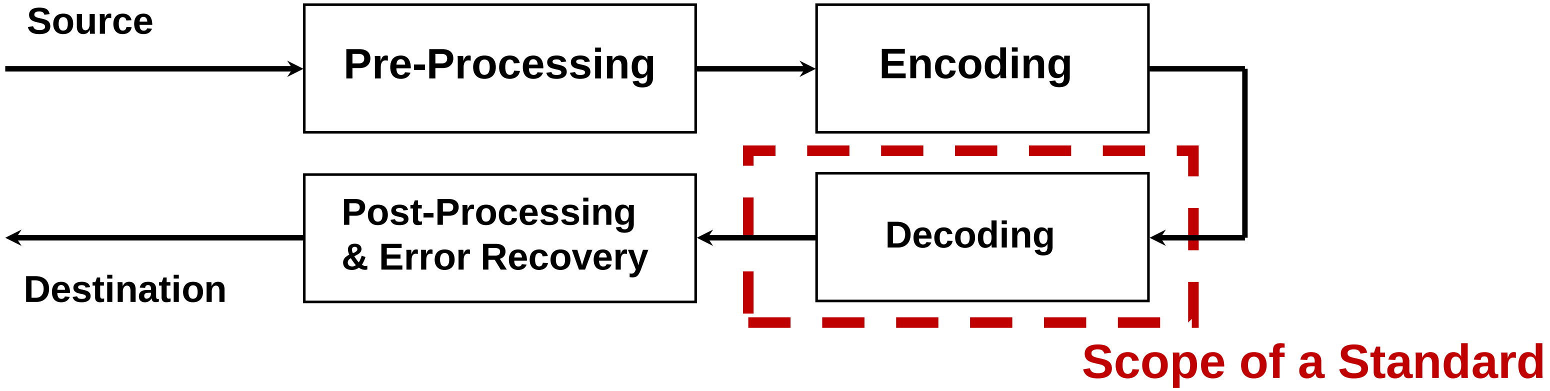
- ITU-T VCEG and ISO/IEC MPEG established Joint Collaborative Team on Video Coding (JCT-VC) and issued joint call for proposals (CfP) on video coding technology in 2010.

- As a result, there was an intensive development of the so-called High-Efficiency Video Coding (HEVC) standard during the next two and the half years.
  - **2013: HEVC version 1;**
  - **2014: HEVC version 2 – Range Extensions (RExt), Scalable Extensions (SHVC), Multiview Extensions (MV-HEVC);**
  - **2015: HEVC version 3 – 3D Video Coding Extensions (3D-HEVC);**
  - **2016: HEVC version 4 – Screen Content Coding Extensions (HEVC-SCC);**
  - **2018: HEVC version 5 – additional SEI messages that include omnidirectional video SEI messages, a Monochrome 10 profile, a Main 10 Still Picture profile.**

Scope of Video Coding Standardization

Only restrictions on bitstream (syntax & semantics), and decoding process **are standardized:**

- Permits optimization beyond the obvious;
- Permits complexity reduction for implementations;
- Provides *no* guarantees of quality.



[Grois2015]

History: Call for Proposals Testing

- **27 complete proposals** submitted (some multi-organizational);
- Each proposal was a **major package** – lots of encoded video, extensive documentation, extensive performance metric submissions, sometimes software, etc;
- **Extensive subjective testing** (3 test labs, 4 200 video clips evaluated, 850 human subjects, 300 000 scores);
- Quality of the proposal video was **compared to H.264/MPEG-AVC** anchor encodings;
- In a number of cases, **comparable quality at half bit rate;**
- Test report issued as document JCTVC-A204.

[Grois2015]

History: Call for Proposals Results

All proposals basically conceptually similar to H.264 / AVC (and prior standards):

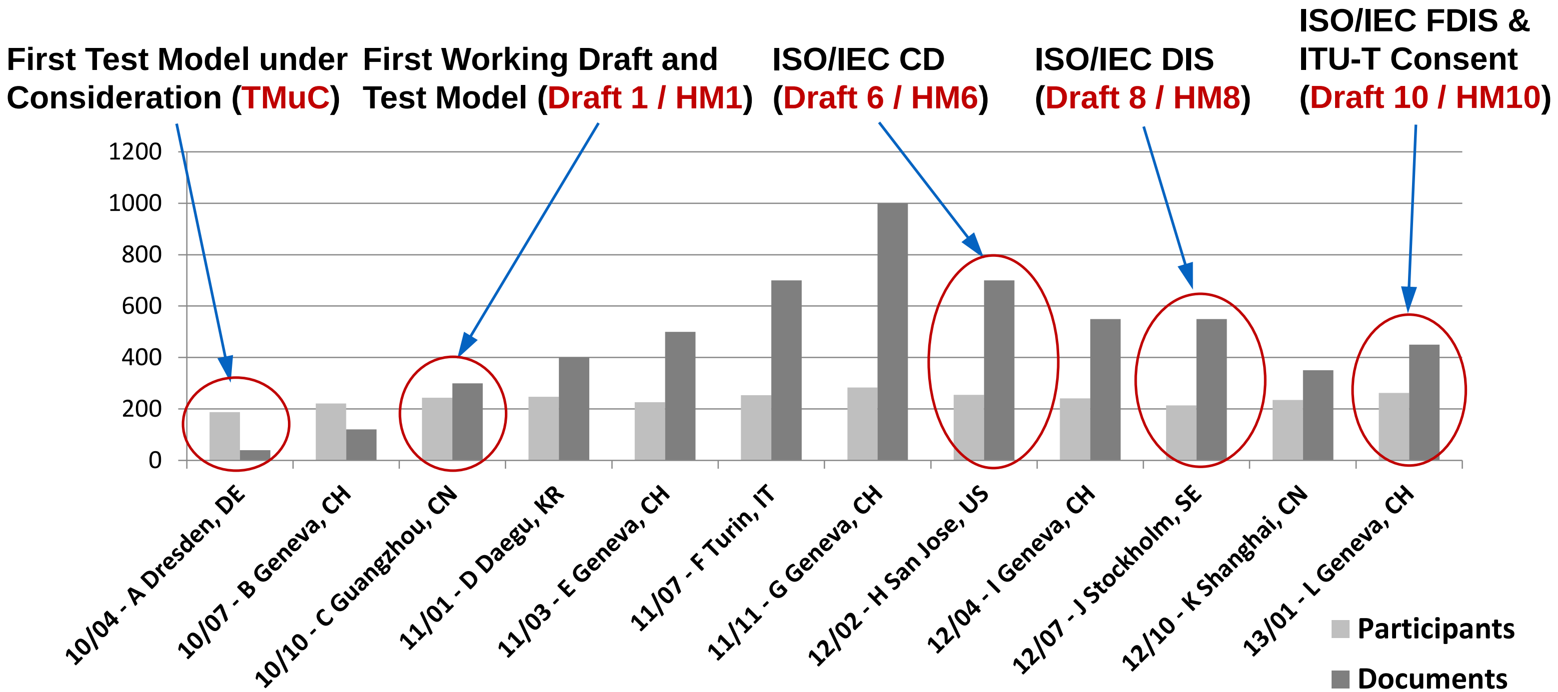
- Block-based with variable block sizes;
- Block motion compensation;
- Fractional-pel motion vectors;
- Spatial intra prediction;
- Spatial transform of residual difference;
- Integer-based transform designs;
- Arithmetic or VLC-based entropy coding;
- Various methods of in-loop filtering to form final decoded picture and improve prediction.

"Test Model under Consideration" was set up from common design elements of well-performing proposals (Document JCTVC-A205).

[Grois2015]

History: JCT-VC Meetings

April 2010 to January 2013 – 12 JCT-VC Meetings



[Grois2015]

Design Overview

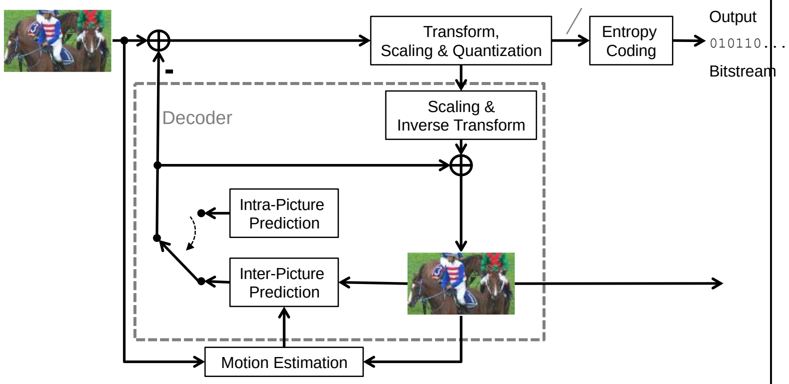
- **High-level design similar to H.264/MPEG-4 AVC:**

Network abstraction layer (NAL):

- Packet oriented payload
- NAL payload types for parameter sets (header information) and data of coding layer
- Pictures structured into slices, with additional features supporting parallel processing (tiles, wavefront) and improved packetization granularity (dependent slices)

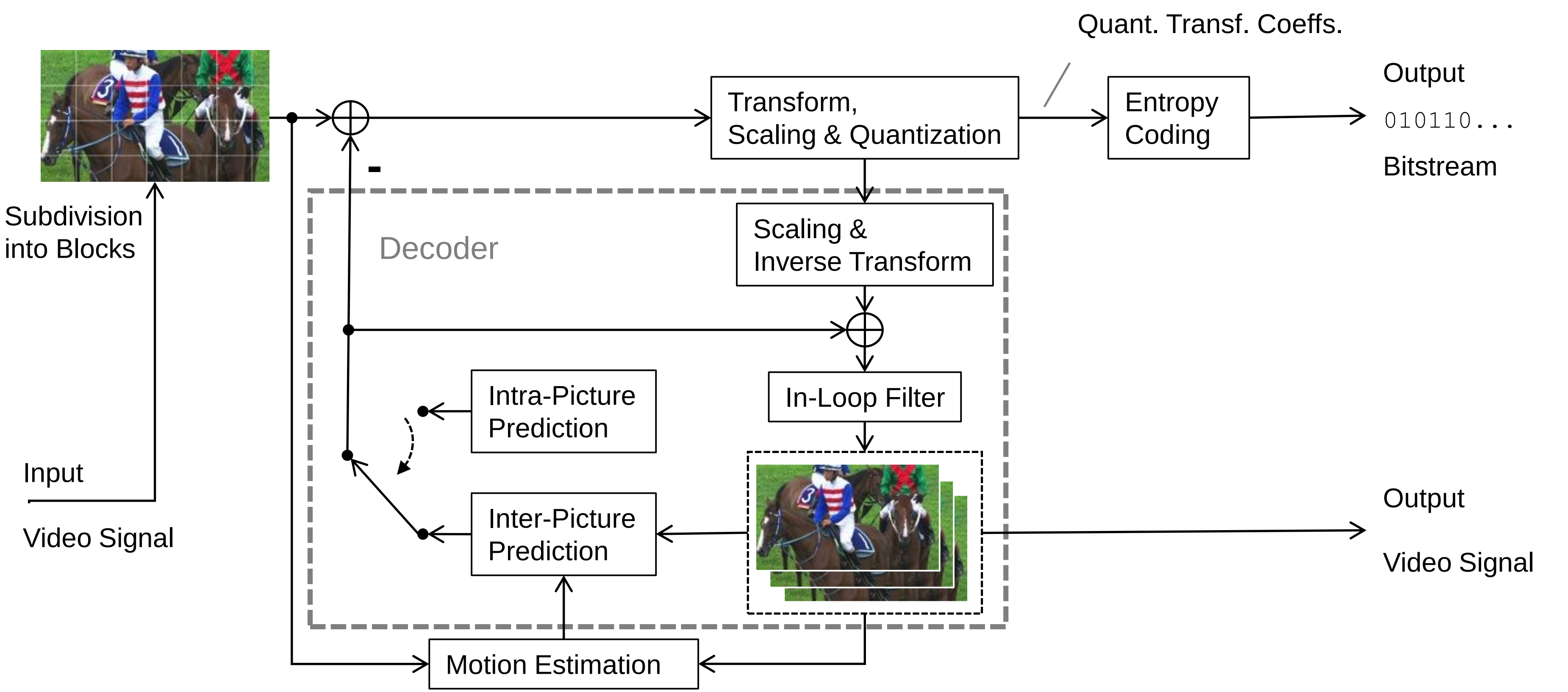
Video coding layer (VCL):

- Coded representation of the picture samples
- Hybrid video coding



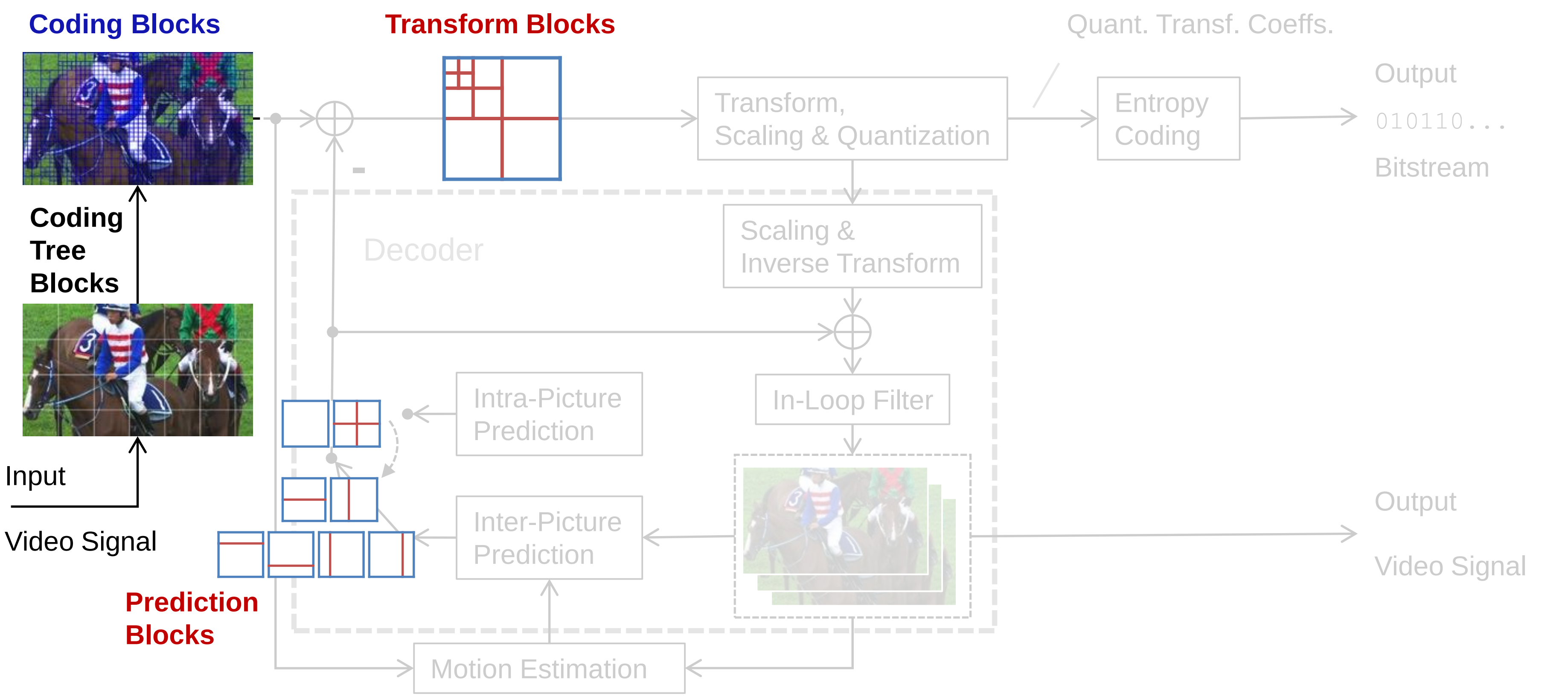
[Grois2015]

Coding-Layer Design



[Grois2015]

Block Structures



[Grois2015]

Block Structures (Cont.)

Variable Block sizes starting from grid of Coding Tree Units (CTU):

- Consisting of Coding Tree Blocks (CTB) with fixed sizes for luma and chroma;
- Luma CTB size typically 64x64 but can be set to 32x32 and 16x16 (size signaled in SPS).
- Processed in raster scan order.

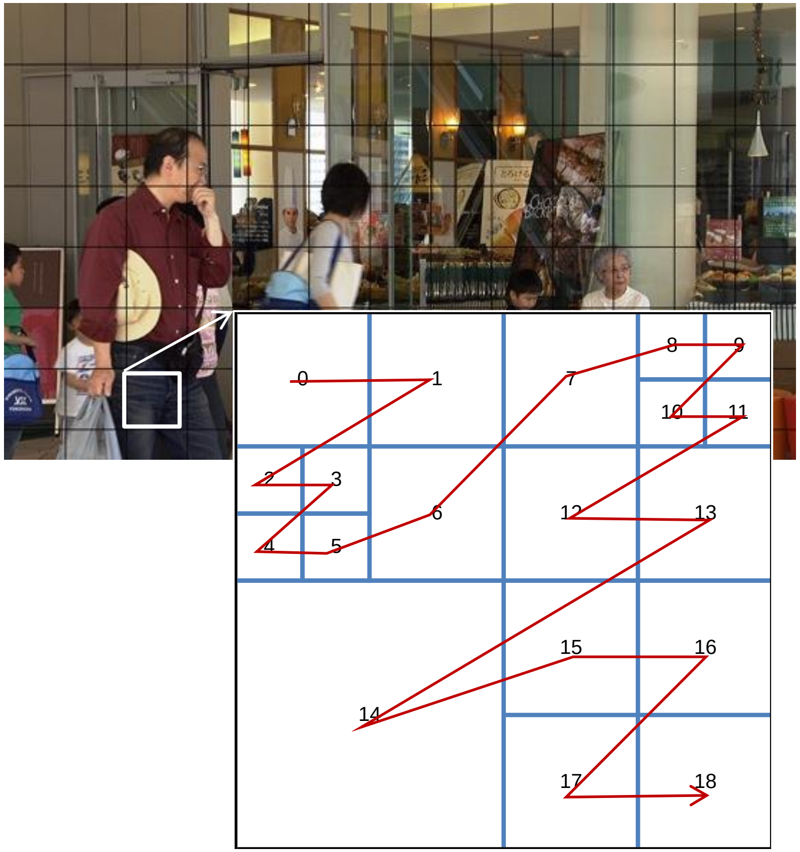
0	1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20	21
22	23	24	25	26	27	28	29	30	31	32
33	34	35	36	37	38	39	40	41	42	43
44	45	46	47	48	49	50	51	52	53	54
55	56	57	58	59	60	61	62	63	64	65
66	67	68	69	70	71	72	73	74	75	76
77	78	79	80	81	82	83	84	85	86	87
88	89	90	91	92	93	94	95	96	97	98

[Grois2015]

Block Structures (Cont.)

Coding Tree Block is the root of the Coding Quadtree:

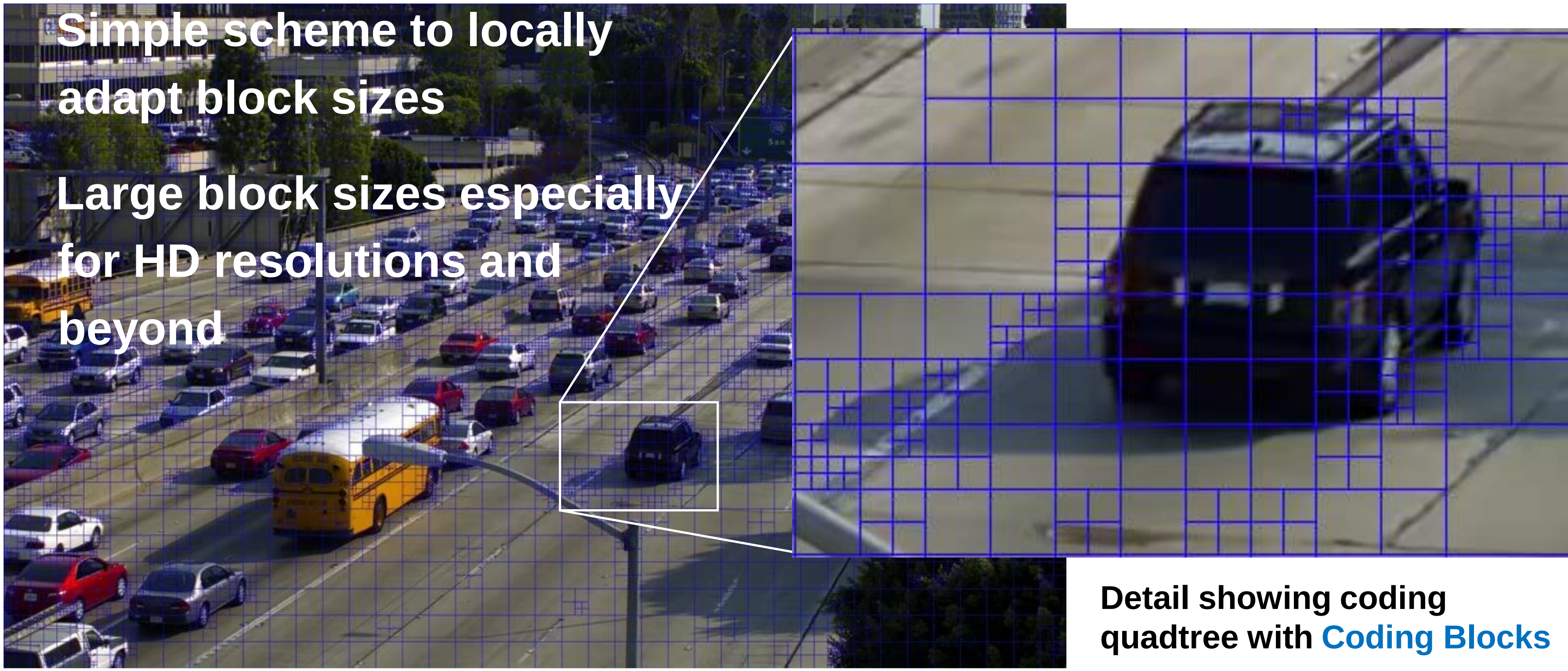
- A Coding Block leave can be predicted using Inter- or Intra prediction;
- The coding quadtree is traversed in Z–Scan Order



[Grois2015]

Block Structures (Cont.)

Coding Quadtree:



Detail showing coding quadtree with Coding Blocks

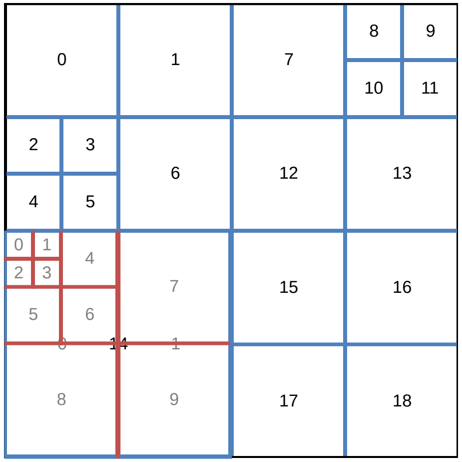
4K sequence *Traffic* (cropped to 2560x1600)

[Grois2015]

Block Structures (Cont.)

A Coding Block can be split:

- once into Prediction Block partitions;
- recursively into Transform Blocks using the Residual Quadtree (RQT): transform sizes ranging from 4x4 to 32x32.



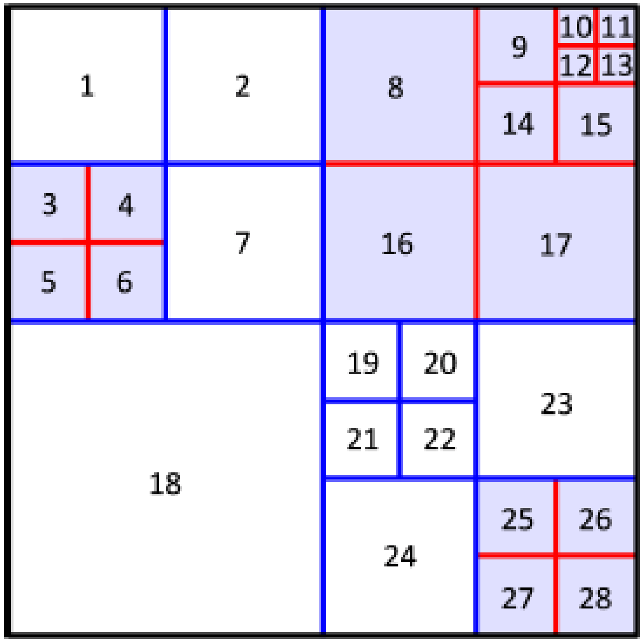
E.g., Nx2N partition with 2 prediction blocks.

E.g., RQT with depth=3 and 10 transform blocks.

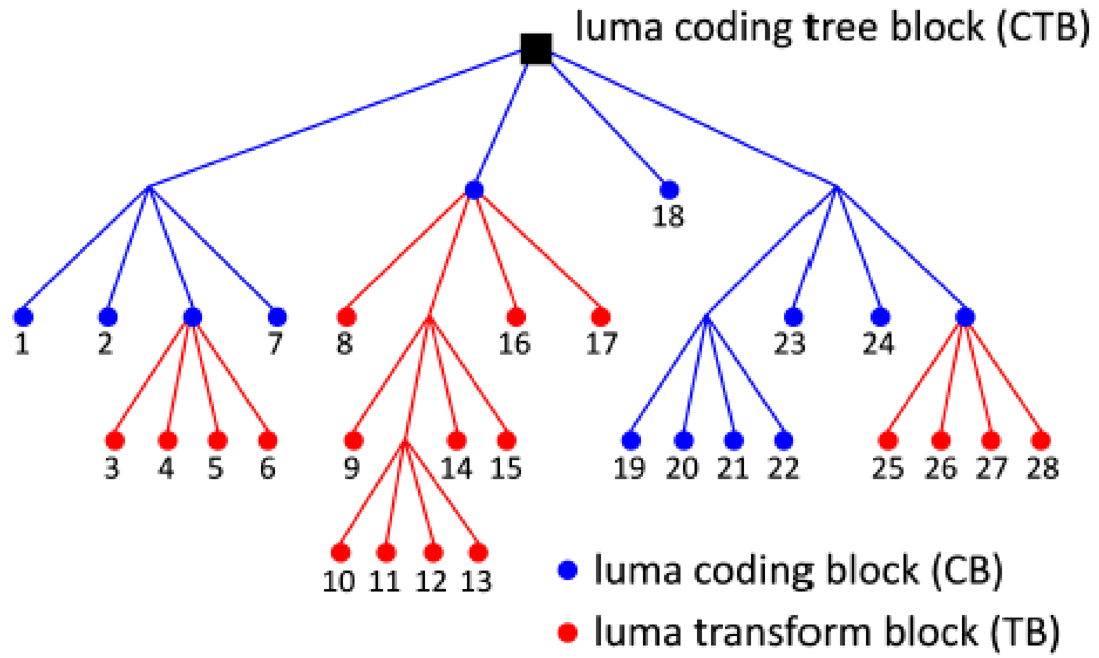
[Grois2015]

Block Structures (Cont.)

Example:



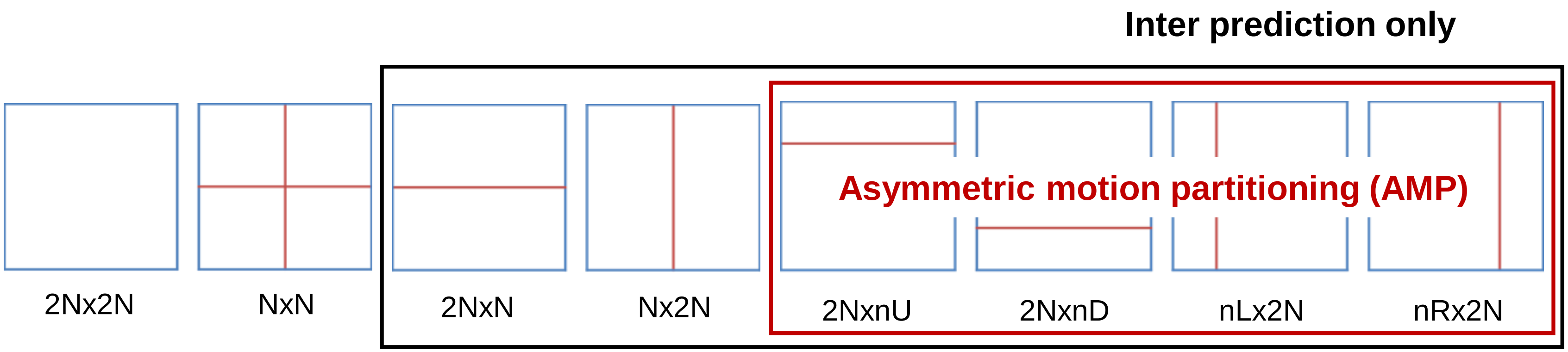
[Schwarz2014]



[Grois2015]

Block Structures (Cont.)

Different **Prediction Block** partition modes:



.

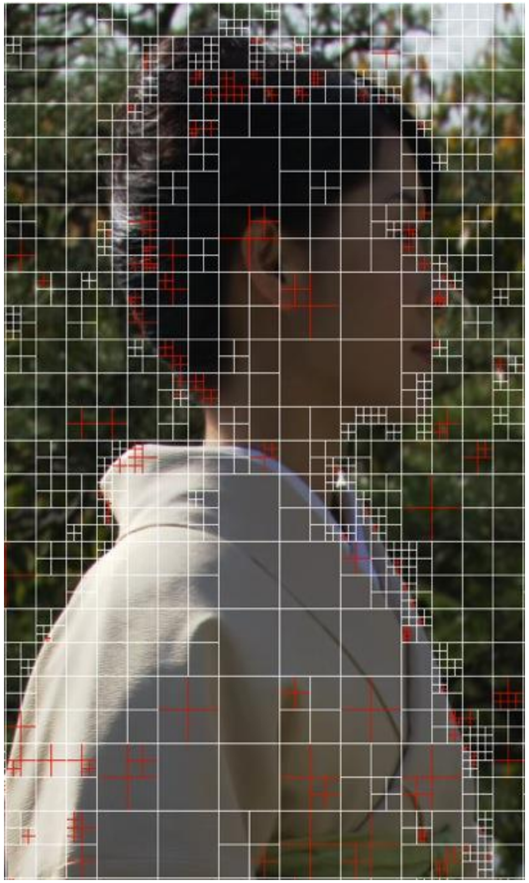
- Each prediction block in a coding block uses the same prediction mode (intra or inter);
- Inter: motion compensation is done per prediction block and prediction blocks can be "merged";
- Intra: mode, e.g. DC, planar, angular,.. defined per prediction block.

[Grois2015]

Block Structures (Cont.)

RQT with variable-size Transform Block leaves:

- Transform of the residual is performed on transform blocks;
- Intra prediction is also performed on transform blocks in intra coding blocks;
- Transform sizes ranging from 4x4 to 32x32;
- Adaptation to varying space-frequency characteristics in the residual signal for the DCT-based integer transform.



[Grois2015]

Block Structures (Cont.)

Average bit-rate savings for successively increasing the CTU size and the number of hierarchy levels in the coding tree:

CTU Size and Minimum CU Size	Entertainment Applications	Interactive Applications
32x32 - 16x16	9.2%	17.4%
32x32 - 8x8	12.1%	20.2%
64x64 - 16x16	12.7%	23.8%
64x64 - 8x8	14.9%	25.5%

[Schwarz2014]

Anchor: 16x16 CTU size and a minimum CU size of 8x8 luma samples.

[Grois2015]

Block Structures (Cont.)

Coding efficiency improvement for successively increasing the maximum TU size:

Maximum TU Size	Entertainment Applications	Interactive Applications
Maximum TU Size of 8x8	6.8%	8.5%
Maximum TU Size of 16x16	11.9%	14.7%
Maximum TU Size of 32x32	13.9%	17.5%

[Schwarz2014]

Anchor: 4x4 TUs, 64x64 CTU, all CU and PU sizes

[Grois2015]

Block Structures (Cont.)

Average bit-rate savings for successively enabling various PU sizes:

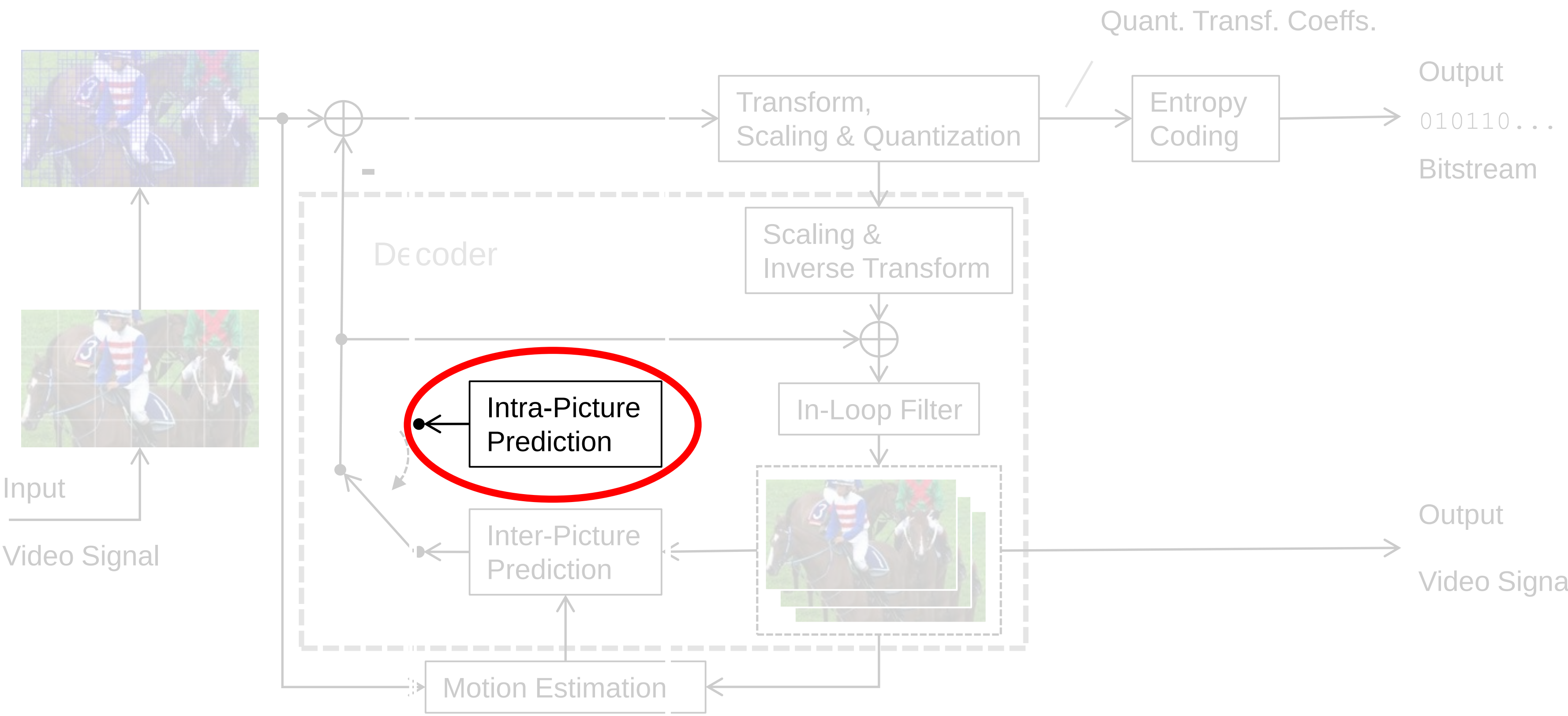
Enabled PU Sizes	Entertainment Applications	Interactive Applications
16x16 and 8x8	2.7%	4.4%
Square PUs from 4x4 to 16x16	6.1%	5.6%
Square PUs from 4x4 to 32x32	15.4%	23.0%
Square PUs from 4x4 to 64x64	18.7%	30.3%
All modes except asym. (+4x4 PUs)	20.0%	31.0%
All HEVC PU Sizes (+4x4 PUs)	20.7%	33.0%

[Schwarz2014]

Anchor: 16x16 PUs and 4x4 TUs

[Grois2015]

Intra-Picture Prediction



[Grois2015]

Intra-Picture Prediction: Main Tools

H.264/AVC intra-picture prediction drawbacks:

- **Insufficient range of supported coding block sizes**: especially high-resolution videos (HD or UHD) cannot be coded properly due to the poor representation of some picture textures.
- **Insufficient number of intra prediction directions**: especially for larger block sizes.
- **Insufficient prediction of homogeneous regions**: visible artifacts introduced by discontinuities at block boundaries
- **Inconsistency across block sizes**: depending on the size of the block, H.264/AVC uses different methods for predicting a block and the color component, which is represented by the block; it turn, this can be especially critical for a large variety of block sizes.

[Grois2015]

Intra-Picture Prediction: Main Tools

HEVC intra-picture prediction addresses H.264/AVC drawbacks by:

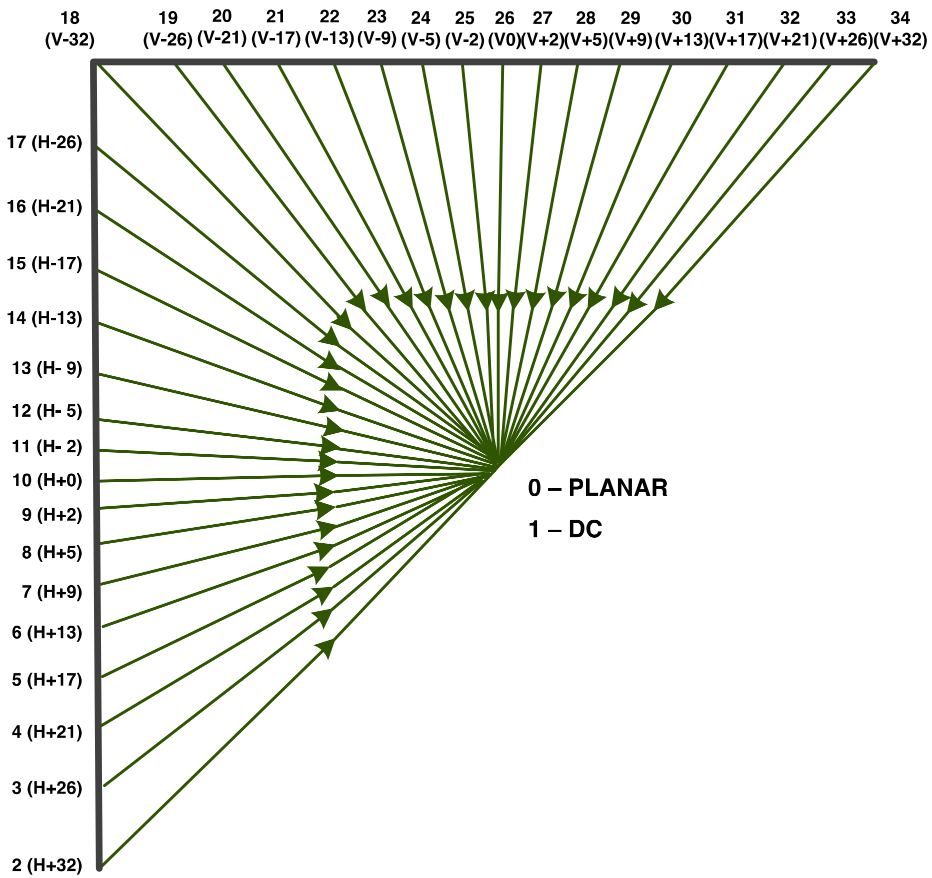
- Reference samples computed with **1/32 pel accuracy** (bilinear interpolation);
- Angular prediction with **33 directional modes** as well as Planar and DC modes;
- **Reference sample smoothing** for diagonal directions and planar mode;
- **Boundary smoothing** (across block boundary) for the horizontal, vertical and DC modes;
- Prediction modes **unified across all block sizes.**

[Grois2015]

Intra Prediction: Main Tools (Cont.)

Three prediction types:

- **Planar** prediction (0),
- **DC** prediction (1),
- **33 angular prediction directions** (2-34).



[Grois2015]

Intra Prediction: Main Tools (Cont.)

Only 5 modes for chroma can be signaled:

- Planar (0);
- DC (1);
- Horizontal (10);
- Vertical (26);
- **Same directional mode as luma**.

[Grois2015]

Intra Prediction: Reference Sample Smoothing

HEVC adaptive smoothing depends on:

- **Block size;**
- **Directionality;**
- **Amount of detected discontinuity.**

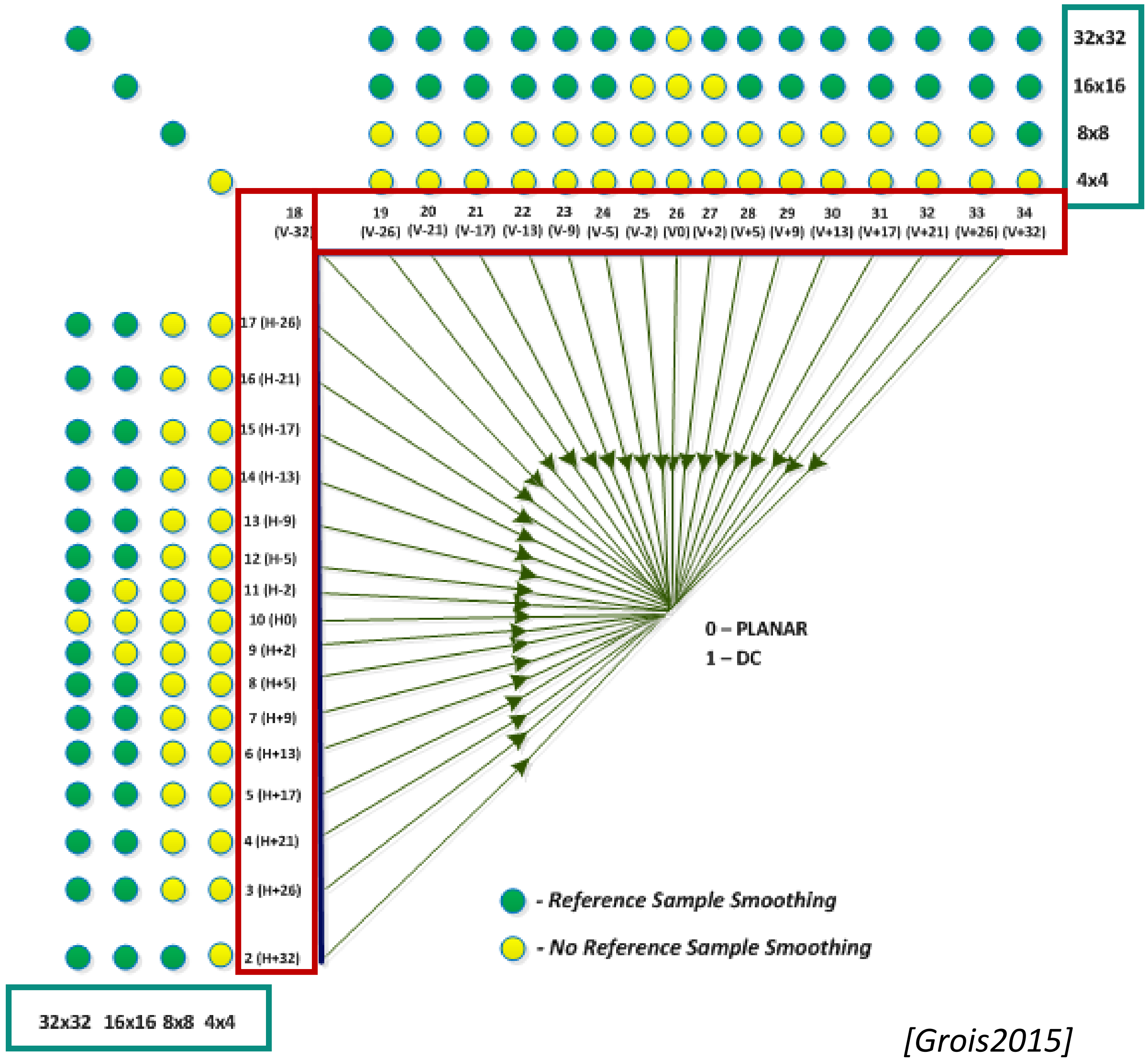
- Two smoothing filters:
  - **Normal filtering;**
  - **Strong filtering.**
- Applied to each reference sample using the neighboring reference samples.

[Grois2015]

Intra Prediction: Reference Sample Smoothing (Cont.)

Reference Sample Smoothing depends on:

- **Block size**;
- **Intra direction**;
- Discontinuity by comparing minimal distance of direction to horizontal and vertical mode with predefined thresholds



[Grois2015]

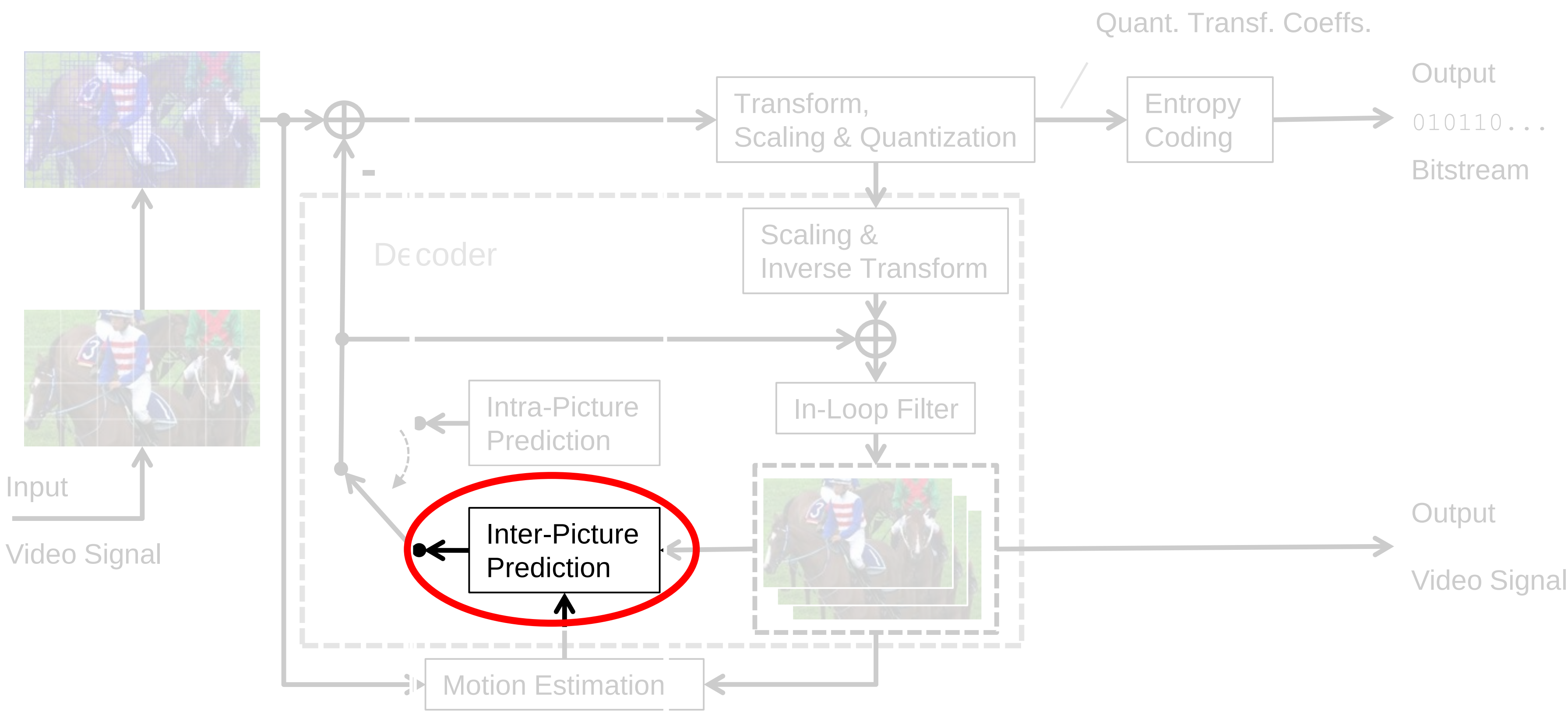
Intra Prediction: Boundary Sample Smoothing

Discontinuities along block boundaries may be introduced by applying intra-prediction modes.

- Hence, HEVC employs boundary sample smoothing for:
  - **Luma TBs;**
  - **TB sizes < 32x32;**
  - **Horizontal prediction mode**, applied to the first row;
  - **Vertical prediction mode**, applied to the first column;
  - **DC intra-prediction mode**, both the first row and column of samples in the TB are filtered.
- Prediction for chroma components tends to be very smooth -> **no boundary smoothing for chroma TBs to reduce the computational complexity**

[Grois2015]

Inter-Picture Prediction



[Grois2015]

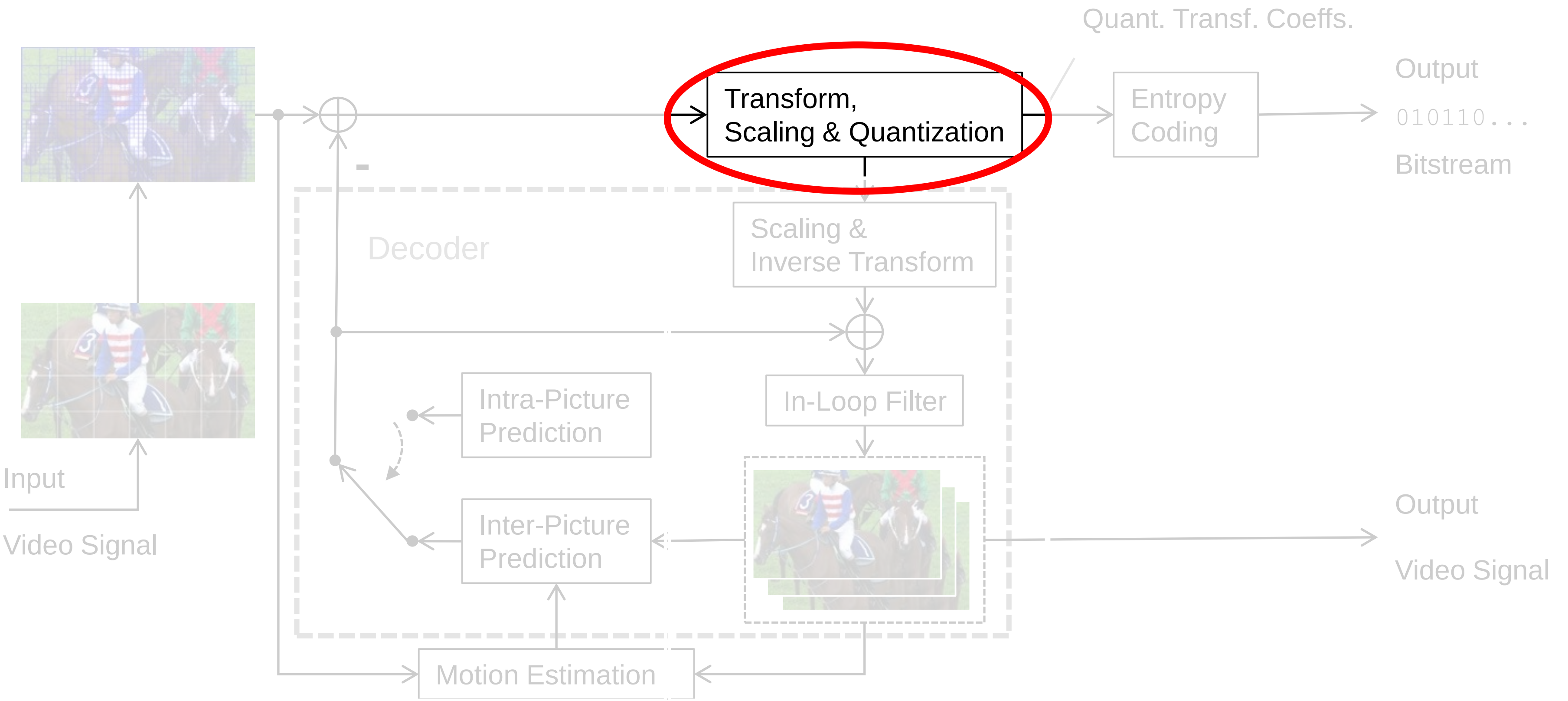
Inter-Picture Prediction: Main Tools

HEVC improves motion compensated prediction by:

- Asymmetric Motion Partitions (AMP) as explained in *Block Structures*;
- Reference Picture Sets (RPS) for simplified decoded picture buffer management;
- Improved interpolation filters for luma and chroma;
- More efficient motion data coding including
  - Advanced Motion Vector Prediction (AMVP);
  - Inter-picture prediction block merging (Merge);
  - Motion Data Storage Reduction (MDSR);
- Simplified weighted sample prediction.
- No 4x4 blocks and only uni-prediction for 4x8/8x4 to reduce memory bandwidth

[Grois2015]

Transform and Quantization



[Grois2015]

Transform and Quantization

- **Prediction residual is transformed** (unless signaled as zero by coded block flag, skip mode or alternative bypass modes);
- Core transforms 4x4 ... 32x32 are **integer approximations of DCT:**
  - Close to orthogonality;
  - Nearly identical norms of all basis vectors: Unique scaling factor for each transform size;
  - Matrices of smaller-size transforms are sub-sampled versions of length-32 transform matrix.
- **2D transforms separable** (except for the rounding after each transform step), only square transforms used.

[Grois2015]

Transform and Quantization (Cont.)

- **Example: length-16 transform matrix (Euclid. norm approx. 256):**

8x8

$$H = \left[\begin{array}{cccccccccccccccc}
64 & 64 & 64 & 64 & 64 & 64 & 64 & 64 & 64 & 64 & 64 & 64 & 64 & 64 & 64 & 64 \\
90 & 87 & 80 & 70 & 57 & 43 & 25 & 9 & -9 & -25 & -43 & -57 & -70 & -80 & -87 & 90 \\
89 & 75 & 50 & 18 & -18 & -50 & -75 & -89 & -89 & -75 & -50 & -18 & 18 & 50 & 75 & 89 \\
87 & 57 & 9 & -43 & -80 & -90 & -70 & -25 & 25 & 70 & 90 & 80 & 43 & -9 & -57 & -87 \\
83 & 36 & -36 & -83 & -83 & -36 & 36 & 83 & 83 & 36 & -36 & -83 & -83 & -36 & 36 & 83 \\
80 & 9 & -70 & -87 & -25 & 57 & 90 & 43 & -43 & -90 & -57 & 25 & 87 & 70 & -9 & -80 \\
75 & -18 & -89 & -50 & 50 & 89 & 18 & -75 & -75 & 18 & 89 & 50 & -50 & -89 & -18 & 75 \\
70 & -43 & -87 & 9 & 90 & 25 & -80 & -57 & 57 & 80 & -25 & -90 & -9 & 87 & 43 & -70 \\
64 & -64 & -64 & 64 & 64 & -64 & -64 & 64 & 64 & -64 & -64 & 64 & 64 & -64 & -64 & 64 \\
57 & -80 & -25 & 90 & -9 & -87 & 43 & 70 & -70 & -43 & 87 & 9 & -90 & 25 & 80 & -57 \\
50 & -89 & 18 & 75 & -75 & -18 & 89 & -50 & -50 & 89 & -18 & -75 & 75 & 18 & -89 & 50 \\
43 & -90 & 57 & 25 & -87 & 70 & 9 & -80 & 80 & -9 & -70 & 87 & -25 & -57 & 90 & -43 \\
36 & -83 & 83 & -36 & -36 & 83 & -83 & 36 & 36 & -83 & 83 & -36 & -36 & 83 & -83 & 36 \\
25 & -70 & 90 & -80 & 43 & 9 & -57 & 87 & -87 & 57 & -9 & -43 & 80 & -90 & 70 & -25 \\
18 & -50 & 75 & -89 & 89 & -75 & 50 & -18 & -18 & 50 & -75 & 89 & -89 & 75 & -50 & 18 \\
9 & -25 & 43 & -57 & 70 & -80 & 87 & -90 & 90 & -87 & 80 & -70 & 57 & -43 & 25 & -9
\end{array}\right]$$

[Grois2015]

Transform and Quantization (Cont.)

- **Example: length-16 transform matrix (Euclid. norm approx. 256):**

4x4

$$H = \begin{bmatrix}
64 & 64 & 64 & 64 & 64 & 64 & 64 & 64 & 64 & 64 & 64 & 64 & 64 & 64 & 64 & 64 \\
90 & 87 & 80 & 70 & 57 & 43 & 25 & 9 & -9 & -25 & -43 & -57 & -70 & -80 & -87 & 90 \\
89 & 75 & 50 & 18 & -18 & -50 & -75 & -89 & -89 & -75 & -50 & -18 & 18 & 50 & 75 & 89 \\
87 & 57 & 9 & -43 & -80 & -90 & -70 & -25 & 25 & 70 & 90 & 80 & 43 & -9 & -57 & -87 \\
83 & 36 & -36 & -83 & -83 & -36 & 36 & 83 & 83 & 36 & -36 & -83 & -83 & -36 & 36 & 83 \\
80 & 9 & -70 & -87 & -25 & 57 & 90 & 43 & -43 & -90 & -57 & 25 & 87 & 70 & -9 & -80 \\
75 & -18 & -89 & -50 & 50 & 89 & 18 & -75 & -75 & 18 & 89 & 50 & -50 & -89 & -18 & 75 \\
70 & -43 & -87 & 9 & 90 & 25 & -80 & -57 & 57 & 80 & -25 & -90 & -9 & 87 & 43 & -70 \\
64 & -64 & -64 & 64 & 64 & -64 & -64 & 64 & 64 & -64 & -64 & 64 & 64 & -64 & -64 & 64 \\
57 & -80 & -25 & 90 & -9 & -87 & 43 & 70 & -70 & -43 & 87 & 9 & -90 & 25 & 80 & -57 \\
50 & -89 & 18 & 75 & -75 & -18 & 89 & -50 & -50 & 89 & -18 & -75 & 75 & 18 & -89 & 50 \\
43 & -90 & 57 & 25 & -87 & 70 & 9 & -80 & 80 & -9 & -70 & 87 & -25 & -57 & 90 & -43 \\
36 & -83 & 83 & -36 & -36 & 83 & -83 & 36 & 36 & -83 & 83 & -36 & -36 & 83 & -83 & 36 \\
25 & -70 & 90 & -80 & 43 & 9 & -57 & 87 & -87 & 57 & -9 & -43 & 80 & -90 & 70 & -25 \\
18 & -50 & 75 & -89 & 89 & -75 & 50 & -18 & -18 & 50 & -75 & 89 & -89 & 75 & -50 & 18 \\
9 & -25 & 43 & -57 & 70 & -80 & 87 & -90 & 90 & -87 & 80 & -70 & 57 & -43 & 25 & -9
\end{bmatrix}$$

[Grois2015]

Transform and Quantization (Cont.)

Integer approximation of **Discrete Sine Transform (DST)** is applied to 4x4 intra residual:

- In intra prediction (in particular directional and planar), the prediction error increases with larger distance from the boundary;
- DST basis vectors are better fitting such behavior;
- For **intra residual of 4x4 PBs**, the following transform matrix is used (Euclid. norm approx. 128, same as length-4 DCT (*the Euclidean norm is the square root of the sum of all the squares*)).

$$H = \begin{bmatrix} 29 & 55 & 74 & 84 \\ 74 & 74 & 0 & -74 \\ 84 & -29 & -74 & 55 \\ 55 & -84 & 74 & -29 \end{bmatrix}$$

- **Provides a 1% bit-rate reduction** but was restricted to Intra 4×4 luma transform blocks due to marginal benefits for the other transform cases.

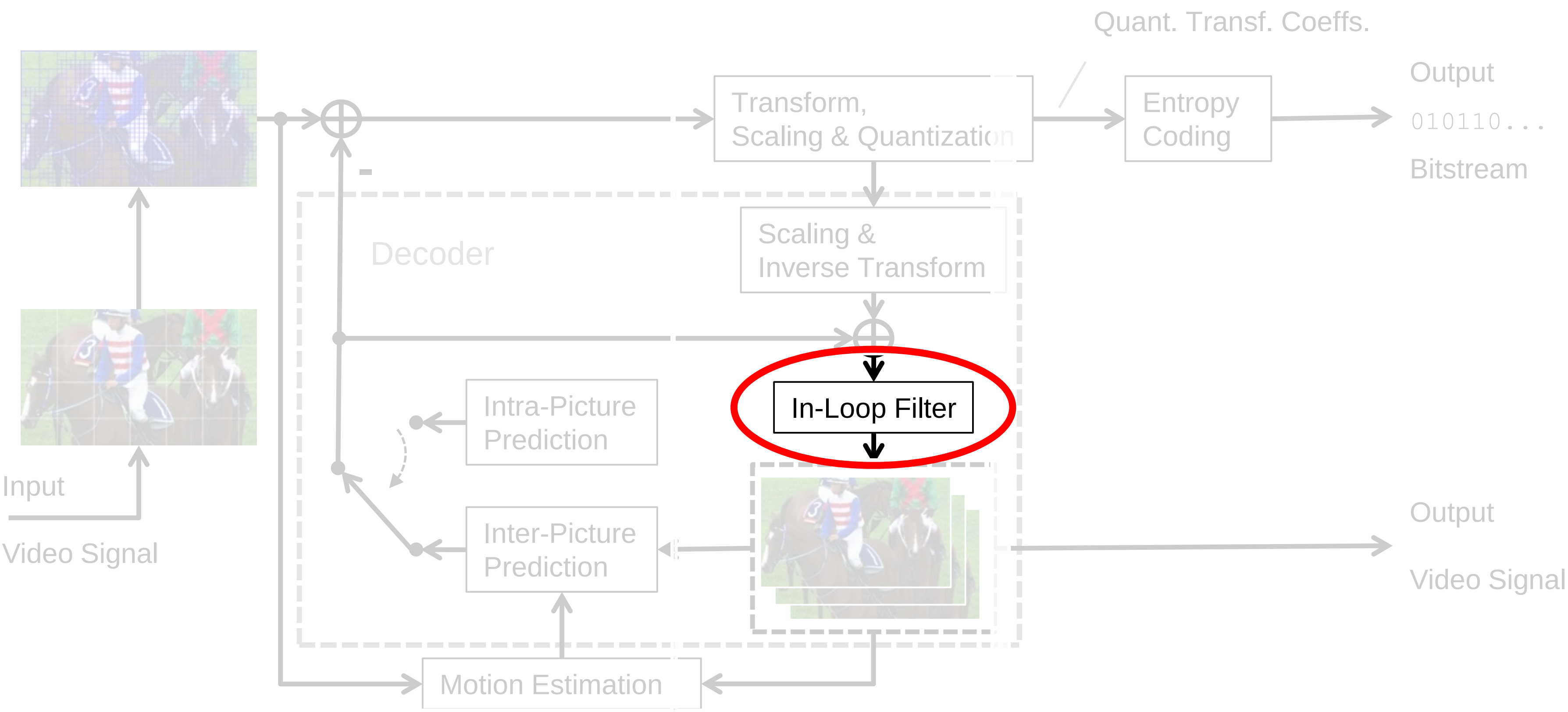
[Grois2015]

Transform and Quantization (Cont.)

- **Quantization similar to H.264/MPEG-AVC** (QP+6 = double step size, QP values are defined from 0 to 51).
- The QP to Qstep mapping has a reduction of about 12.5% in the bitrate for the increase of 1 in QP.
- **CU level adaption** of quantizer step size.
- Coding of QP performed differentially within CTU.
- **Frequency weighted quantization** possible via quantization matrices (encoded in SPS or PPS):
  - For the larger transforms (16x16, 32x32) a subsampled quantization matrix of size 8x8 is used, i.e. same quantization step sizes used for groups of 2x2 or 4x4 adjacent coefficients);
  - Different quantization matrices for intra and inter, Y/Cb/Cr;
  - Matrix entries coded differentially.

[Grois2015]

In-loop Filters



[Grois2015]

In-loop Filters

Two filters to remove coding artifacts and preserve edges applied before writing the output to reference memory (not effective in intra prediction) :

- **Deblocking Filter** (similar to H.264/MPEG-4 AVC, but having a reduced number of filtering strengths and better parallelization) – operated only on 8x8 block boundaries (not 4x4) with 4-sample units.

- **Sample Adaptive Offset (SAO)** - two different offset methods:
  - **Individual mapping with *edge offset values*** applied to samples based on classification as an edge or non-edge.
  - **Non-linear amplitude mapping function with *band offset values*** applied to samples based on their values lying in one of four consecutive samples value ranges (bands).

[Grois2015]

Deblocking Filter

Generally, when designing a deblocking filter, several issues should be carefully considered:

- Filter has a **direct impact on the subjective picture quality.**
- The filtering decisions contain **challenges that lead to the following main questions:**
  - Is the block boundary **natural edge or artifact (filter off/on)**?
  - Which **filtering strength** should be used?

[Grois2015]

Deblocking Filter (Cont.)

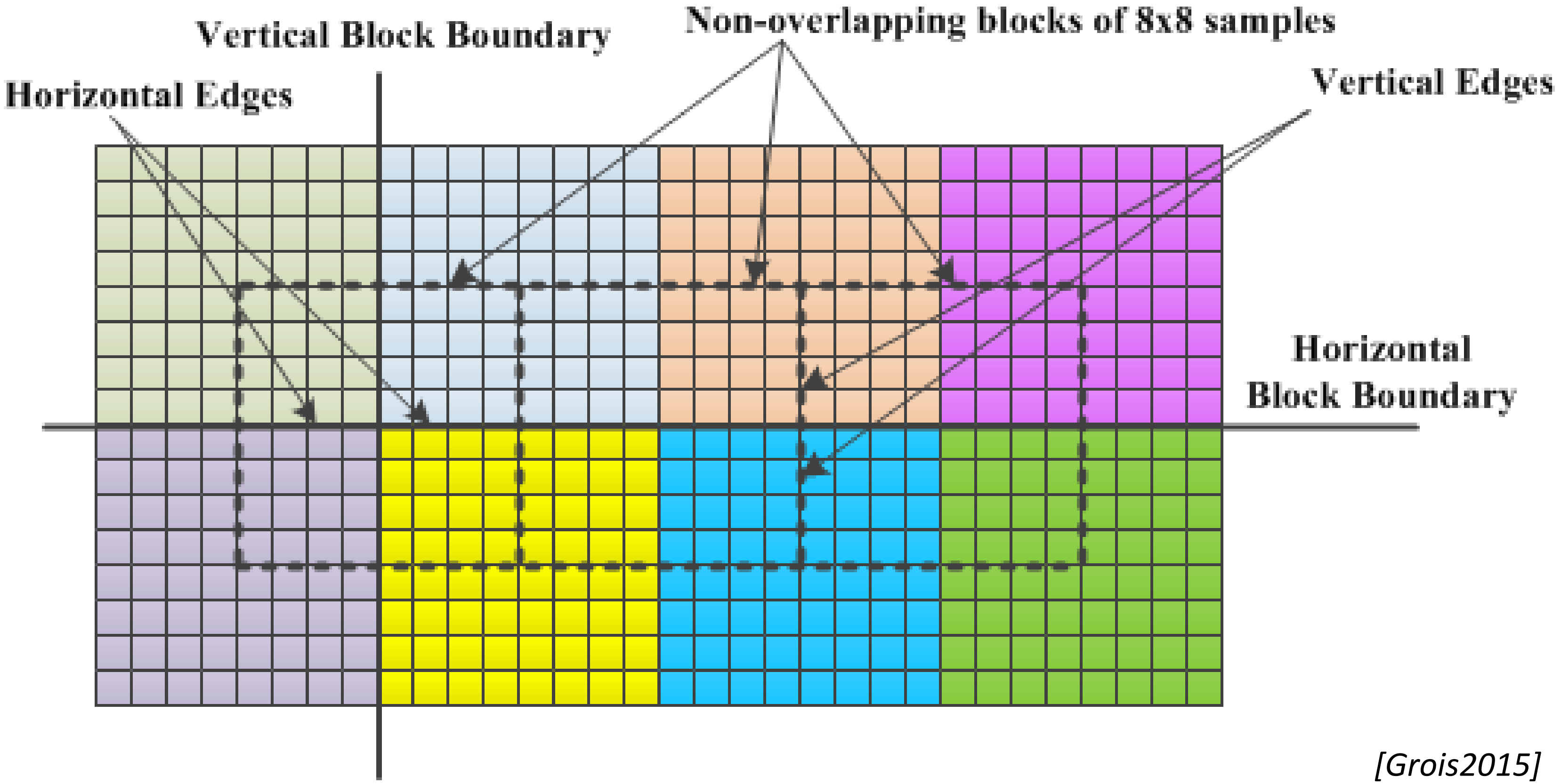
The deblocking is performed on a **four-sample portion of a 8x8 block boundary**, when the following conditions are held:

- the block boundary is a prediction unit or transform unit boundary;
- the block boundary strength, which is determined according to a predefined criteria, is greater than zero;
- variation of signal on both sides of a block boundary is below a specific threshold.

[Grois2015]

Deblocking Filter (Cont.)

Splitting a picture on 8x8. The dotted-lines represents non-overlapping blocks of 8x8 samples: these non-overlapping blocks can be deblocked in a parallel manner → better parallelization.



[Grois2015]

Deblocking Filter (Cont.)

- **BS values for the boundary between two neighbor luma blocks**
- **2 – Strong Filtering, 1 – Weak Filtering, 0 – No Filtering:**

No.	Conditions for Applying a Deblocking Filter	BS Values
1	At least one of the blocks P or Q is intra predicted	2
2	At least one of the blocks P or Q has non-zero coded residual coefficient and boundary is a transform boundary	1
3	Absolute differences between corresponding spatial motion vector components of the two blocks P and Q are ≥ 1 in units of integer pixels	1
4	Motion-compensated prediction for the two blocks P and Q refers to different reference pictures or the number of motion vectors is different for the two blocks	1
5	Otherwise	0

[Grois2015]

Deblocking: Weak/Strong Filtering

- The **strong filtering** is applied:
  - **on three samples on both sides of the block boundary;**
  - within the four-sample segment;
  - similar to H.264/MPEG-4 AVC.

- The **weak filtering** is applied:
  - **on two samples on both sides of the block boundary;**
  - within the four-sample segment.

[Grois2015]

Deblocking Filter: Parallelism

The deblocking process in HEVC provides **improved parallelization, compared to H.264/MPEG-4 AVC:**

- the deblocking process of **non-overlapping 8x8 samples** can be fully parallelized;
- any **vertical block edge** can be deblocked in parallel with the deblocking of any other vertical block edge;
- any **horizontal block edge** can be deblocked in parallel with the deblocking of any other horizontal block edge;
- **the updated sample values after the deblocking of vertical block boundaries are used as input for filtering the horizontal block boundaries.**

[Grois2015]

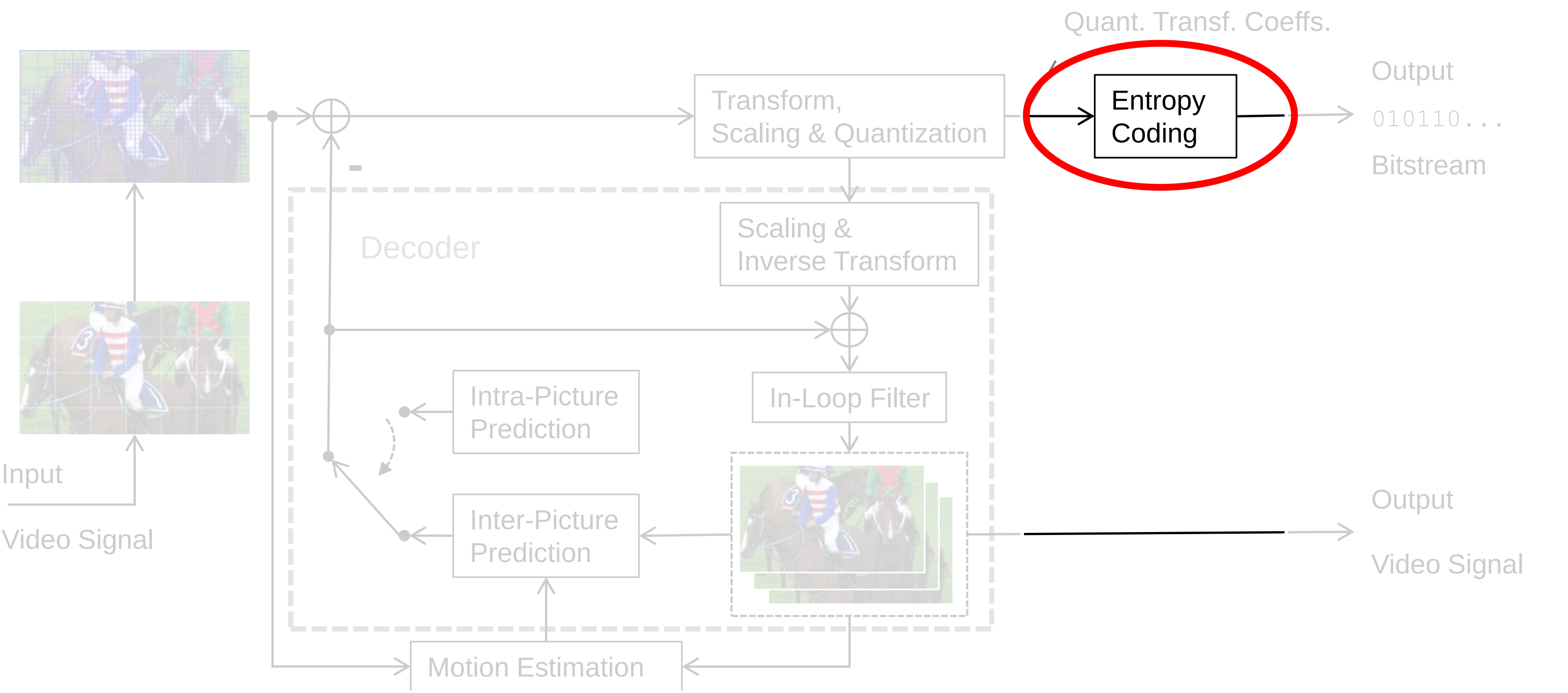
Sample Adaptive Offset: Motivation

- **Sample Adaptive Offset filter is designed to add corrective offset values for attenuating:**
  - **Systematic Errors** introduced by quantization and phase shifts from inaccurate motion vectors;
  - **Ringing Artefacts (Gibbs Phenomenon)**, introduced mainly by large transform sizes.

- **Two different offset methods can be used:**
  - **Non-linear amplitude mapping function** with band offset values applied to samples based on their values lying in one of four consecutive samples value ranges (bands) out of 32;
  - **Individual mapping with edge offset values** applied to samples based on classification as edge or non-edge, whereas the gradient orientation is determined by the encoder.

[Grois2015]

Entropy Coding



[Grois2015]

Context-based Adaptive Binary Arithmetic Coding

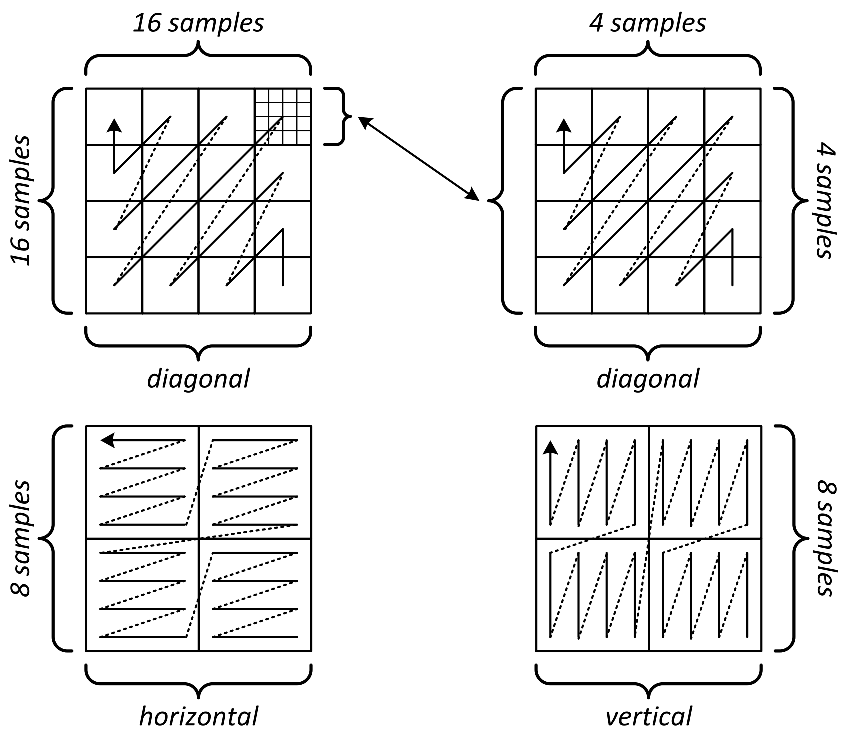
Single entropy coding scheme in HEVC using Context-based Adaptive Binary Arithmetic Coding (CABAC) instead of two in H.264/AVC:

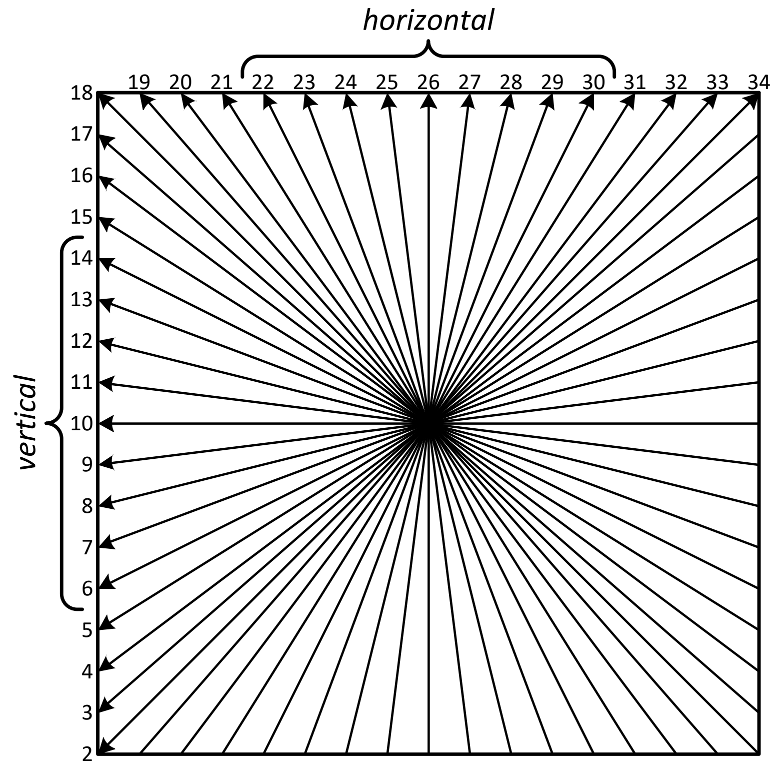
- Usage of **adaptive** probability models for most symbols;
- Exploiting symbol correlations by using **contexts;**
- Restriction to **binary arithmetic coding** based on table look-ups and shifts only;
- Main improvements, compared to H.264/AVC:
  - **Reduced number of contexts**;
  - **Reduced number of context coded binary decisions** to avoid throughput bottleneck;
  - **Removed dependencies** to facilitate parallel context derivation;
  - **Truncated Rice Codes** added as binarization.

[Grois2015]

Entropy Coding of Transform Coefficients

- Sub-blocks and the 16 coefficients in a sub-block are processed using a reverse **diagonal scan.**





- Intra 4x4 TBs and 8x8 luma TBs use a **horizontal scan** and a **vertical scan.**

[Grois2015]

Alternative Coding Modes (I)

Three special coding tools give support for special cases (without any significant implementation cost).

- **Transform bypass**
- **Lossless bypass**
- **Intra PCM Mode**

[Grois2015]

Alternative Coding Modes (II)

Transform bypass:

- Signaled at **TB level** (transform_skip_flag);
- Useful particularly for graphics content (**sharp edges, flat areas**), e.g. as in **screen content coding applications**;
- CABAC contexts of transform coding are directly applied to prediction error signal (**becoming spatial contexts to close neighbor samples**).

Bypass enabling "lossless" coding:

- Signaled at **CU level** (cu_transquant_bypass_flag);
- **Bypass of scaling, transform and in-loop filters**;
- CABAC entropy coding still applied as is;
- Can also be used locally, e.g. for graphics/text

[Grois2015]

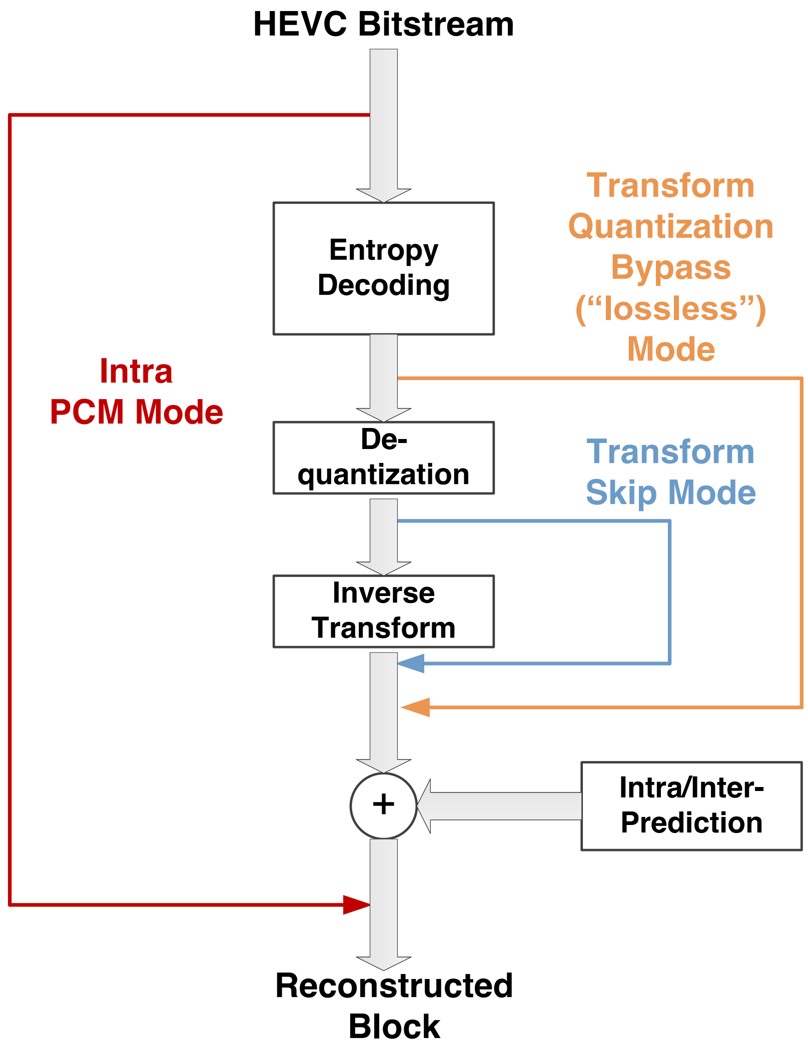
Alternative Coding Modes (III)

Intra PCM mode:

- Signaled at **CU level** (pcm_flag);
- **Direct coding of sample values**;
- Is intended for **"emergency" situations** when encoder:
  - faces complicated content and would produce more bit rate than uncoded samples (e.g., in case of the uncorrelated noise);
  - would overrun its processing capabilities.

[Grois2015]

Alternative Coding Modes (IV)



[Grois2015]

High-Level Syntax

- In general, all syntax elements above the slice segment data layer are called high-level syntax.

- High-level syntax:
  - Access to packets
  - Settings of low level coding tools
  - Random-access information
  - Metadata

[Grois2015]

High-Level Syntax: Parameter Sets

- **Sequence Parameter Set (SPS)** and **Picture Parameter Set (PPS)** similar as H.264/MPEG-AVC
- New **Video Parameter Set (VPS)**
  - Describes overall characteristics of coded video sequences, including the dependencies between layers.
  - Enables compatible extensibility in terms of signaling at the systems layer.

[Grois2015]

High-Level Syntax: VPS

The (HEVC version 1) Video Parameter Set contains:

- Maximum number of **layers** in the bitstream and the highest layer ID
- Maximum number of **temporal sub-layers**
- **Profile/Tier/Level** (for each temporal sub-layer)
- DPB parameters (optional for temporal sub-layers)
- Layer sets (which can be extracted as sub-bitstreams)
- Timing (optional)
- HRD parameters (optional)

[Grois2015]

High-Level Syntax: VPS (Cont.)

The Video Parameter Set extension (HEVC version 2) contains:

- Scalability types
  - Scalable
  - Multi-View
  - Depth (v3)
  - Auxiliary pictures
- Dependencies between layers
- Output layer sets
- Representation Format
- DPB information
- VPS VUI

[Grois2015]

High-Level Syntax: SEI and VUI

Supplemental Enhancement Information (SEI) and Video Usability Information (VUI):

- SEI and VUI concepts similar to H.264/MPEG-AVC
  - no impact on normative decoder behavior
  - usage optional
- Example SEI messages: Buffering Information, Picture Timing, Frame packing (for stereo), display orientation, interlaced-scan indicators (frame/field arrangement);
- Example VUI parameters: Hypothetical Reference Decoder (HRD) and clock parameters, color space, aspect ratio, constraint flags.

[Grois2015]

Parallel Picture Processing

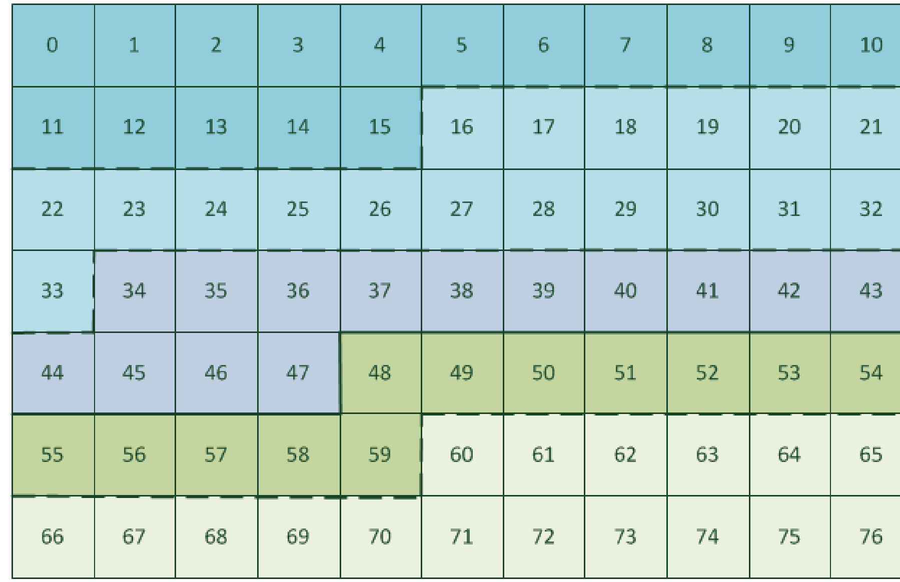
- Slices / Slice segments
- Tiles
- Wavefront Parallel Processing (WPP)

[Grois2015]

Parallelization Tools: Slices

Slice coding:

- Slices can be coded independent of each other.
- In-loop filters can be disabled at slice boundaries.



Dependent slice segments

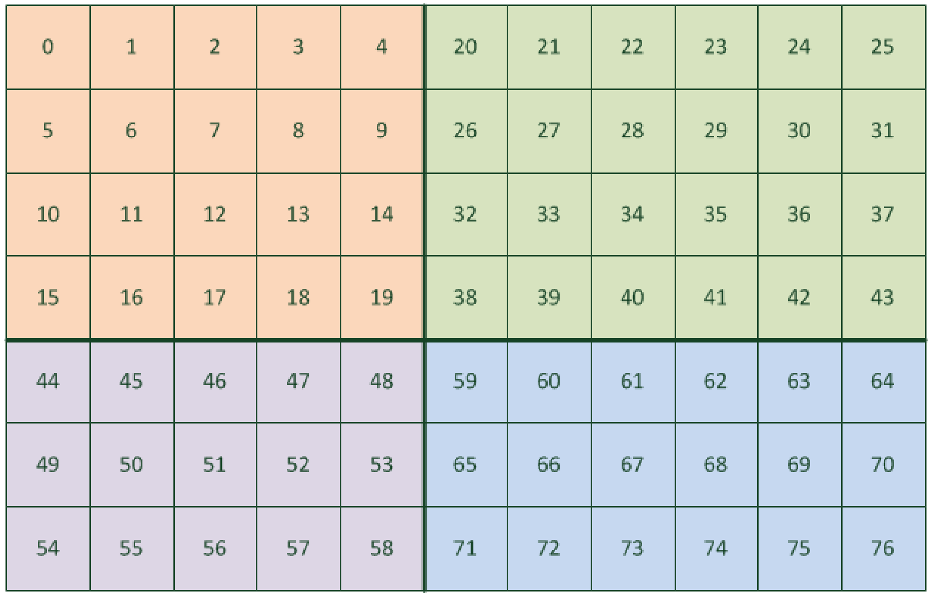
- Inherit the previous entropy coding state

[Grois2015]

Parallelization Tools: Tiles

Tiles are:

- Independent rectangular regions of the picture
- In a regular pattern (division by horizontal and vertical lines within the picture)



Processing of tiles

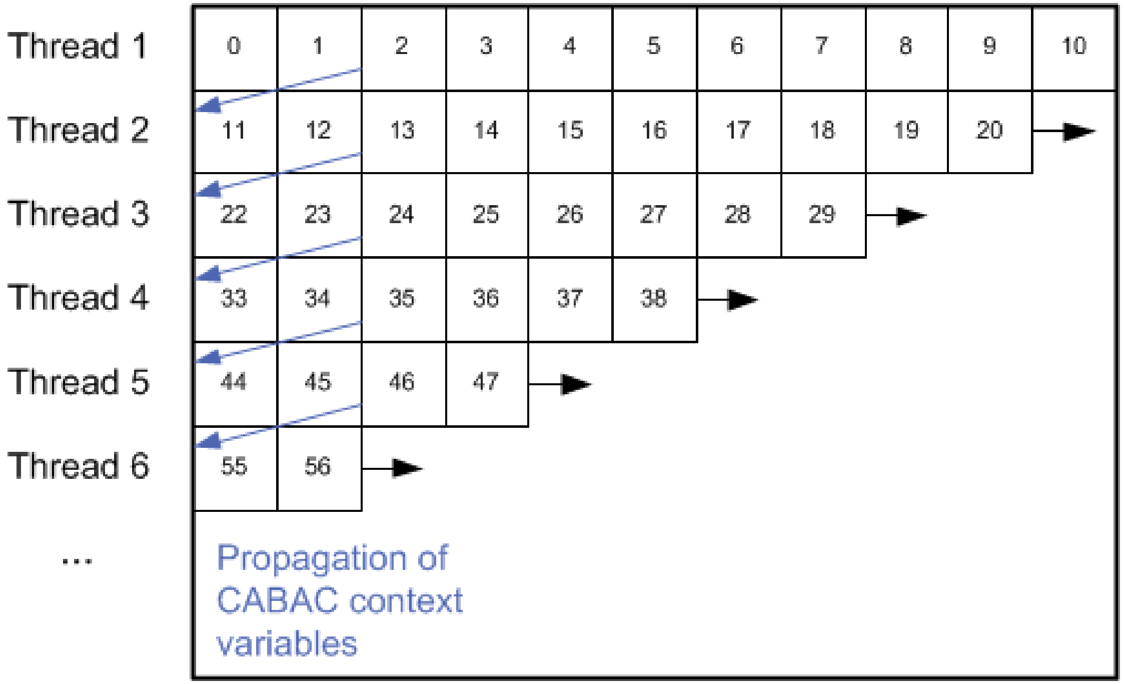
- In raster scan order over the tiles
- and CTU-wise in raster scan order within the tiles.

[Grois2015]

Parallelization Tools: Wavefronts

Wavefront processing:

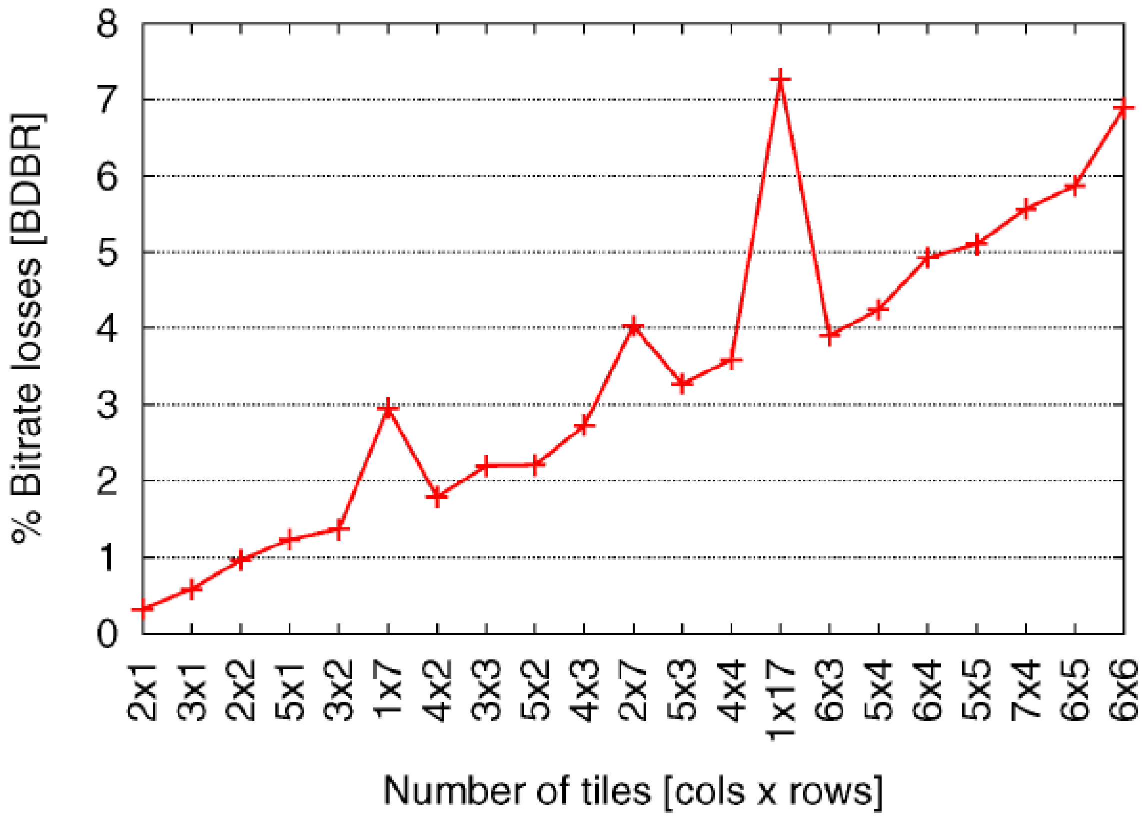
- Allows to run several processing threads in a slice over rows of CTUs with a delay that allows adaptation;
- CABAC contexts are inherited from a row above



[Grois2015]

Parallelization Tools: Performance

Total coding losses (using weighted BD-Rate) of different tile configurations for 1080 videos.



[Chi2012] *[Grois2015]*

Parallelization Tools: Performance

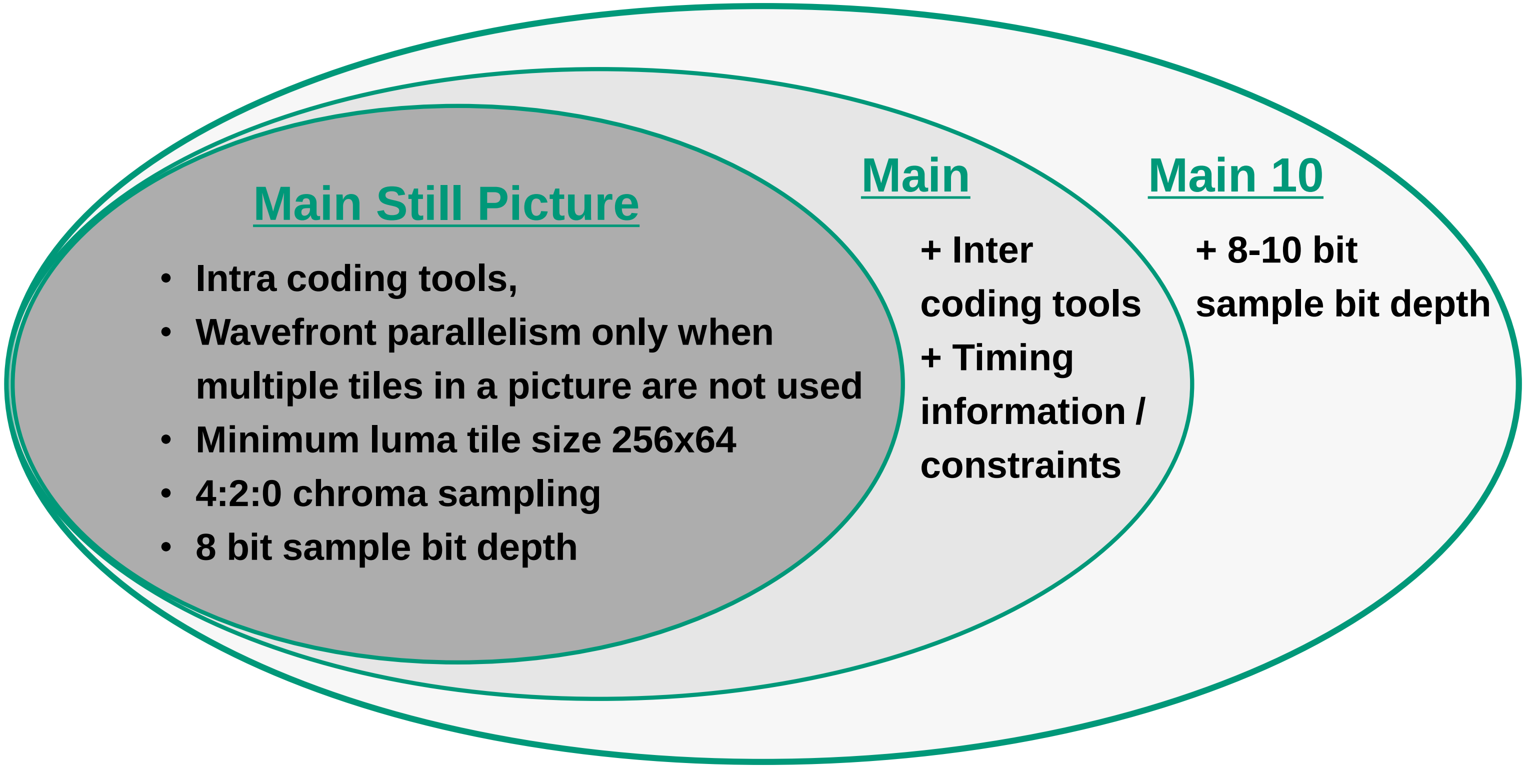
Comparison of Parallelization Approaches

Properties	Slices	Tiles	WPP
Coding loss	Very high	High	Low
Boundary artifacts	Yes	Yes	No
Single-core issues	No	Yes	No
Parallel scalability	Medium	Medium	Medium/high
Region of interest	No	Yes	No

[Chi2012]

Profiles, Levels and Tiers

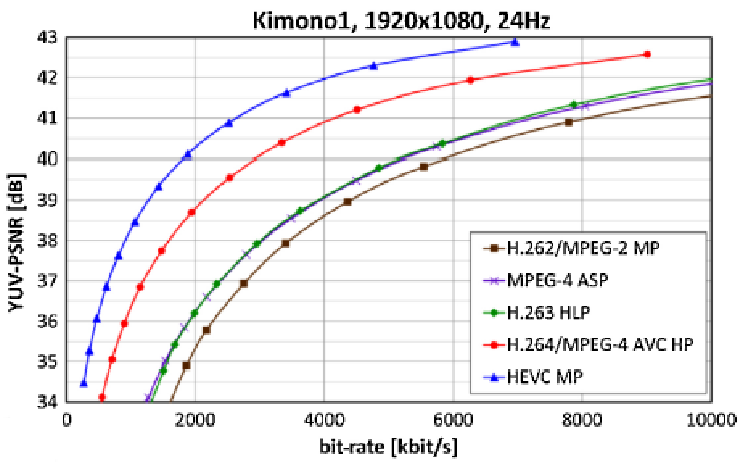
Onion-like structure

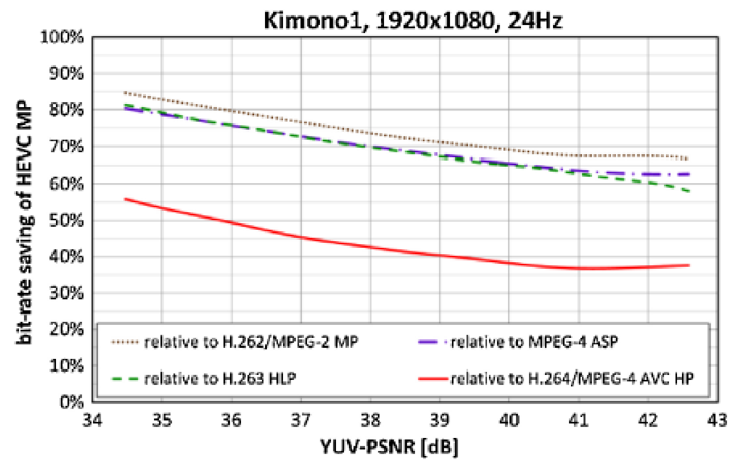


[Grois2015]

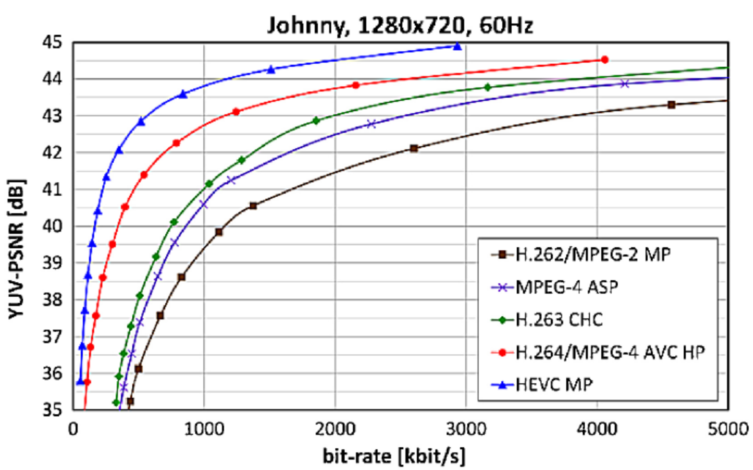
Rate-Distortion Performance

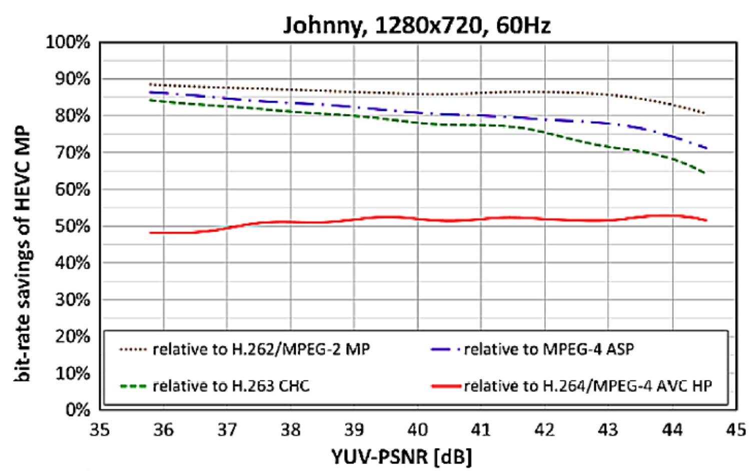
Entertainment Applications (Random Access)





Interactive Applications (Low Delay)

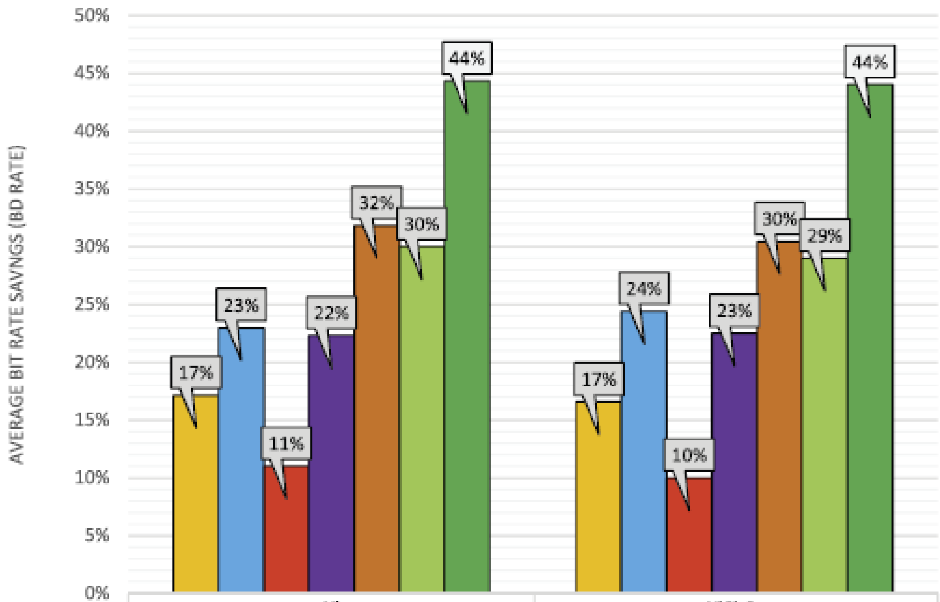




[Ohm2012]

Average Bit-rate Savings (Still Picture Coding)

Average bit-rate savings for the HEVC Main Still Picture Profile:

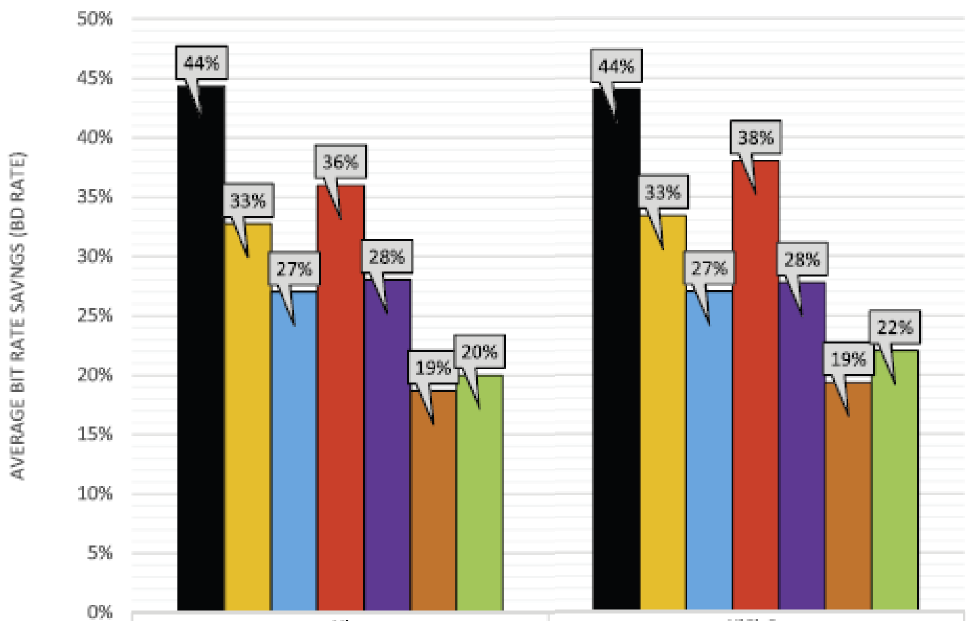


	Y'	Y'CbCr
AVC	17%	17%
VP8	23%	24%
VP9	11%	10%
JPEG 2000	22%	23%
JPEG XR	32%	30%
WebP	30%	29%
JPEG	44%	44%

[Nguyen2015]

Average Bit-rate Savings (Still Picture Coding)

Average bit-rate savings relative to JPEG:



	Y'	Y'CbCr
HEVC	44%	44%
AVC	33%	33%
VP8	27%	27%
VP9	36%	38%
JPEG 2000	28%	28%
JPEG XR	19%	19%
WebP	20%	22%

[Nguyen2015]

Subjective Verification Tests of HEVC vs. AVC

Verification test completed in April, 2014 (JCTVC-Q1011):

- A **subjective evaluation** was conducted comparing the HEVC Main profile to the AVC High profile;
- 20 test sequences: **480p to Ultra HD (UHD)** various bit rates/quality levels;
- Average bit-rate savings for test sequences:
  - **UHD - 64%**
  - **1080p - 62%**
  - **720p - 56%**
  - **480p - 52%**

[Grois2015]

Average Bit-Rate Savings (Random Access)

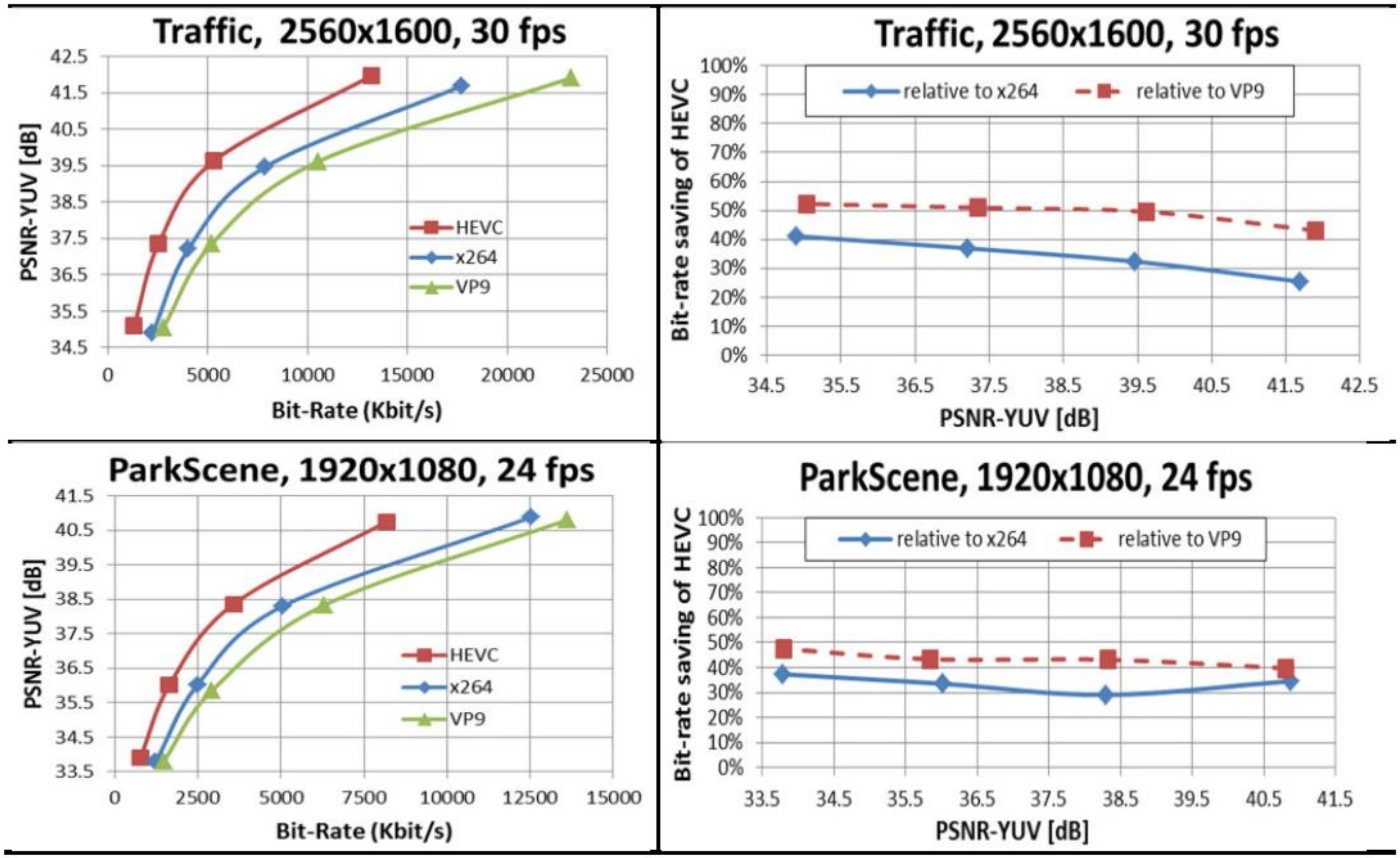
PCS 2013:

Sequences	HEVC vs. VP9 [%]	HEVC vs. x264 High Profile [%]
Traffic	50.1	38.2
PeopleOnStreet	26.4	24.9
Kimono	33.1	41.2
ParkScene	44.9	32.9
Cactus	45.3	39.6
BQTerrace	49.3	47.3
Basketball Drive	32.1	45.0
FourPeople	47.1	34.2
Johnny	52.2	47.9
KristenAndSara	49.5	41.9
BaskeballDrillText	45.4	43.4
ChinaSpeed	44.2	34.8
Averages	43.3	39.3
Total Average	**43.3**	**39.3**

[Grois2013]

Average Bit-Rate Savings (Random Access)

PCS 2013: Rate-Distortion plot examples



[Grois2013]

Average Bit-Rate Savings (Random Access & Low Delay)

HEVC vs. H.264/AVC High Profile (x264) and VP9

Random Access Configuration

PCS 2013:

	HEVC	x264	VP9
HEVC		-39.3%	-43.3%
x264	66.4%		-6.2%
VP9	79.4%	8.4%	

[Grois2013]

Low Delay Configuration

SPIE 2014:

	HEVC	x264	VP9
HEVC		-40.8%	-32.5%
x264	73.5%		17.0%
VP9	48.2%	-12.5%	

[Grois2014]

Fixed QP Test Case

SPIE 2017:

BD-BR: Weighted $PSNR_{YUV}$

AV1 and VP9 with Rate Control Disabled

(negative BD-BR values indicate actual bit-rate savings)

test candidate \ anchor	AV1	JEM	VP9	HM
AV1		111.8%	-17.1%	47.7%
JEM	-51.4%		-62.0%	-29.8%
VP9	21.0%	173.7%		92.5%
HM	-30.6%	43.4%	-46.6%	

[Grois2017]

Rate Control Test Case

SPIE 2017:

BD-BR: Weighted $PSNR_{YUV}$

AV1 and VP9 with Rate Control Enabled

(negative BD-BR values indicate actual bit-rate savings)

		anchor			
		AV1	**JEM**	**VP9**	**HM**
test candidate	**AV1**		55.0%	-20.0%	9.5%
	JEM	-34.8%		-47.3%	
	VP9	28.5%	92.2%		37.9%
	HM	-7.8%		-27.0%	

[Grois2017]

Fixed QP Test Case

PCS 2018:

BD-BR: Weighted $PSNR_{YUV}$
AV1 and VP9 with Rate Control Disabled
(negative BD-BR values indicate actual bit-rate savings)

CODECS	JEM	HM	AV1	VP9
JEM		-31.6%	-45.6%	-58.8%
HM	47.4%		-21.7%	-40.3%
AV1	89.3%	30.5%		-23.4%
VP9	154.8%	73.5%	31.1%	

[Nguyen2018]

Fixed QP Test Case

PCS 2018:

Encoders Run Time

AV1 and VP9 with Rate Control Disabled

(negative BD-BR values indicate actual bit-rate savings)

CODECS	JEM	HM	AV1	VP9
JEM		8.48 X	0.26 X	15.2 X
HM	0.12 X		0.03 X	1.79 X
AV1	3.83 X	32.45 X		58.16 X
VP9	0.07 X	0.56 X	0.02 X	

[Nguyen2018]

Rate Control Test Case

PCS 2018:

BD-BR: Weighted $PSNR_{YUV}$
AV1 and VP9 with Rate Control Enabled
(negative BD-BR values indicate actual bit-rate savings)

CODECS	JEM	HM	AV1	VP9
JEM		-31.6%	-32.0%	-48.7%
HM	47.4%		-1.4%	-25.0%
AV1	48.6%	2.3%		-22.9%
VP9	97.9%	34.5%	30.2%	

[Nguyen2018]

Rate Control Test Case

PCS 2018:

Encoders Run Times

AV1 and VP9 with Rate Control Enabled

(negative BD-BR values indicate actual bit-rate savings)

CODECS	JEM	HM	AV1	VP9
JEM		8.48 X	0.40 X	22.58 X
HM	0.12 X		0.05 X	2.66 X
AV1	2.47 X	20.95 X		55.82 X
VP9	0.04 X	0.38 X	0.02 X	

[Nguyen2018]

HEVC version 2

- **Format Range Extensions (RExt)**
- **Multilayer Extensions:**
  - Scalability Extension (SHVC)
  - Multiview Extension (MV-HEVC)

REXt: Motivation

Extent 4:2:0 8-10 bit consumer oriented scope of HEVC version 1 by:

- high quality distribution in broadcast, 4:2:0, 12 bit
- contribution in broadcast, 4:2:2, 10/12 bit
- production and high fidelity content acquisition, 4:4:4, 16 bit, R'G'B', high bit rate
- medical imaging, 4:0:0 monochrome, 12-16 bit, (near) lossless
- alpha channels and depth maps, 4:0:0 monochrome, 8-bit
- high quality still pictures, 4:4:4, 8-16 bit, arbitrary picture size
- and many others...

[Grois2015]

RExt: Modifications of HEVC version 1

Three categories:

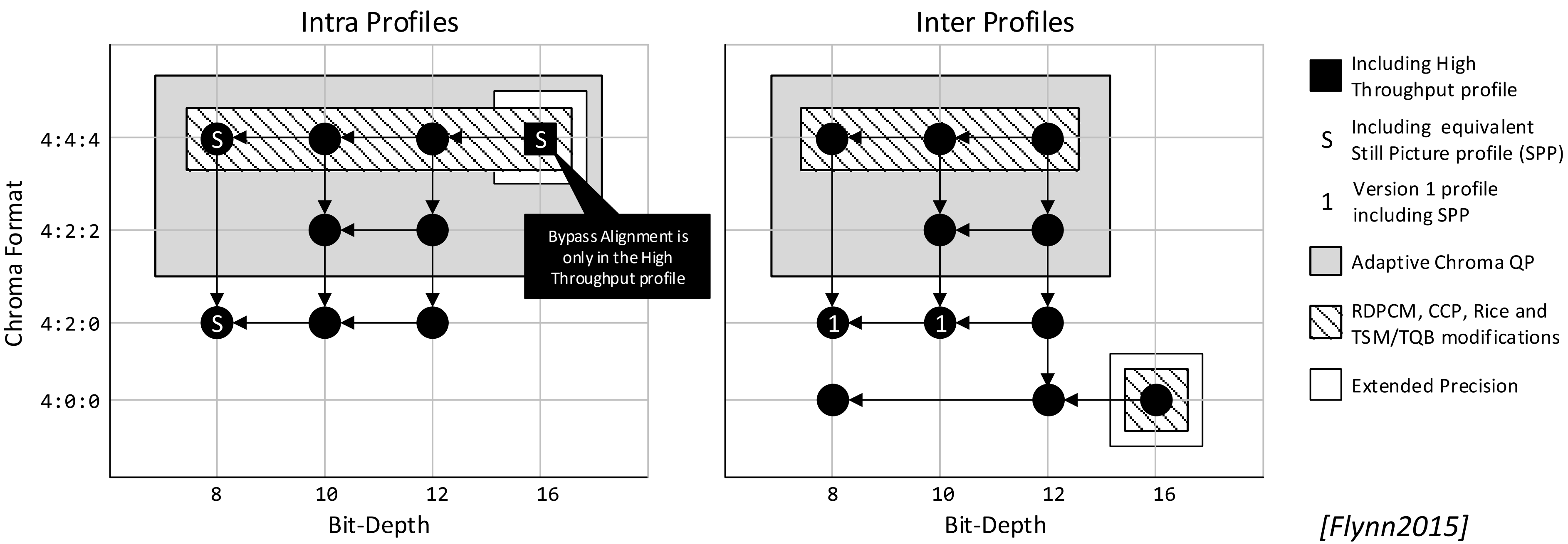
1. Necessary modifications to extend support for chroma formats beyond 4:2:0 and bit depth beyond 10 bits per sample.
2. Coding efficiency improvements for extended formats, lossless and near lossless coding by means of:
   - Modified HEVC v1 tools;
   - New tools:
     - Adaptive chroma QP offset (ACQP)
     - Cross Component Prediction (CCP)
     - Residual Delta Pulse Code Modulation (RDPCM)
3. Precision and throughput optimizations for very high bit rates and bit depths.

[Grois2015]

RExt (HEVC Version 2): Profiles

21 profiles added resulting from combination samples of

- Prediction type (Intra/Inter);
- Chroma format;
- Bit-depth;
- Tool set.



[Flynn2015]

RExt: Profiles (Cont.)

	Still Picture	Intra	Inter
4:0:0			Monochrome
			Monochrome 12
			Monochrome 16
4:2:0	Main Still Picture*	Main Intra	Main*
		Main 10 Intra	Main 10*
		Main 12 Intra	Main 12
4:2:2		Main 4:2:2 10 Intra	Main 4:2:2 10
		Main 4:2:2 12 Intra	Main 4:2:2 12
4:4:4	Main 4:4:4 Still Picture	Main 4:4:4 Intra	Main 4:4:4
		Main 4:4:4 10 Intra	Main 4:4:4 10
		Main 4:4:4 12 Intra	Main 4:4:4 12
	Main 4:4:4 16 Still Picture	Main 4:4:4 16 Intra	
		High Throughput 4:4:4 16 Intra	

*HEVC v1

[Grois2015]

SHVC: Motivation

Traditional approach:

- Encode and store a separate video stream for all possible clients and connection speeds

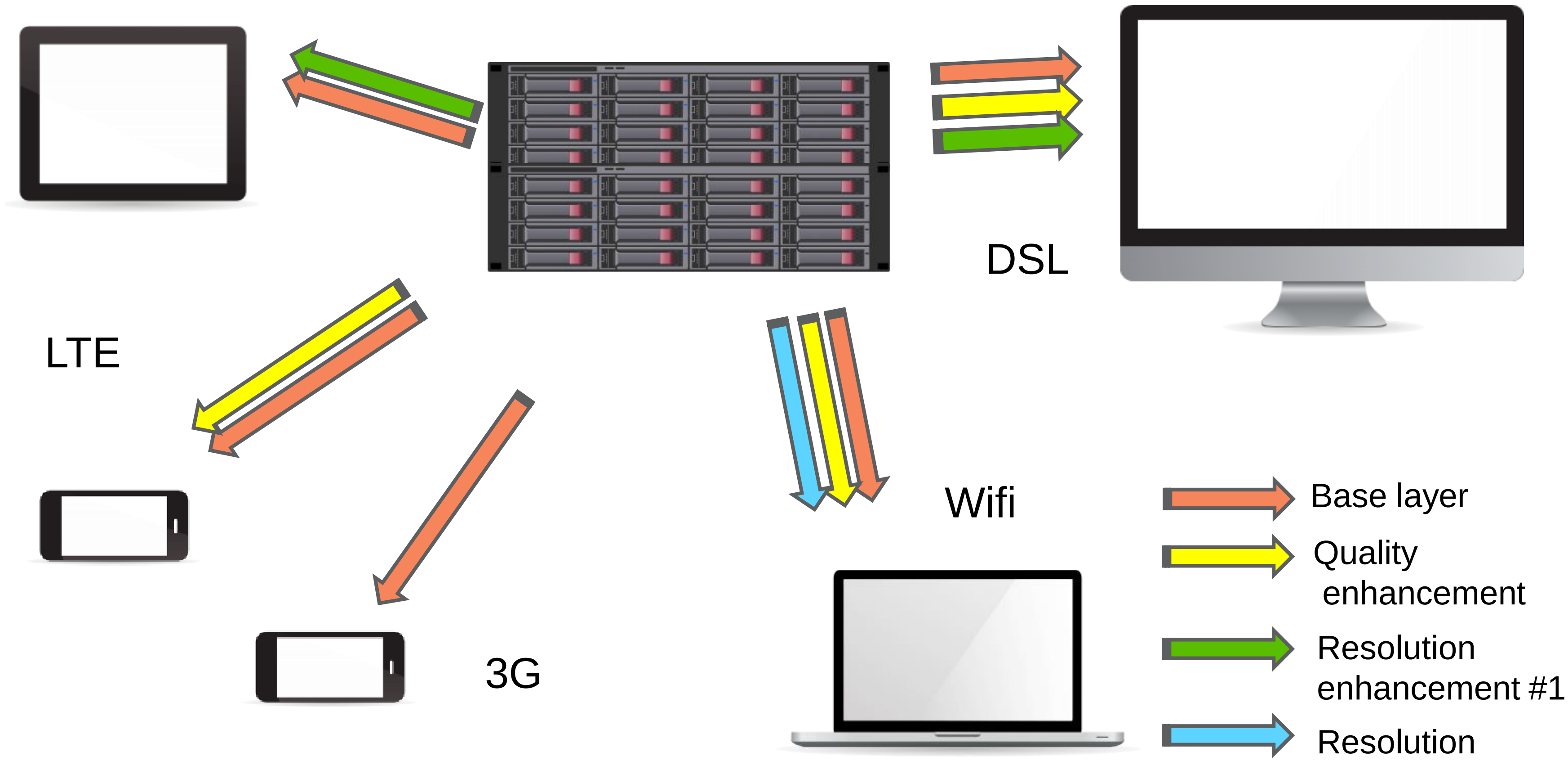
Scalable Video Coding:

- Encode a common base layer
- Add enhancement layers as needed

[Grois2015]

SHVC: Motivation (Cont.)

Video streaming with multiple layers



[Images by Freepik.com](#)

[Grois2015]

SHVC: Advantages and disadvantages of scalable coding

Generic advantages:

- Less storage space
- Less data rate in multi- and broadcast environments
- (Less encoding time)
- More flexibility (i.e. combinations of layers)
- Built-in support for up- and down-switching
- Error resilience: Unequal error protection

Generic disadvantages:

- Overhead compared to single layer
- Higher decoder complexity

[Grois2015]

SHVC: Single- vs. multi-loop functionality

Single-loop decoder (e.g. SVC):

1. Parse base layer
2. Parse enhancement layer, using information from base layer
3. (decode base-layer intra blocks)
4. Decode enhancement layer

One decoding process **overall**

Multi-loop decoder (e.g. SHVC):

1. Decode base layer
2. Upsample result as reference signal
3. Decoder enhancement layer

One decoding process **per layer**

[Grois2015]

SHVC: Properties of single- vs. multi-loop

Single-loop decoder (e.g. SVC):

- Low decoding complexity
- Always requires changes in low-level coding tools
- Minimal re-use of existing components

Multi-loop decoder (e.g. SHVC):

- Higher decoding complexity
- May not need changes in low-level coding tools
- Allows re-use of existing single-layer designs as base for each layer-decoder

[Grois2015]

SHVC: Scalability types (I)

- **Temporal scalability** (HEVC version 1)
  - Higher frame rates in enhancement layer
  - e.g. 30 fps base layer to 60 fps enhancement layer

- **Spatial scalability**
  - Higher spatial resolutions in enhancement layer
  - e.g. 720p base layer to 1080p enhancement layer

- **Coarse grain SNR scalability**
  - Higher SNR qualities in enhancement layers
  - e.g. low-quality base-layer at 1 MBit/s to high-quality enhancement-layer at 8 MBit/s

- **External base layer scalability (new)**
  - Base layer encoded by another external encoder
  - e.g. H.264/AVC base layer with SHVC enhancement layer

[Grois2015]

SHVC: Scalability types (II)

- **Bit depth scalability (new)**
  - Higher bit depths in enhancement layer
  - e.g. base layer with bit depth of bit 8 to enhancement layer with bit depth of 10 bit

- **Interlace-to-progressive scalability**
  - Base layer in interlace format, enhancement layer in progressive format

- **Color gamut scalability (new)**
  - Higher color gamut in enhancement layers
  - e.g. BT.709 color gamut in base layer to BT.2020 in enhancement layer

[Grois2015]

MV-HEVC: Motivation

Use cases

- Stereo (2-view) “3D” movies and TV programs
  - Broadcast
  - Distributed media (Blu-Ray)
  - On-demand streaming
  - Cinema
- Multiple view displays

Alternatives

- Frame-compatible formats
- Simulcast

MV has to provide better performance.

[Grois2015]

MV-HEVC: Design

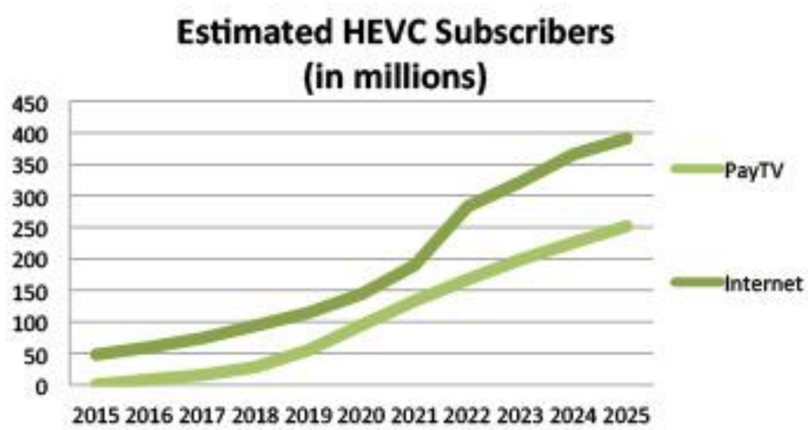
High-Level Syntax only

- Similar to MVC
- Takes advantage on multi-layer syntax elements in HEVC design
- No changes at block-level
- Allows re-use of existing HEVC encoder and decoder components
- Only changes in decoded picture buffer (DPB) and reference picture list creation

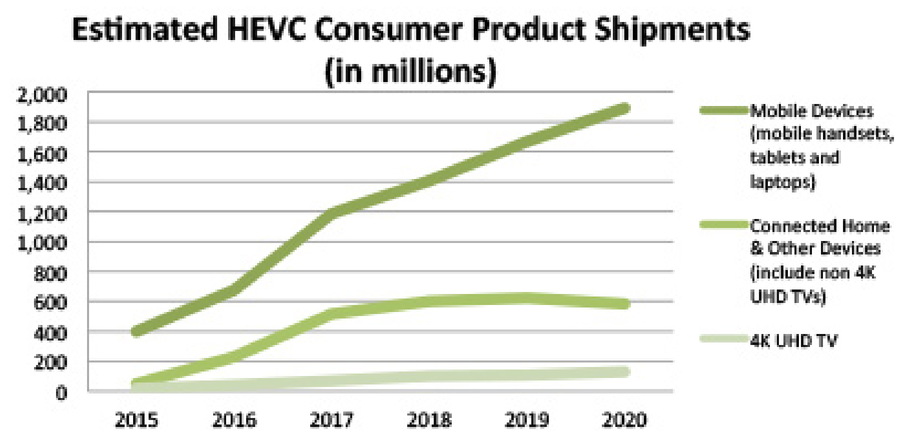
[Grois2015]

HEVC Products Forecast Overview

"The outlook for HEVC use in the digital video market is extremely positive..." [DTC2016]



Source: DTC



Source: DTC

What is Next?

Future Video Coding Development

Future video coding standard should consider from the beginning (among others) *[Bross2016]:*

- UHD: 4K and up
- High Dynamic Range (HDR) and Wide Color Gamut content
- High Frame Rates
- High-Level Scalability (like SHVC)
- Drone Video
- 360 Video

The work on the video coding techniques beyond HEVC started already in 2015:

- **Joint Video Exploration Team (JVET) of MPEG and VCEG organizations** was established last October, 2015, in Geneva *[Bross2016]*.
- **JEM: Joint Video Exploration Model Software.**

Future Video Coding Development (Cont.)

List of several coding tools that improve coding efficiency of HEVC:
[SG16−C0806]

- **Larger coding tree blocks and larger transforms:**
  - The CTU size signaled in the sequence level is set to be **256x256** by default;
  - Supporting Coding Tree Units (CTUs) **larger than 64x64**;
  - Supporting larger transforms, i.e., **64x64 DCT**.

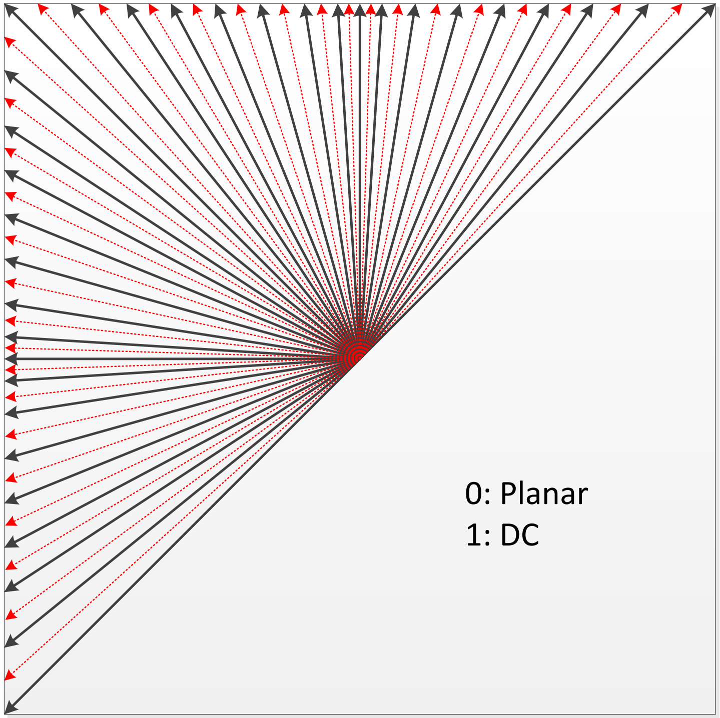
- **Adaptive Transform:**
  - Performed in addition to DCT-II and 4x4 DST-VII, which are employed in HEVC;
  - **The newly introduced transform matrices are: DST-VII, DCT-VIII, DST-I and DCT-V.**

[Bross2016]

Future Video Coding Development (Cont.)

Additional improvements as proposed, for example, by VCEG-AZ07:

- **Intra-Picture Prediction:**
  - Extended to support 65 intra prediction direction;



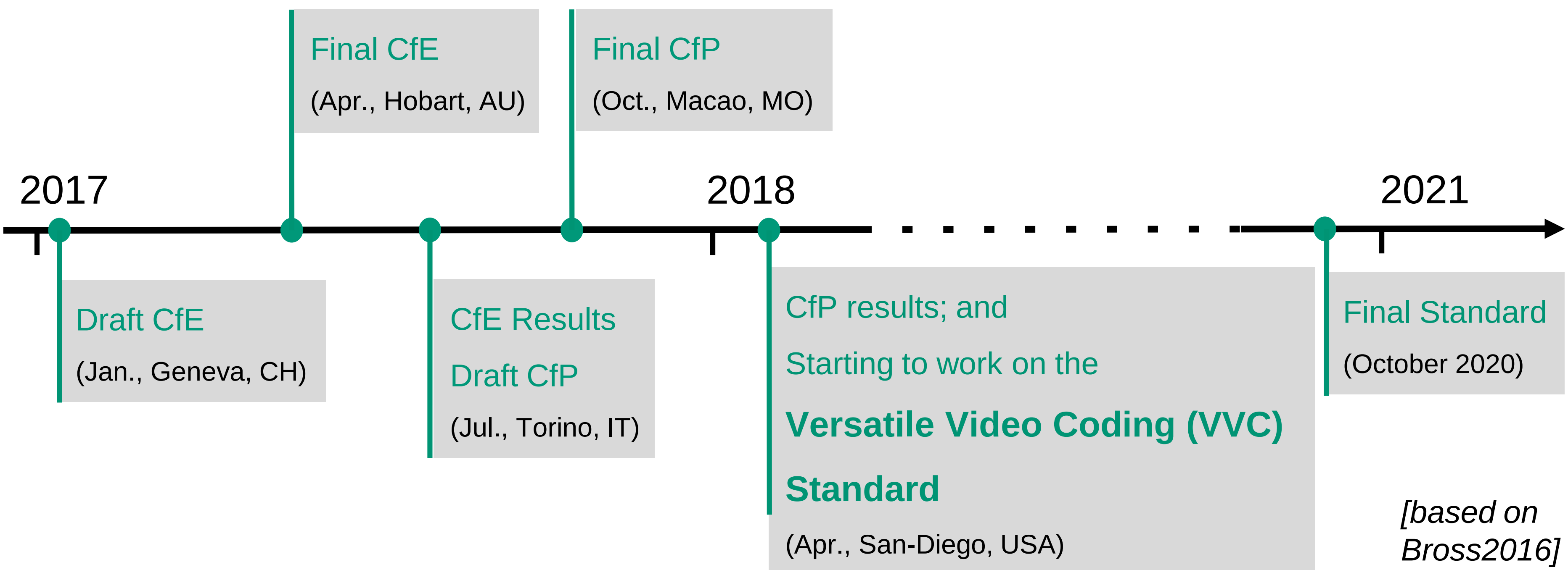
[VCEG-AZ07]

- **And many other tools…**

[Grois2015]

What is Next? – Current Standardization Timeline

- Call For Evidence (CfE): Subjective verification of the JEM coding efficiency compared to HEVC
- Call for Proposals (CfP): Submission and subjective evaluation of new video coding technologies



[based on Bross2016]

So, what is next?

The next is the VVC development, which already started in April, 2018!

Further Information

Document archives are publicly accessible

- http://phenix.it-sudparis.eu/jct
- http://ftp3.itu.ch/av-arch/jctvc-site
- http://www.itu.int/ITU-T/studygroups/com16/jct-vc/index.html

Overview page:

- http://hevc.hhi.fraunhofer.de

HEVC Reference Model (HM) software:

- https://hevc.hhi.fraunhofer.de/svn/svn_HEVCSoftware

JVET Joint Exploration Model (JEM) software:

- https://jvet.hhi.fraunhofer.de/svn/svn_HMJEMSoftware

JVET VVC Test Model (VTM) software:

- https://jvet.hhi.fraunhofer.de/svn/svn_VVCSoftware_VTM

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Video Coding and HEVC

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