Video Coding

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Outline

- Video coding approaches & algorithms
  - Overview. Main observations.
  - Several simple video codecs
  - Block motion estimation (BME) and motion compensation
- Video coding international standards
  - H.261, H.263, H.263+: video conferencing
  - MPEG1, MPEG2, MPEG4: video broadcasting & archiving
- Latest development in video coding standard
  - H.264

Main Observations

- Video signal is a sequence of still images or frames
- Correlation in video sequence
  - Temporal correlation: similar background with a few moving objects in the foreground
  - Spatial correlation: similar pixels seem to group together – just like spatial correlation in images
  - There is usually much more temporal correlation then spatial
- Motion model in video sequence
  - Natural motion
    - moving people & moving objects
    - translational, rotational, scaling
  - Camera motion
    - camera panning, camera zooming, fading

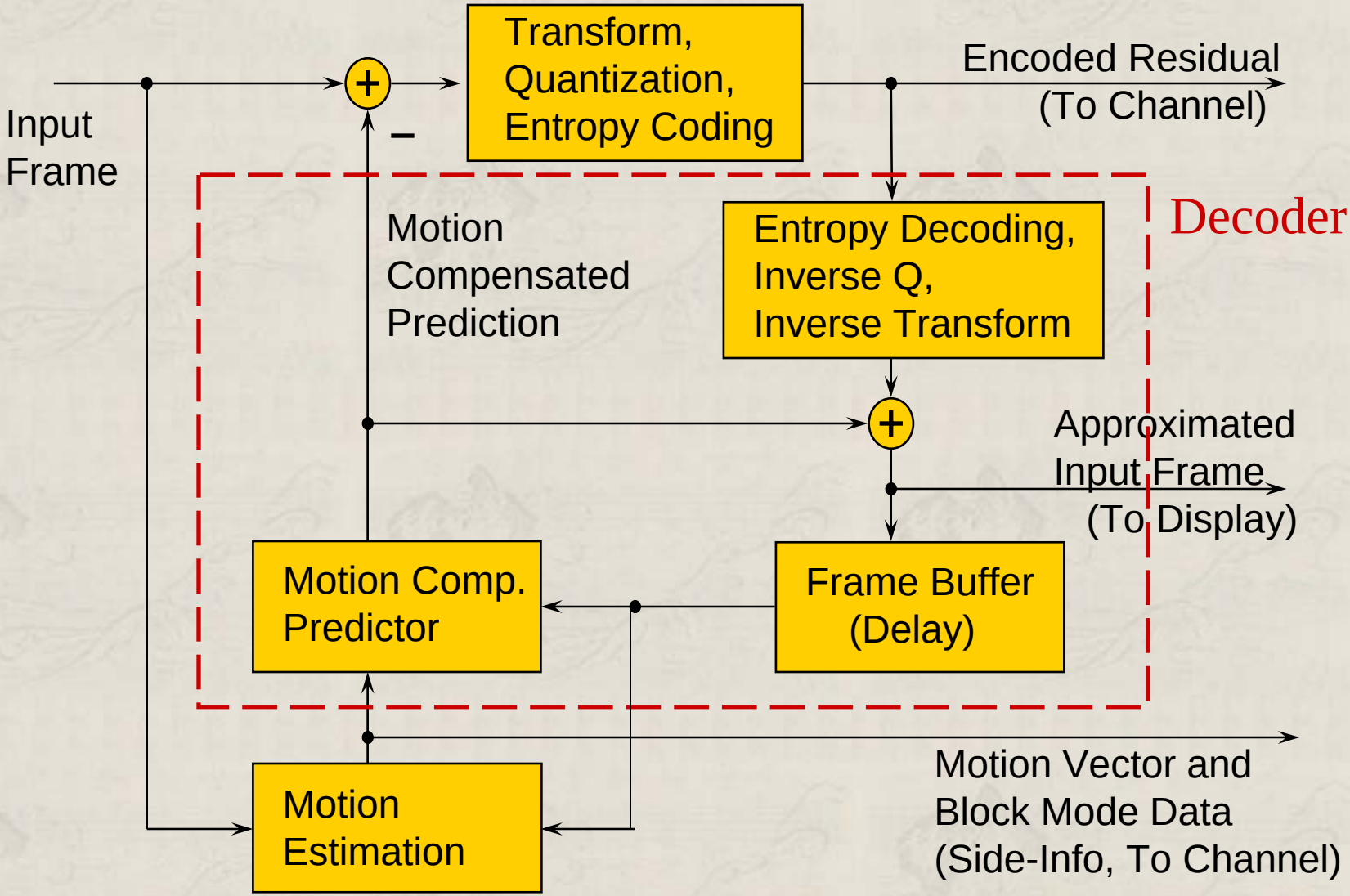
Simple Video Coders

- JPEG/JPEG2000 encodes every frame independently
  - Quite popular: Motion-JPEG, Motion-JPEG2000
  - Does not take into account any temporal correlation
  - Advantage: very simple and fast, no latency (frame delay), easy frame access for video editing
  - Disadvantage: low coding performance
- JPEG/JPEG2000 encodes frame difference
  - Requires very stationary background to be effective
  - Advantage: improves compression, low latency
  - Disadvantage: still low coding performance, open-loop design, quantization error accumulation from coder/decoder mismatch
- JPEG/JPEG2000 encodes frame difference – closed-loop
  - Advantage: no error accumulation, low latency, simple
  - Disadvantage: too simple motion model, still low compression

Motion-Compensated Framework

- Transform-based coding on motion-compensated prediction error (residue)
- Popular transformations: block DCT or wavelet
- Closed-loop DPCM to prevent error propagation (drifting)
- Usually employed block-translation motion model
- All international video coding standards are based on this coding framework
  - Video teleconferencing: H.261, H.263, H.263++, H.26L/H.264
  - Video archive & play-back: MPEG-1, MPEG-2 (in DVDs) MPEG-4

Typical MC Codec

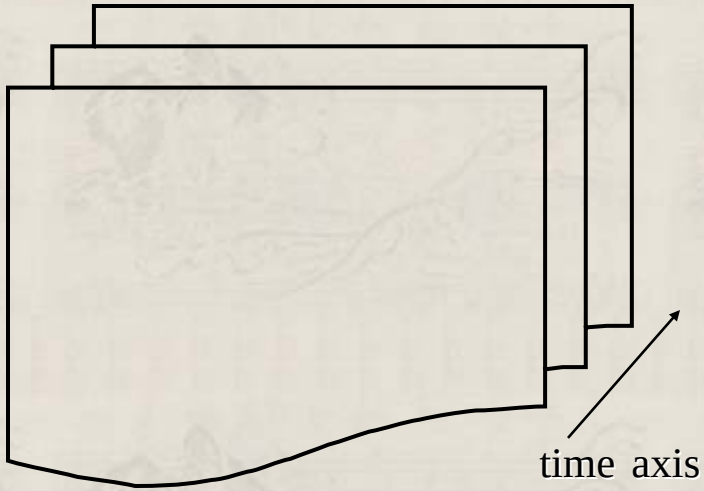


Motion Estimation

- Goal: extract correlation between adjacent video frames to improve compression efficiency
- General problem statement:

Given the current frame $C(x, y)$
and the reference frame $R(x,y)$,
find functions $f(x, y)$ and $g(x, y)$ to
minimize

$$E = d\{C(x,y), R(f(x,y),g(x,y))\}$$



- Practical motion model: small objects or regions moving in translational fashion $f(x, y) = x - dx;\ g(x, y) = y - dy$
- Block-based motion estimation (BME) and compensation (BMC)

Intra- and Inter-Coding

- Inter-coding:
  - blocks of predicted motion error labeled P-block is encoded
- Intra-coding
  - any block that motion estimation fails to find a good match is labeled I-block and encoded as is (without any motion compensation)
- Conditional replenishment
  - when prediction error is low, no coding or decoding is necessary
  - we simply record the motion vector and replenish the block from the reference frame.

Motion Models

- Translation

$$\boxed{\begin{cases} f(x,y) = x - d_x \\ g(x,y) = y - d_y \end{cases}}$$

- Affine

$$\begin{cases} f(x,y) = a_{00}x + a_{01}y + d_x \\ g(x,y) = a_{10}x + a_{11}y + d_y \end{cases}$$

- Bilinear

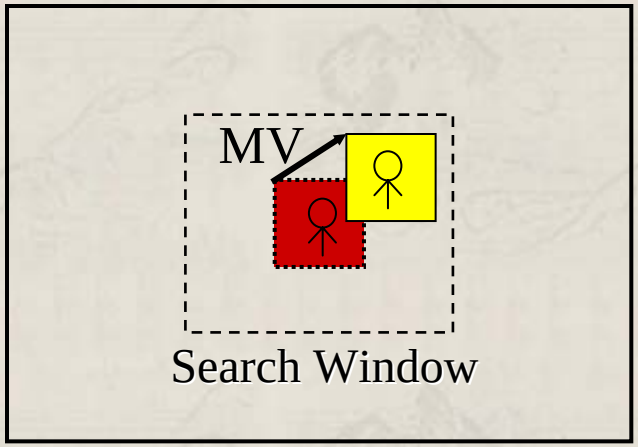
$$\begin{cases} f(x,y) = a_{00}x + a_{01}y + a_{02}xy + d_x \\ g(x,y) = a_{10}x + a_{11}y + a_{12}xy + d_y \end{cases}$$

- Perspective

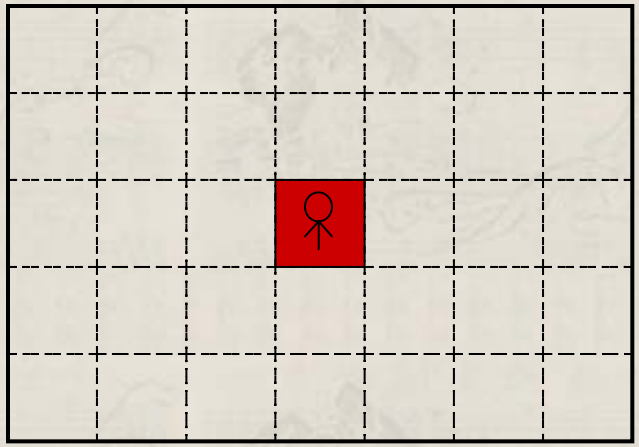
$$\begin{cases} f(x,y) = \dfrac{a_{00}x + a_{01}y + a_{02}}{a_{20}x + a_{21}y + a_{22}} \\ g(x,y) = \dfrac{a_{10}x + a_{11}y + a_{12}}{a_{20}x + a_{21}y + a_{22}} \end{cases}$$

Principle of BME

- Partition current frame into small non-overlapped blocks called macro-blocks (MB)
- For each block, within a search window, find the motion vector (displacement) that minimizes a pre-defined mismatch error
- For each block, motion vector and prediction error (residue) are encoded



Reference Frame



Current Frame

BME: Error Measure

- Sum of absolute differences

search range

$$SAD(dx,dy) = \sum_{i=0}^{Rx}\sum_{j=0}^{Ry}\left|C(x+i, y+j) - R(x+i+dx, y+j+dy)\right|$$

current block reference block

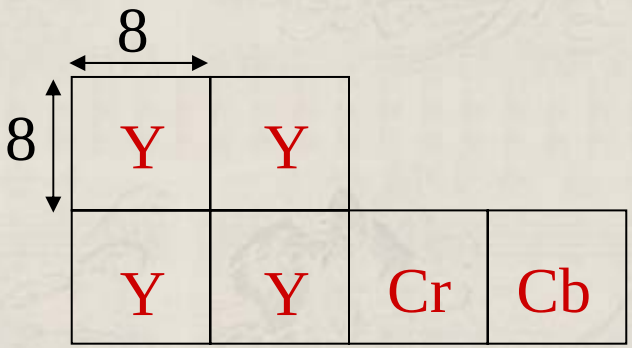
- Sum of squared errors (mean-squared error)

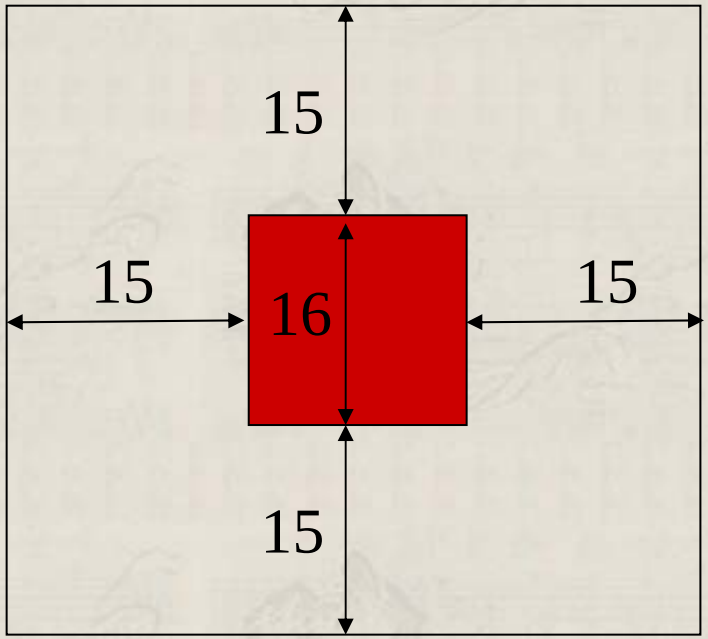
$$SSE(dx,dy) = \sum_{i=0}^{Rx}\sum_{j=0}^{Ry}\left|C(x+i, y+j) - R(x+i+dx, y+j+dy)\right|^2$$

- Discussions:
  - Other norms, correlation measure have been tested
  - Approximately same coding performance
  - SAD is less complex for some hardware architectures

Common Setting

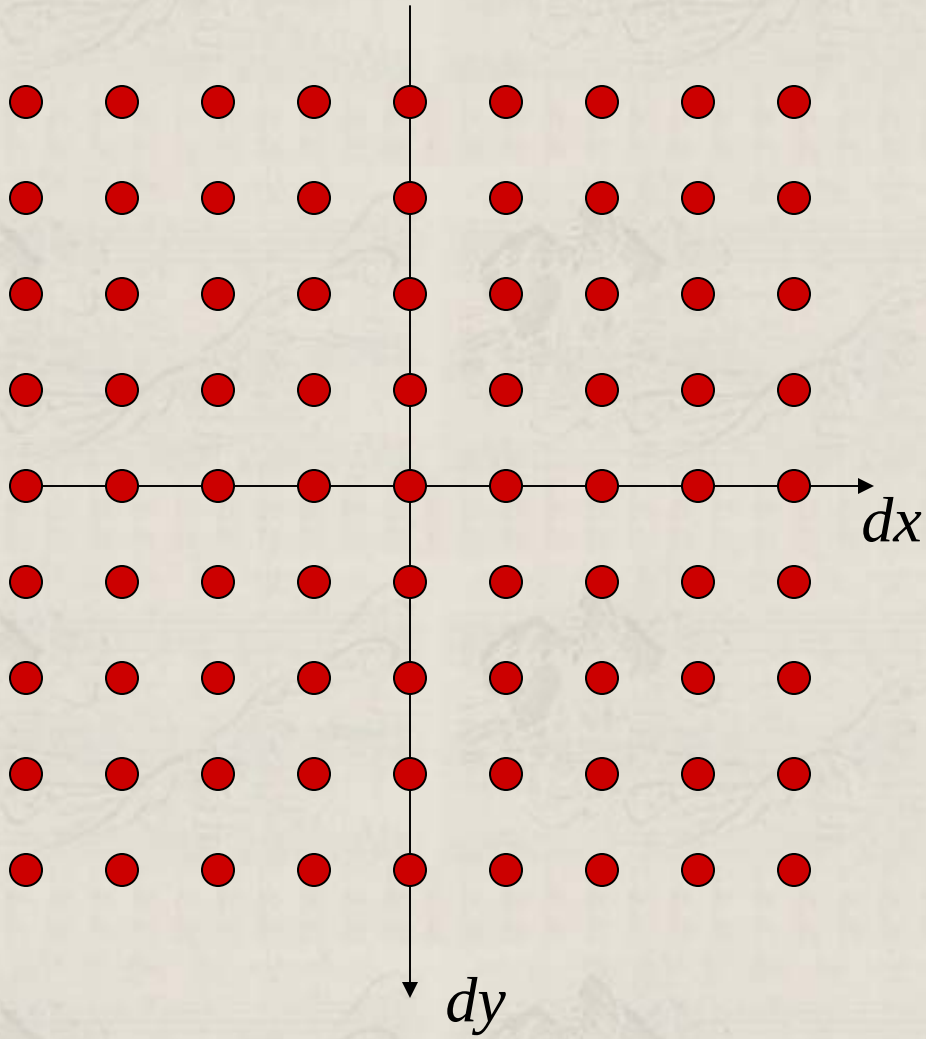
- Macro-block
  - Luminance: 16x16, four 8x8 blocks
  - Chrominance: two 8x8 blocks
  - Motion estimation only performed for luminance
- Motion vector range
  - [-15, 15]





Search Area

Search Strategies I



Exhaustive Search

- All possible MV candidates within the search range are investigated
- Very computationally expensive
- Optimal, highly regular, parallel computable

Search Strategies II

Divide and Conquer

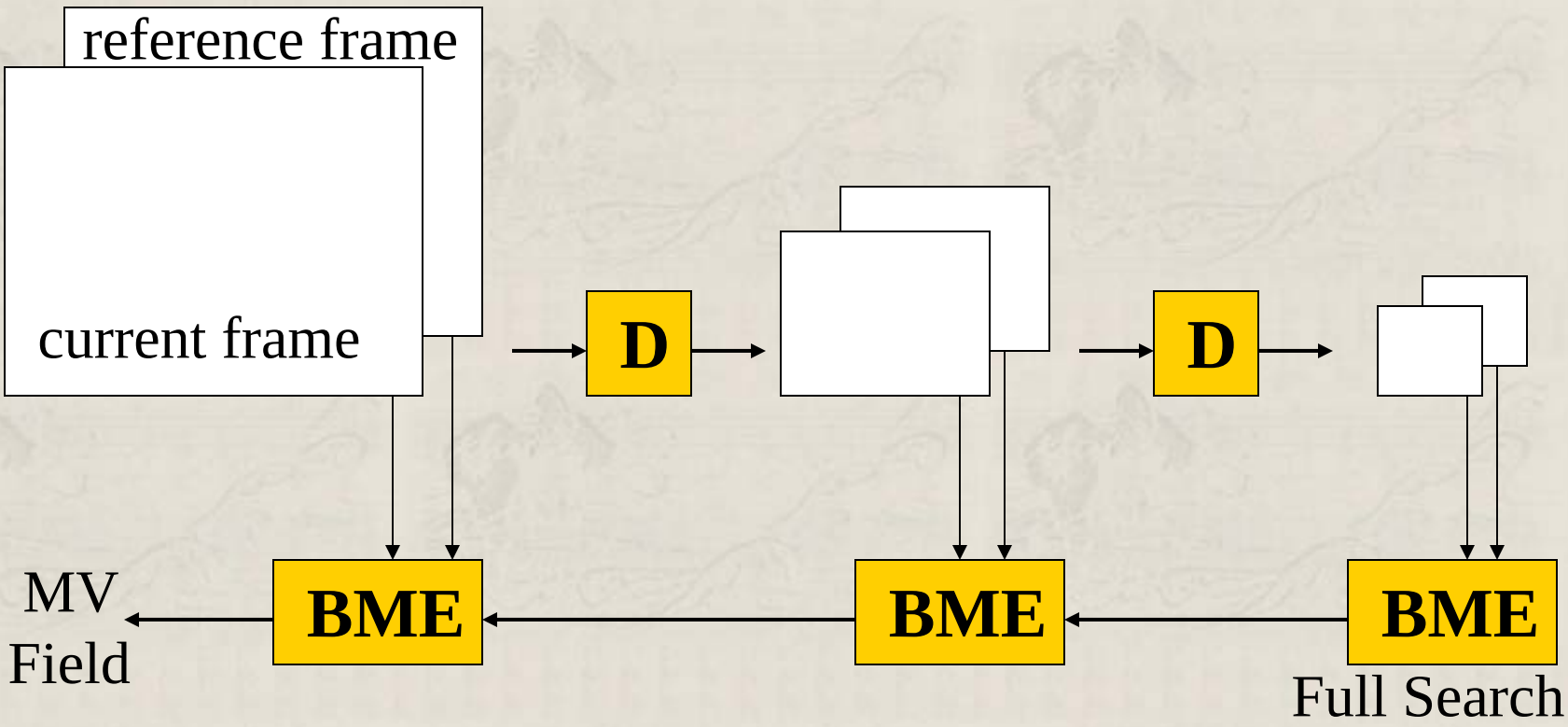
- Sampling the search space
- Divide search space into regions
- Pick a center point for each region
- Perform more elaborate search on the region with best center

Gradient Search

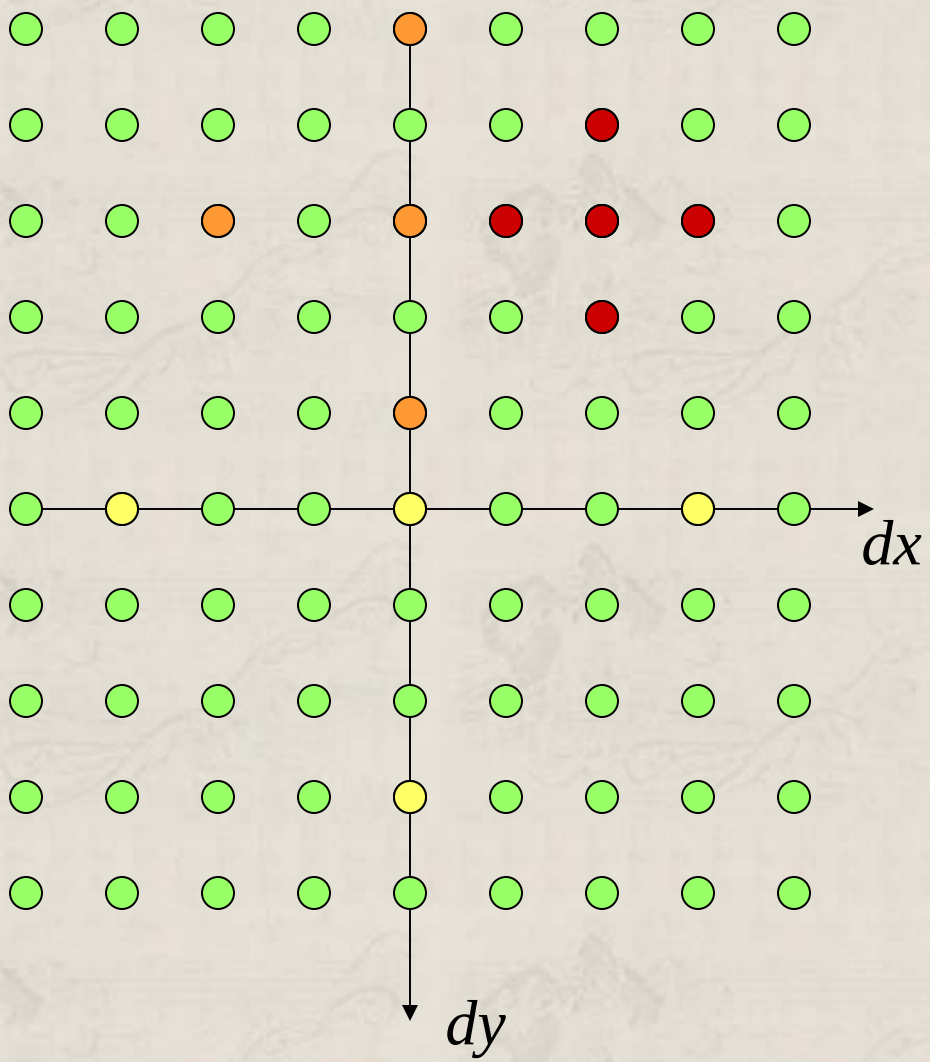
- Sampling the search space
- At every stage, investigate a few candidates
- Move in the direction of the best match
- Can adaptively reduce the displacement size for each stage

Search Strategies III

Multi-resolution or Hierarchical Search



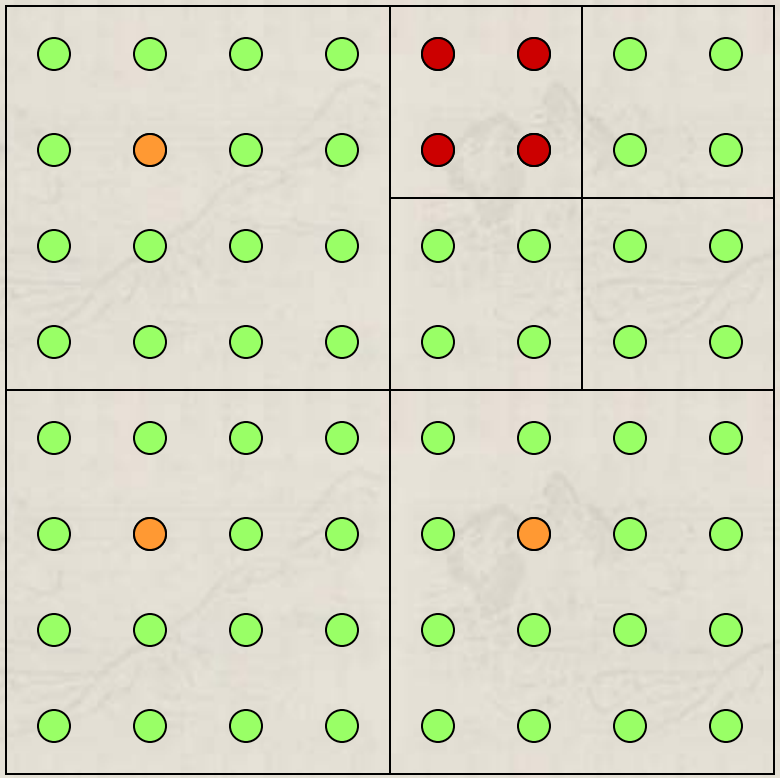
Fast BME Algorithm: Example I



2D Log Search

- Use + pattern at each stage (5 candidates)
- Move center to best match
- Reduce step size at each stage
- Fast, reasonable quality
- Similar algorithms: three-step-search, four-step-search, cross search...

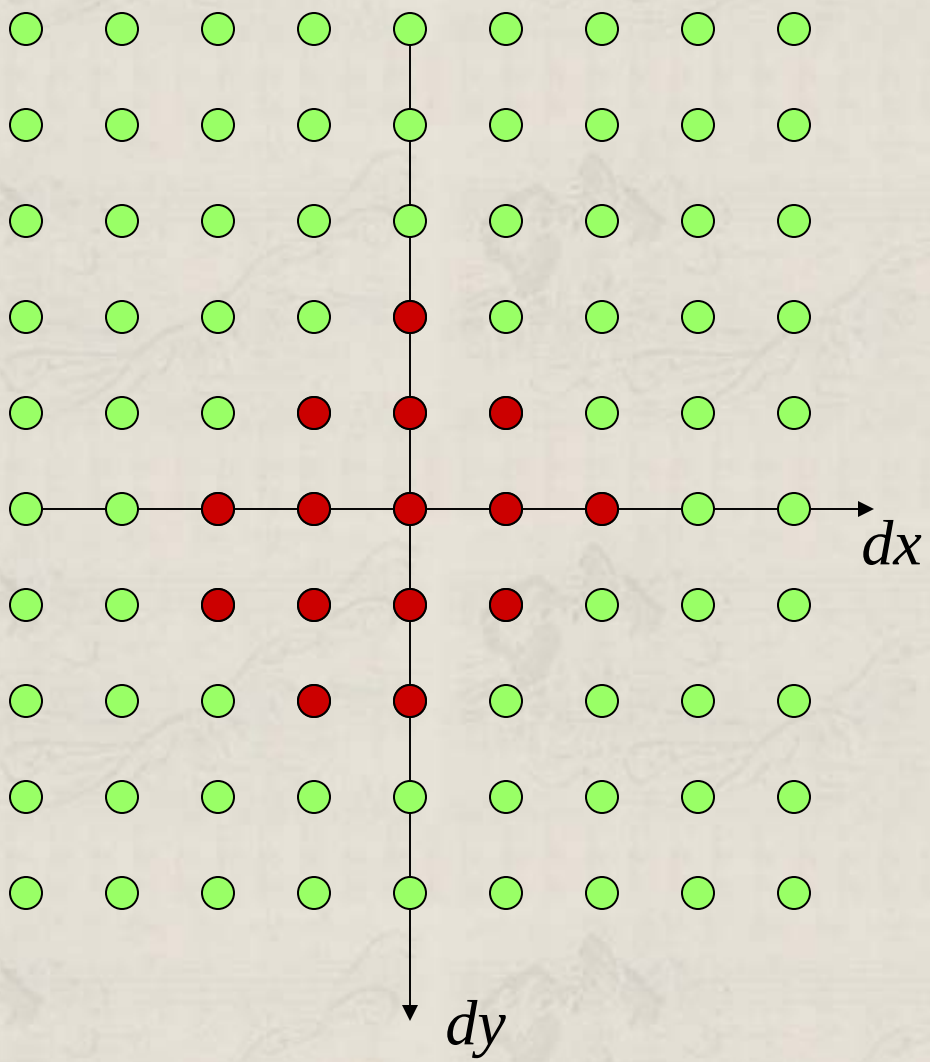
Fast BME Algorithm: Example II



Binary Search

- Divide-and-conquer
- Move search to region with best match
- Finer search at later stages

Optimal BME: Spiral Search



Spiral Search

- Early termination
- Start with a predicted search center, default=(0,0)
- Spiral search around center in diamond or square pattern
- Keep track of best match so far; update whenever a better candidate is found
- MPEG-4, H.263+

Optimal BME: Partial Matching

- Triangle inequality

partial sums

$$MAD(dx,dy) = \sum_{block} |C - R| \geq \left| \sum_{block} (C - R) \right| = \left| \sum_{block} C - \sum_{block} R \right|$$

- Strategy
  - Compute partial sums for macro-blocks in both current and reference frame
  - Eliminate candidates based on partial sums
  - Nice partial sums: row projections, column projections!
  - Avoid full 2D matching, translate the problem into 1D matching
  - Can be combined with spiral search and early termination

Spatial Correlation Based BME

- Exploit intra-frame spatial correlation to narrow down search space for BME
- Blocks covering the same object should move together
- MVs from causal neighboring blocks can be used to predict MV for the current block

2	**3**	**4**
1	**C**	

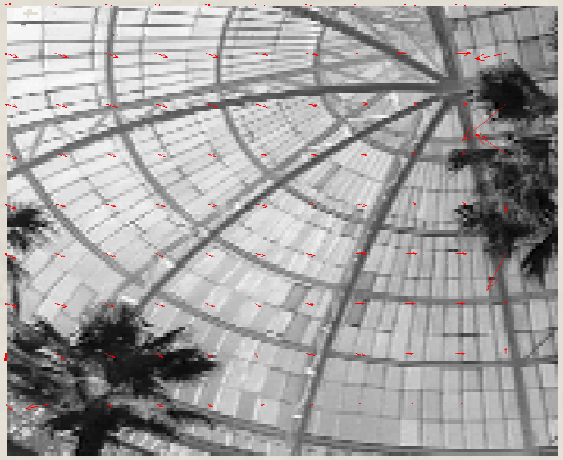
- Reduce bit-rate for MV encoding: regularize the MV field
- Reduce BME complexity

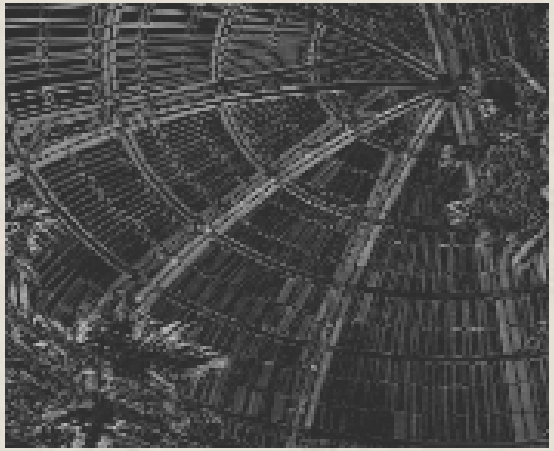
BME/BMC: Example I

Previous Frame

Current Frame

Motion Vector Field





Frame Difference

Motion-Compensated Difference

BME/BMC: Example II

Previous Frame

Current Frame

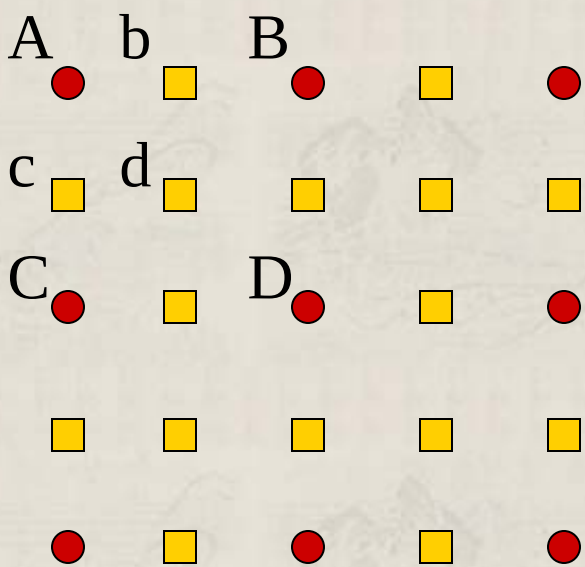
Motion Vector Field

Frame Difference

Motion-Compensated Difference

Sub-Pixel Motion Estimation

- Sub-pixel motion vector resolution
- Use linear/bilinear interpolation to fill in sub-pixels
- Trade-offs: motion accuracy versus MV bit-rate and complexity increase
- H.26L uses down to 1/4-MEMC, maybe even 1/8

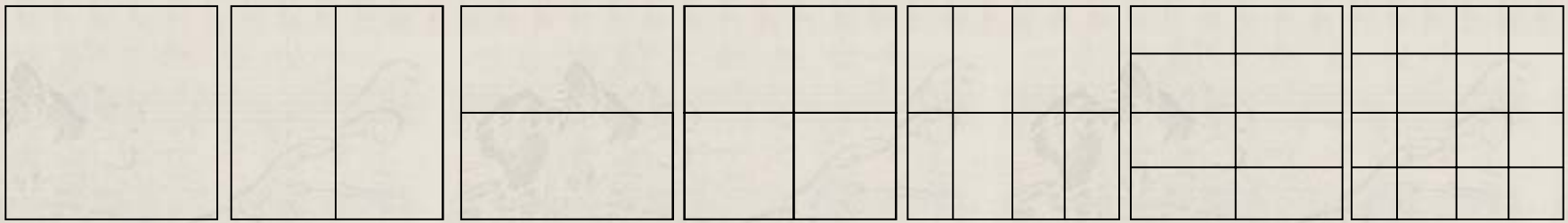


integer pixel

half pixel

b = round[(A+B)/2]
c = round[(A+C)/2]
d = round[(A+B+C+D)/4]

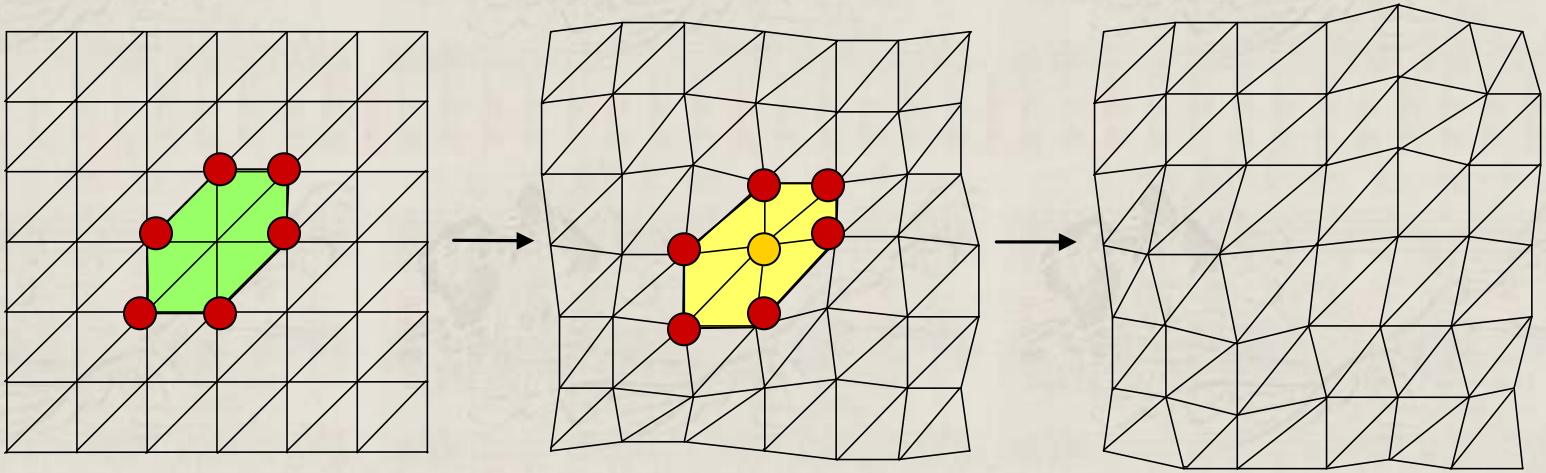
Variable-Block-Size BME



Mode 1 Mode 2 Mode 3 Mode 4 Mode 5 Mode 6 Mode 7

- Motion model for H.264
- Generalization of the traditional translation BME framework
- Sub-divide macro-block: 16x16, 16x8, 8x16, 8x8, 8x4, 4x8, 4x4

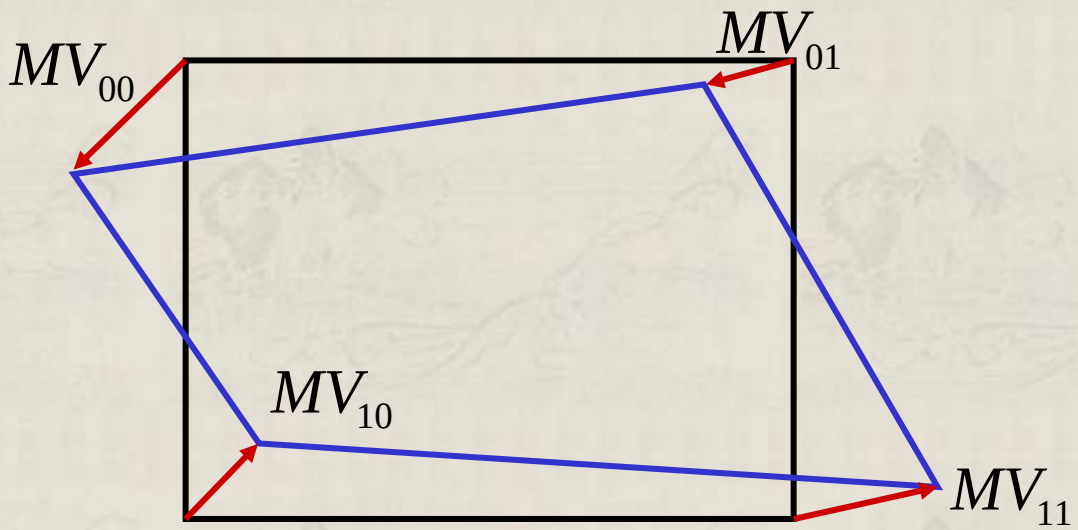
Mesh-Based Motion Estimation



- MPEG-4 object motion
- Affine warping motion model
- Deformable polygon meshes
- Similar MAD, SSE error measures
- Trade-offs: more accurate ME vs. tremendous complexity
- Bilinear and perspective motion models are rarely used in video coding

$$\begin{cases} f(x,y) = a_{00}x + a_{01}y + d_x \\ g(x,y) = a_{10}x + a_{11}y + d_y \end{cases}$$

Global Motion Estimation



- Rarely used in practice: BME/BMC mostly suffices
- Reference frame resampling: an option in H.263+/H.263++
- Global affine motion model: special-effect warping
- 3D subband & wavelet coding: align frames before temporal filtering [Taubman]

Quick Summary

- Temporal correlation dominates spatial correlation in video sequences
- Motion estimation and motion compensation improve coding performance the most in video coding
- State-of-the-art video coders, such as the current H.264 verification model, still employ BME-block DCT coding framework
- Despite its simplicity, BME is still the bottleneck of real-time video communications

Video Compression Standards

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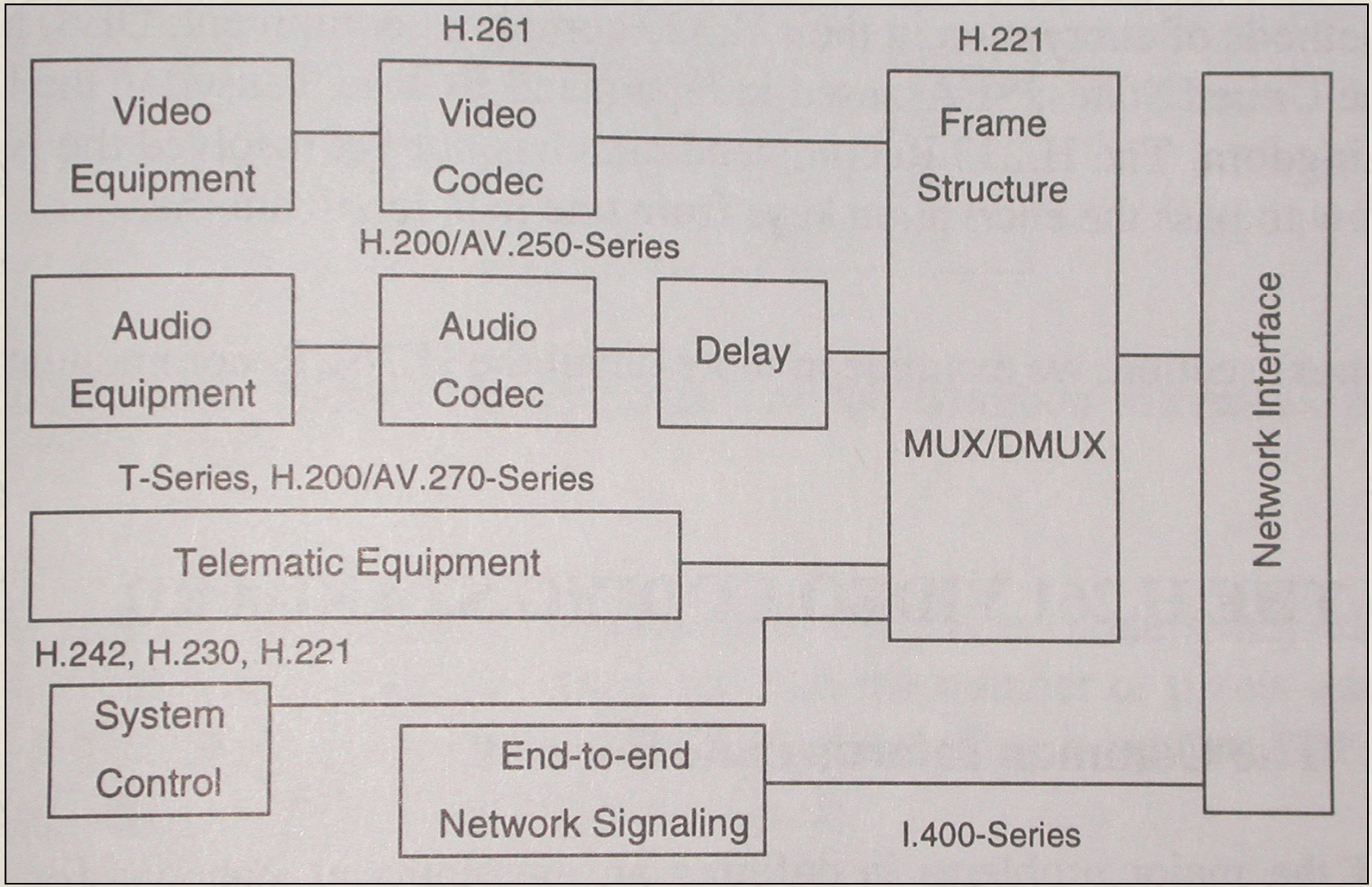
History and Goals

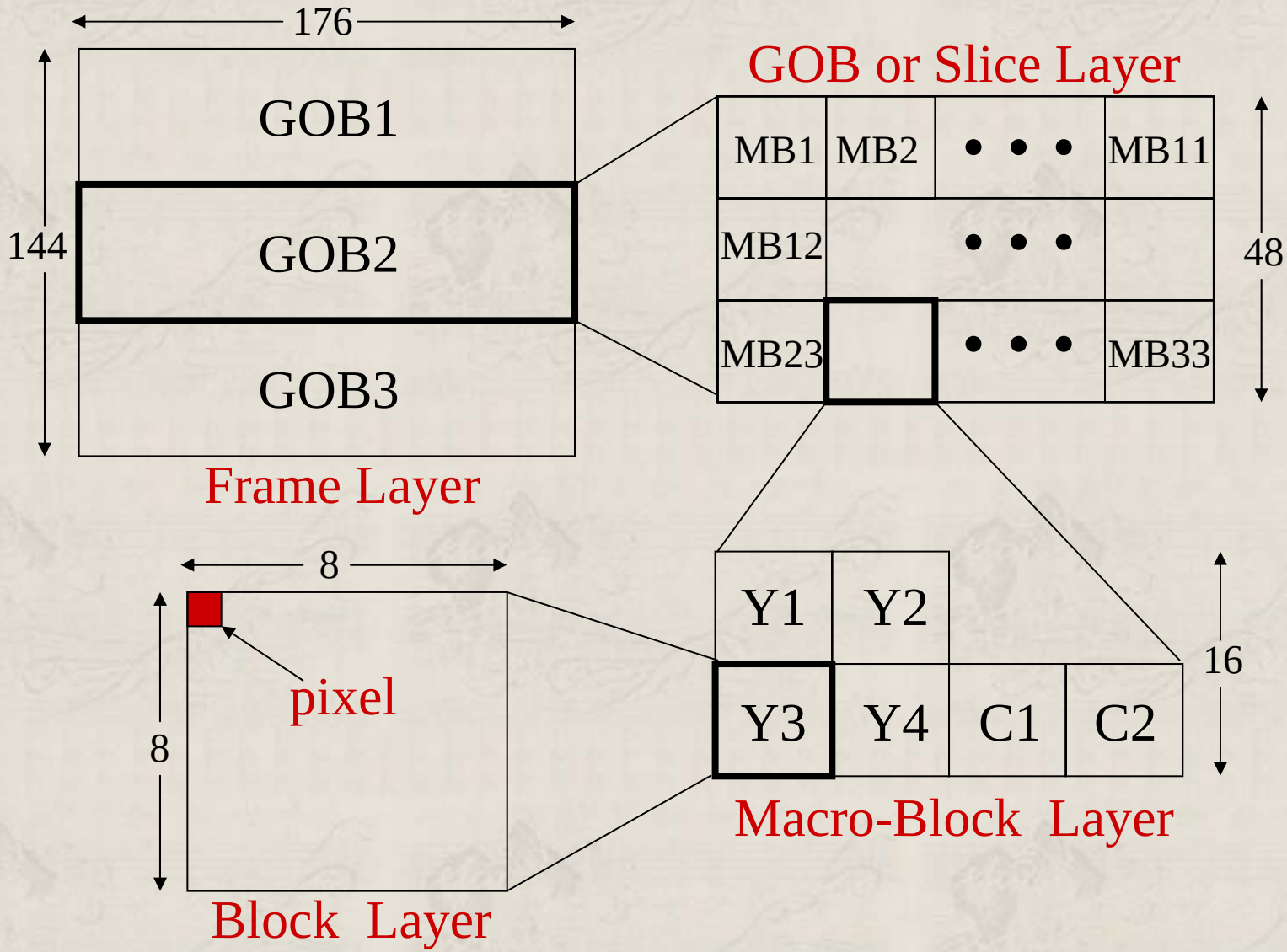
- ITU-T (International Telecommunications Union), Standardization Sector, Study Group 15
- Standardization activities: Dec. 1984 – Dec. 1990
- Goal: real-time videophone and video teleconferencing at rather low bit rates and low delay
- Bit rates: 64 kbps – 1.92 Mbps
- H-Series system
  - H.261: video codec for *p x 64 kbps, p=1,2,…,30*
  - G.722, G.726, G.728: audio codec for *16 – 64 kbps*
  - H.242, H.230, H.221: system control, frame structure, mux, handshaking protocols for compliant equipments / components

  } H.320

Generic H.320 System



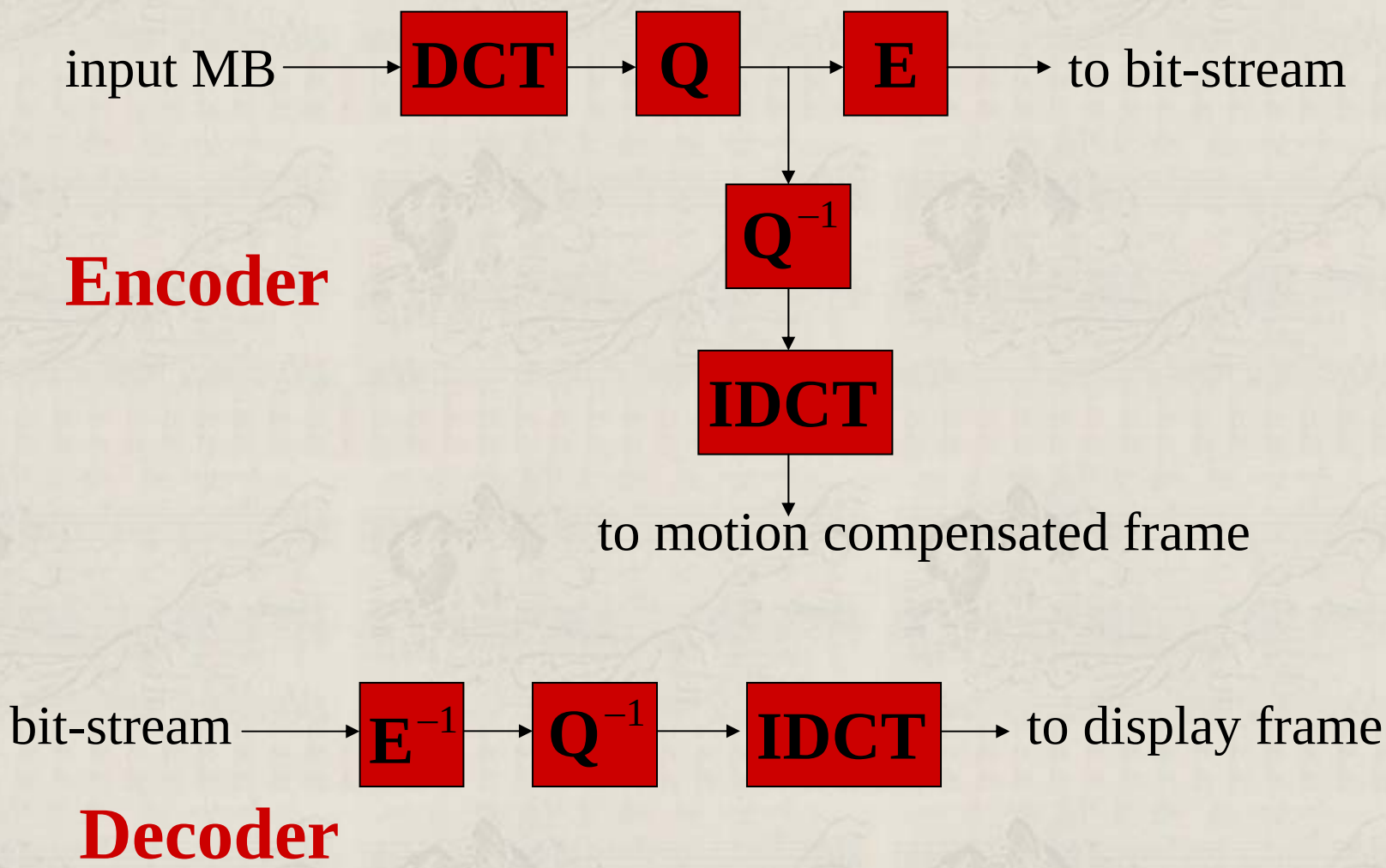
Hierarchical Block Structure



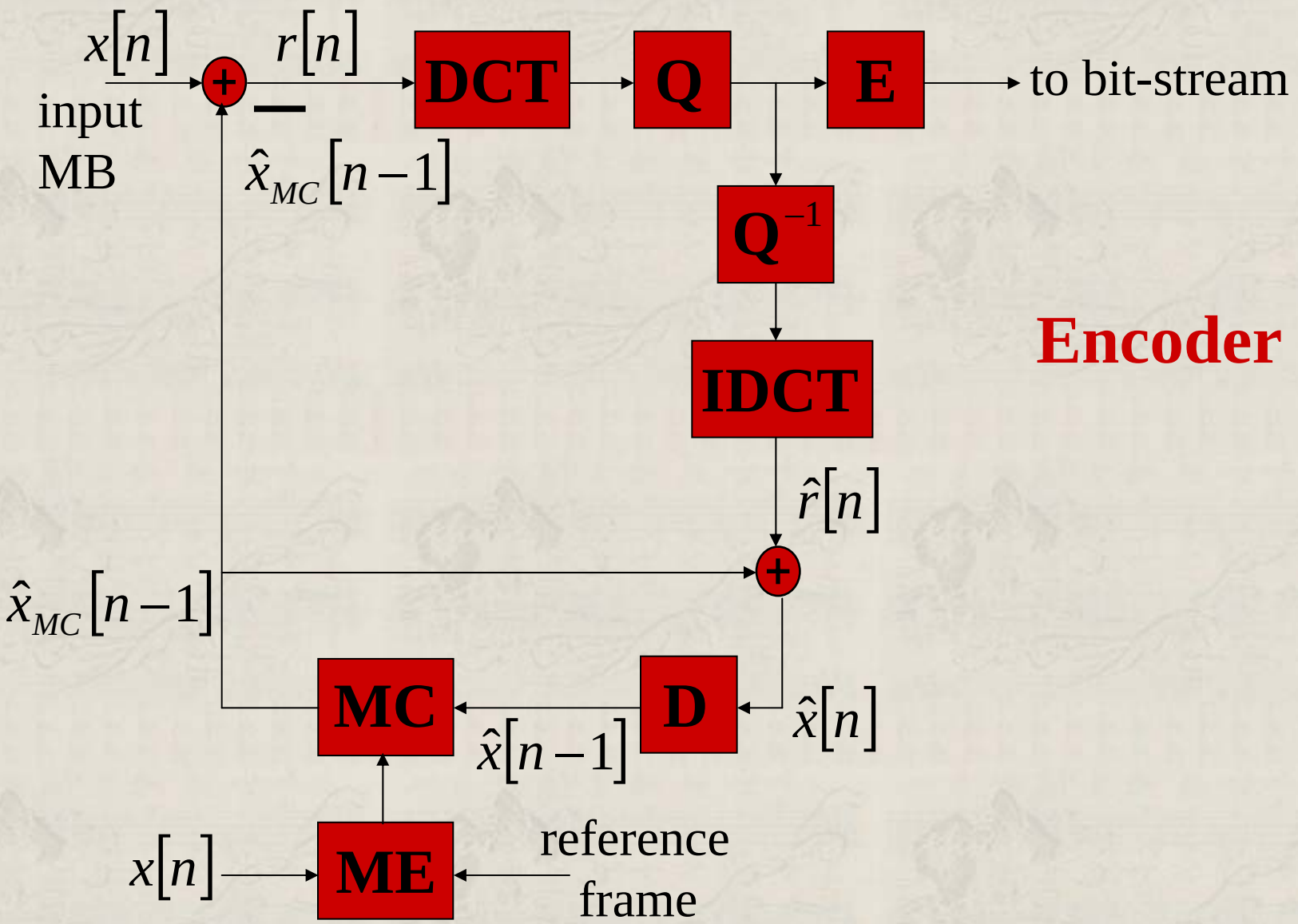
Inter and Intra Coding

- Intra
  - MB is encoded as is without motion compensation
  - DCT followed by Q, zig-zag, run-length, Huffman
- Inter
  - Block-matching motion estimation
  - Predictive motion residue from best-match block is DCT encoded (similarly to intra-mode)
  - Motion vector is differentially encoded

Intra-Coding Mode



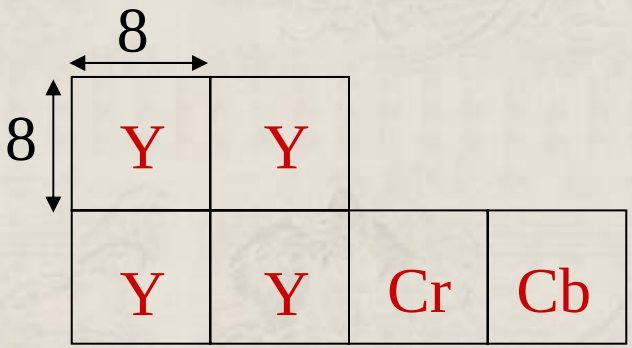
Inter-Coding Mode

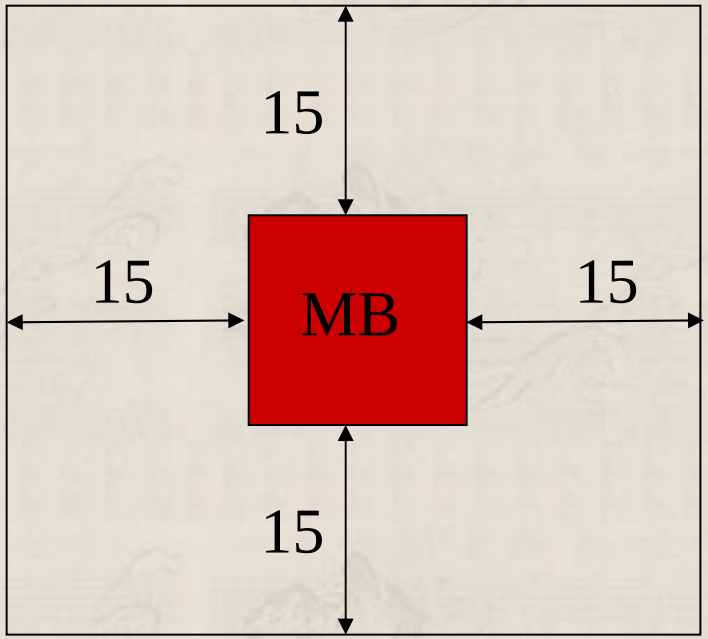


Encoder

Motion Estimation in H.261

- Macro-block
  - Luminance: 16x16, four 8x8 blocks
  - Chrominance: two 8x8 blocks
  - Motion estimation only performed for luminance component
- Motion vector range
  - [-15, 15]

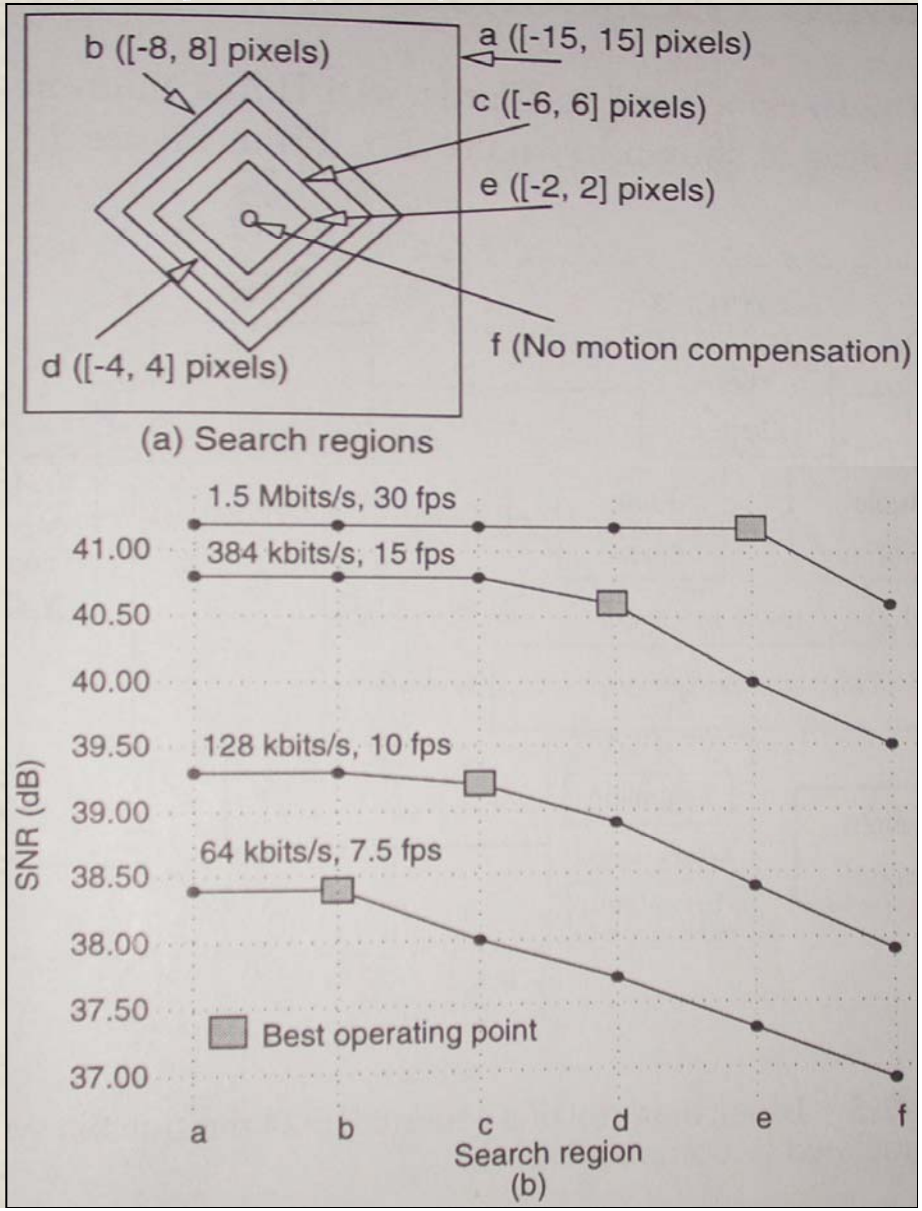




Search Area in Reference Frame

Motion Estimation & Video Quality

- Video teleconferencing
  - Head & shoulders
  - Small diamond-shape search region yields good performance
  - In high bit-rate situations, no benefit from large search window
  - ME complexity can be significantly reduced
  - [Bhaskaran et al, 1997]



Coding of Motion Vectors

- MV has range [-15, 15]
- Integer pixel ME search only
- Motion vectors are differentially & separably encoded

$$MVD_x = MV_x[n] - MV_x[n-1]$$

$$MVD_y = MV_y[n] - MV_y[n-1]$$

- 11-bit VLC for MVD
- Example

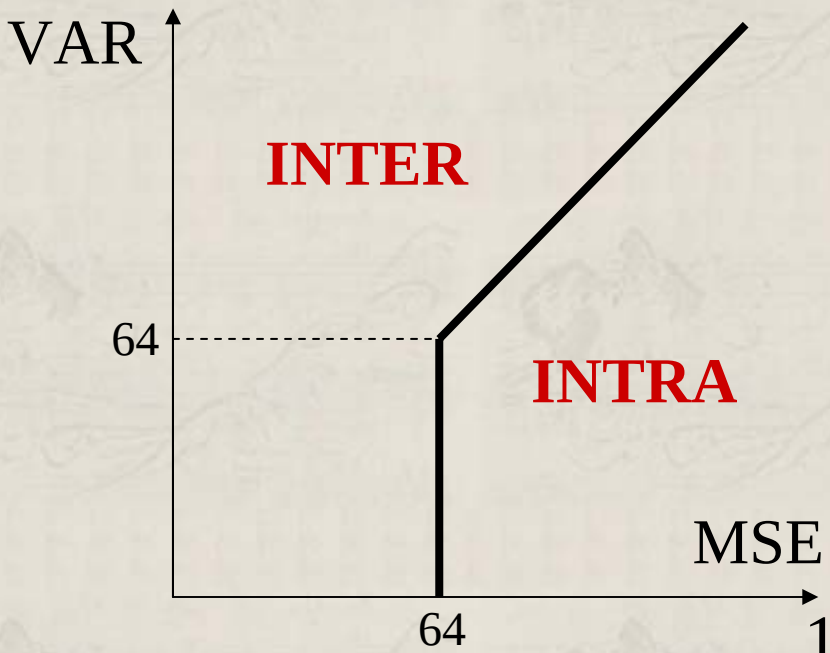
MV = 2 2 3 5 3 1 -1…
MVD = 0 1 2 -2 -2 -2…

Binary: 1 010 0010 0011 0011 0011…

MVD	VLC
…	…
-2 & 30	0011
-1	011
0	1
1	010
2 & -30	0010
3 & -29	0001 0

Inter/Intra Switching

- Based on energy of prediction error
  - High energy: scene change, occlusions, uncovered areas…
    ➔ use intra mode
  - Low energy: stationary background, translational motion …
    ➔ use inter mode



$$VAR = \frac{1}{256}\sum_{MB}\left(c[x,y]-\bar{c}\right)^2$$

$$MSE = \frac{1}{256}\sum_{MB}\left(c[x,y]-r[x+dx,y+dy]\right)^2$$

MC or No MC?

$$BD = \frac{1}{256} \sum_{MB} |c[x, y] - r[x, y]|$$

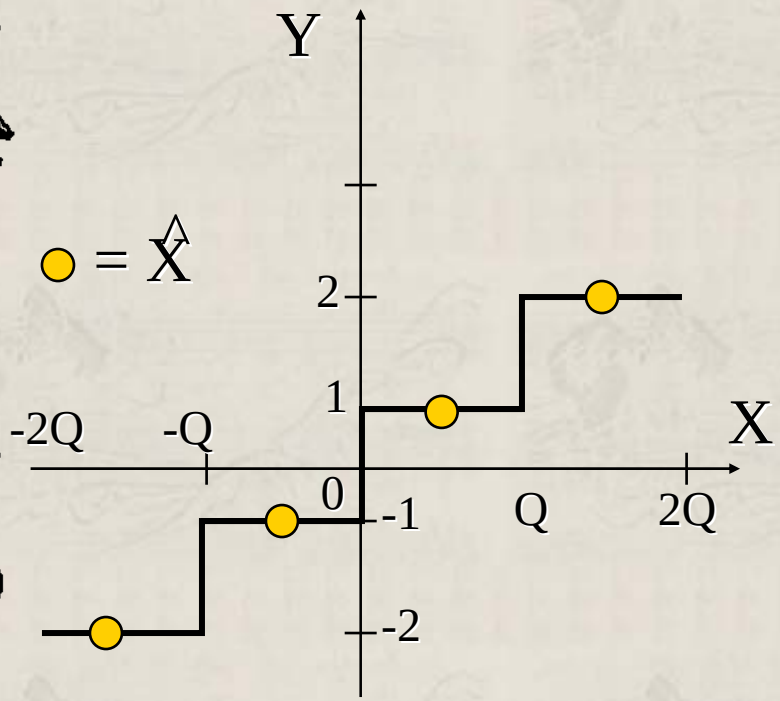
$$DBD = \frac{1}{256} \sum_{MB} |c[x, y] - r[x + dx, y + dy]|$$

Loop Filter

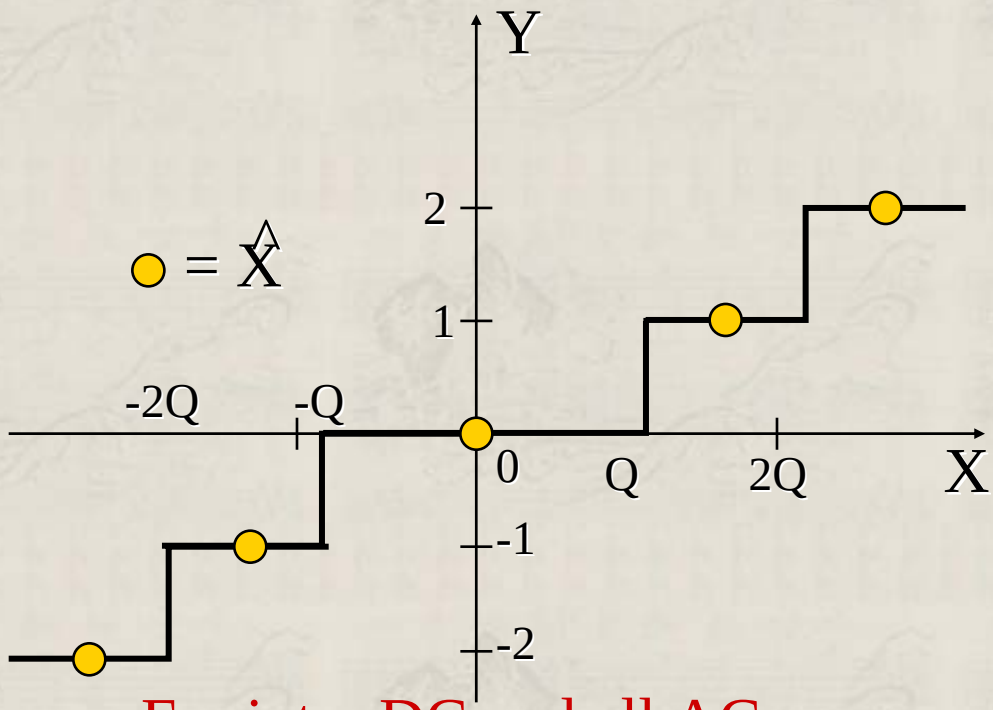
- Optional
- Can be turned on or off for each block, usually go together with MC
- Advantage
  - Decreases prediction error by smoothing the prediction frame
  - Reduces high-frequency artifacts like mosquito effects
- Disadvantage
  - Increases complexity & overhead
- 3-tap FIR separable low-pass filter
  - At block boundary: h[n]=[0 1 0] (no filtering)
  - Inside: h[n] = [1 2 1]/4

Quantization

- Uniform mid-rise quantizer for intra DC coefficients
- Uniform mid-tread quantizer with double dead zone for inter DC and all AC coefficients

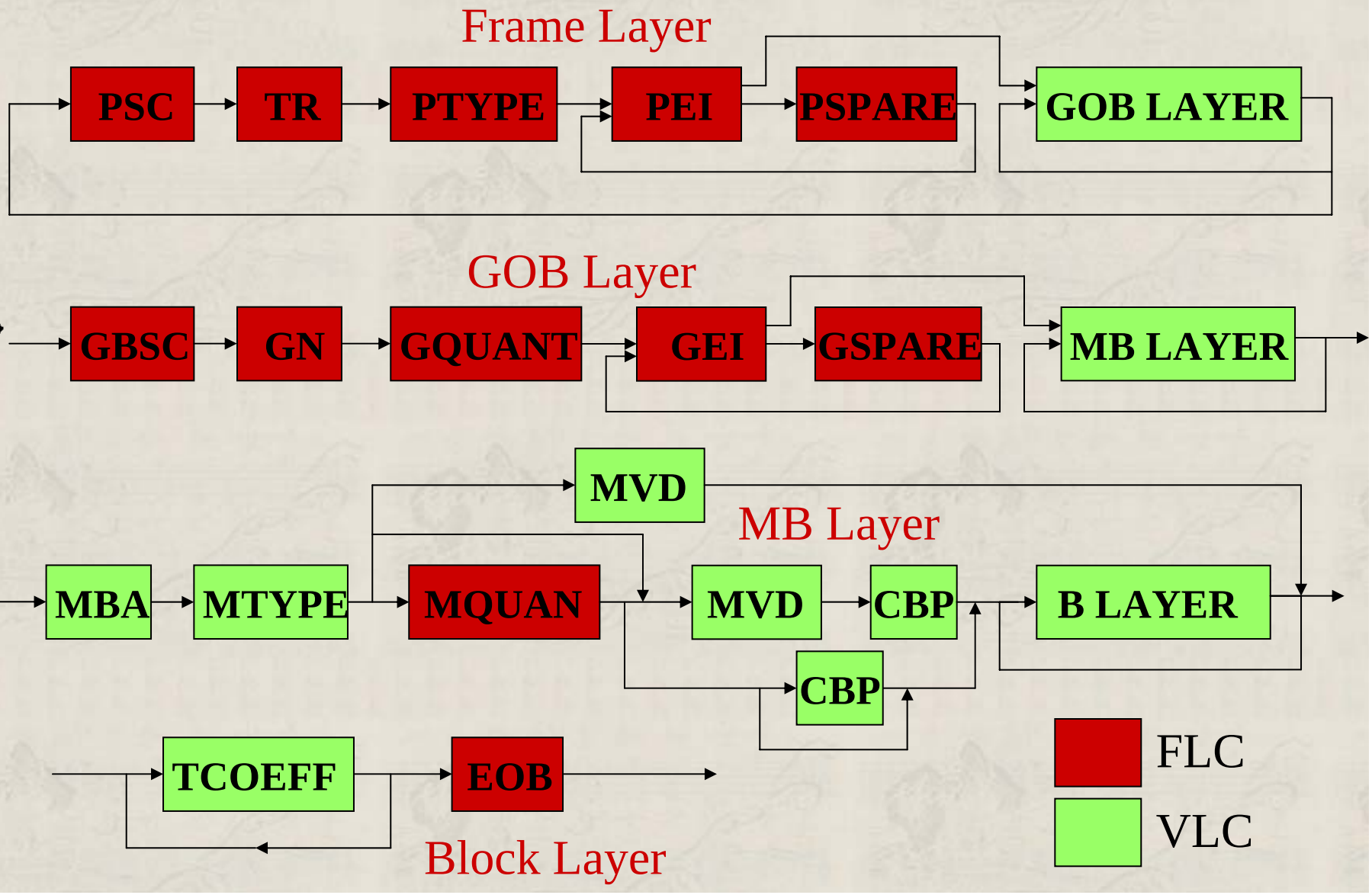


For intra DC



For inter DC and all AC

Bit-Stream Syntax



Bit-Stream Syntax

- Examples of FLC
  - PSC: Picture Start Code, 20 bits
  - PTYPE: Picture Type, 6 bits
  - GBSC: GOB Start Code, 16 bits
  - GN: Group Number, 4 bits, indexing 12 GOBs
  - GQUANT: Group Quantization information, 5 bits
  - MQUANT: MB Quantization information, 5 bits
  - EOB: End-of-Block
- Examples of VLC
  - MBA: MB Address, indexing MBs within a GOP, 11 bits max
  - MTYPE: MB Type information
  - MVD: Motion Vector Data, 11 bits max, 32 VLCs
  - CBP: Coded Block Pattern, 9 bits max, 63 VLCs
  - TCOEFF: Transform Coefficients

H.261 vs MPEG-1

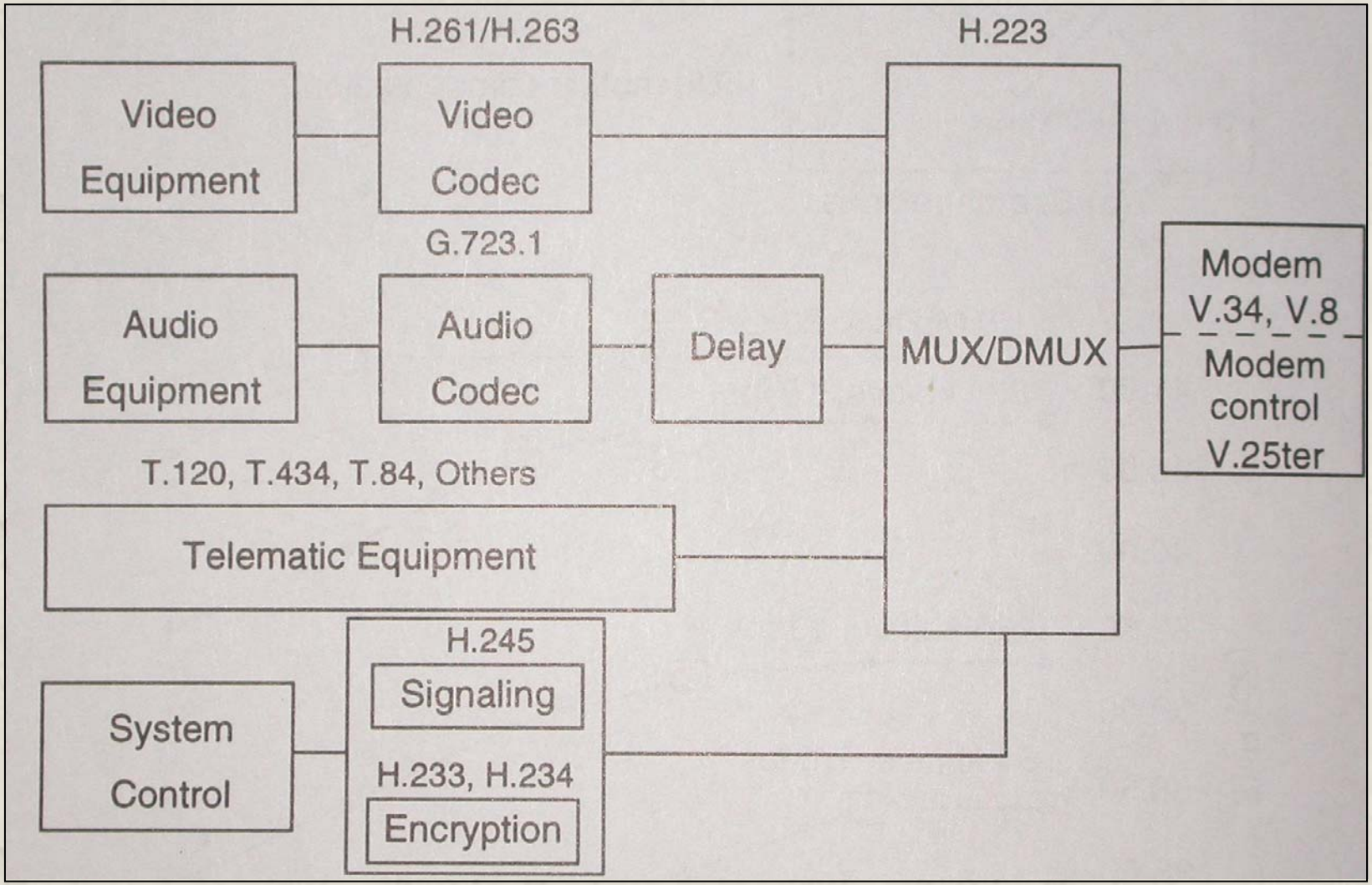
MPEG-1	H.261
Can have higher resolution	CIF & QCIF
Variable aspect ratio	4:3 aspect ratio
GOP: Group of Picture	No GOPs
I, P, B MB	Only I, P MB
Typical 1 Mbps	64 kbps – 2 Mbps
No skip restriction	Can only skip 1, 2, 3 frames
Half-pixel MEMC	Integer MEMC
Typical MV range [-15, 15]	Typical MV range [-7, 7]
End-to-end delay is not critical	Delay is critical

B: Bi-directional motion estimation & compensation

H.263

- Standardization effort started Nov 1993
- Aim
  - low bit-rate video communications, less than 64 kbps
  - target PSTN and mobile network: 10-32 kbps
- Near-term
  - H.263 and H.263+: established late 1997
- Long-term
  - H.26L, H.264: still under investigation
- Main properties
  - H.261 with many MPEG features optimized for low bit rates
  - Performance: 3-4 dB improvements over H.261 at less than 64 kbps; 30% bit rate saving over MPEG-1

H.263 & H.324



block diagram of a generic H.324 multimedia system

H.261 vs H.263

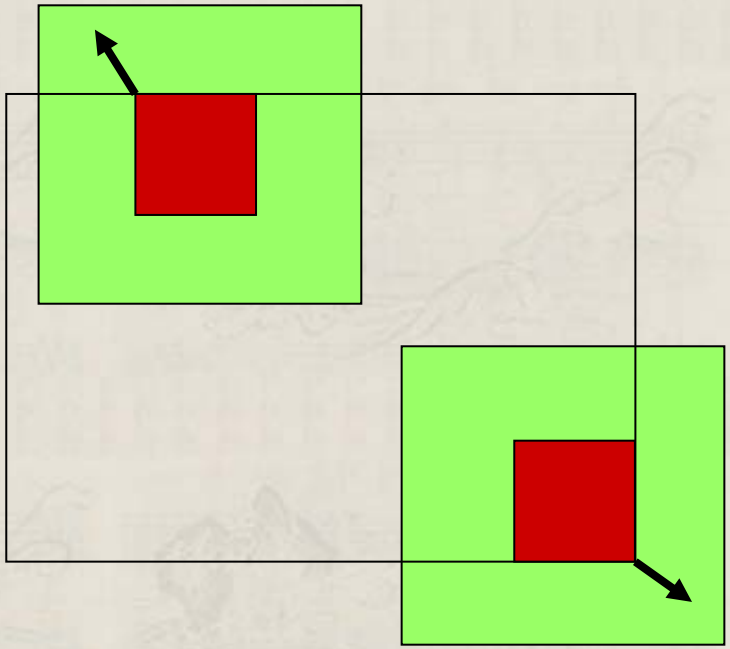
Features	H.261	H.263
Bit Rate	Reasonable, 64 kbps – 2 Mbps	Very low, 64 kbps or less
Format	CIF & QCIF	Sub-QCIF, QCIF, CIF, 4CIF, 16CIF
GOB Structure	GOB=33 MBs	GOB=1 row of MBs
Error Correction	BCH single-error correction code	No specification. Optional
Motion	Integer-pixel	Half-pixel
Loop Filter	Yes	No
MV Coding	Differential coding for MVs	Predictive coding for MVs

H.263+ Advanced Features

- Unrestricted motion vectors mode
- Can have four motion vectors per MB (each for an 8x8 quadrant)
- Overlapped block motion compensation (OBMC)
- Syntax-based adaptive arithmetic coding mode
- PB-frames mode

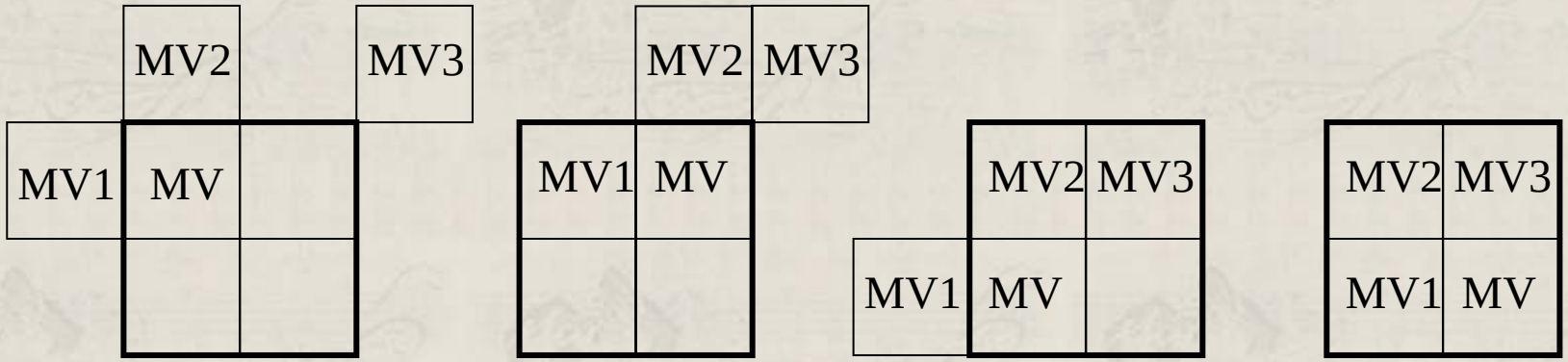
Unrestricted Motion Vectors

- Improve motion accuracy
  - Motion vector range is extended from [-16, 15.5] to [-31.5, 31.5]
  - Motion vector can point *outside* of the frame
  - Closest edge pixel is used (edge pixel is repeated)
- UMV dramatically improves motion estimation when moving objects are entering/exiting the frame or moving around the frame border

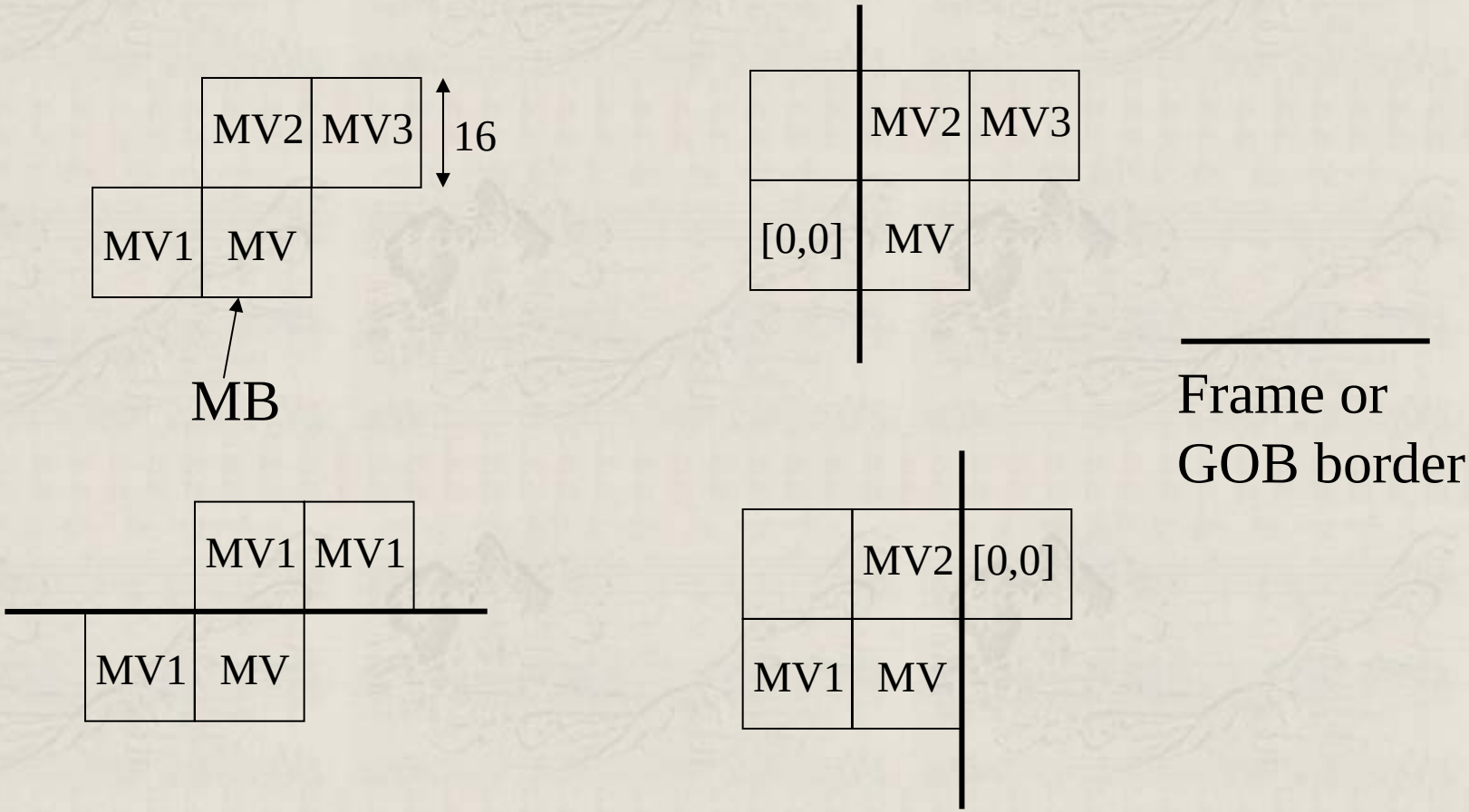


Advanced Prediction Mode

- This option significantly improves image quality
  - Four motion vectors for a macro-block
  - Overlapped block motion compensation (OBMC)
- Four MVs per MB
  - Can be enabled on a block-by-block basis
  - Each MV covers an 8x8 quadrant
  - MV for Cr or Cb is computed by averaging the 4 luminance MVs & scaling by 2 (rounding to nearest half-pixel)



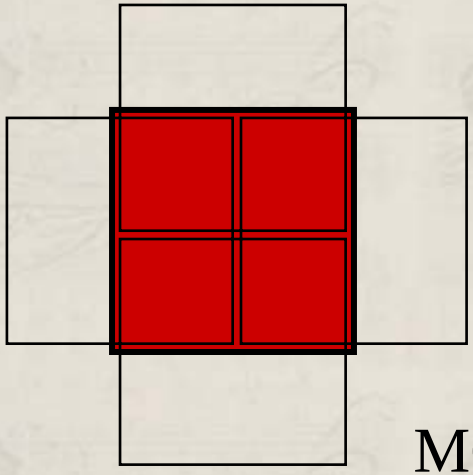
MV Predictive Coding



- MVD = MV – median(MV1, MV2, MV3)

OBMC

$$H_0 = \begin{bmatrix} 4 & 5 & 5 & 5 & 5 & 5 & 5 & 4 \\ 5 & 5 & 5 & 5 & 5 & 5 & 5 & 5 \\ 5 & 5 & 6 & 6 & 6 & 6 & 5 & 5 \\ 5 & 5 & 6 & 6 & 6 & 6 & 5 & 5 \\ 5 & 5 & 6 & 6 & 6 & 6 & 5 & 5 \\ 5 & 5 & 6 & 6 & 6 & 6 & 5 & 5 \\ 5 & 5 & 5 & 5 & 5 & 5 & 5 & 5 \\ 4 & 5 & 5 & 5 & 5 & 5 & 5 & 4 \end{bmatrix} \quad H_1 = \begin{bmatrix} 2 & 2 & 2 & 2 & 2 & 2 & 2 & 2 \\ 1 & 1 & 2 & 2 & 2 & 2 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 2 & 2 & 2 & 2 & 1 & 1 \\ 2 & 2 & 2 & 2 & 2 & 2 & 2 & 2 \end{bmatrix} \quad H_2 = \begin{bmatrix} 2 & 1 & 1 & 1 & 1 & 1 & 1 & 2 \\ 2 & 1 & 1 & 1 & 1 & 1 & 1 & 2 \\ 2 & 2 & 1 & 1 & 1 & 1 & 2 & 2 \\ 2 & 2 & 1 & 1 & 1 & 1 & 2 & 2 \\ 2 & 2 & 1 & 1 & 1 & 1 & 2 & 2 \\ 2 & 2 & 1 & 1 & 1 & 1 & 2 & 2 \\ 2 & 1 & 1 & 1 & 1 & 1 & 1 & 2 \\ 2 & 1 & 1 & 1 & 1 & 1 & 1 & 2 \end{bmatrix}$$



adjacent block

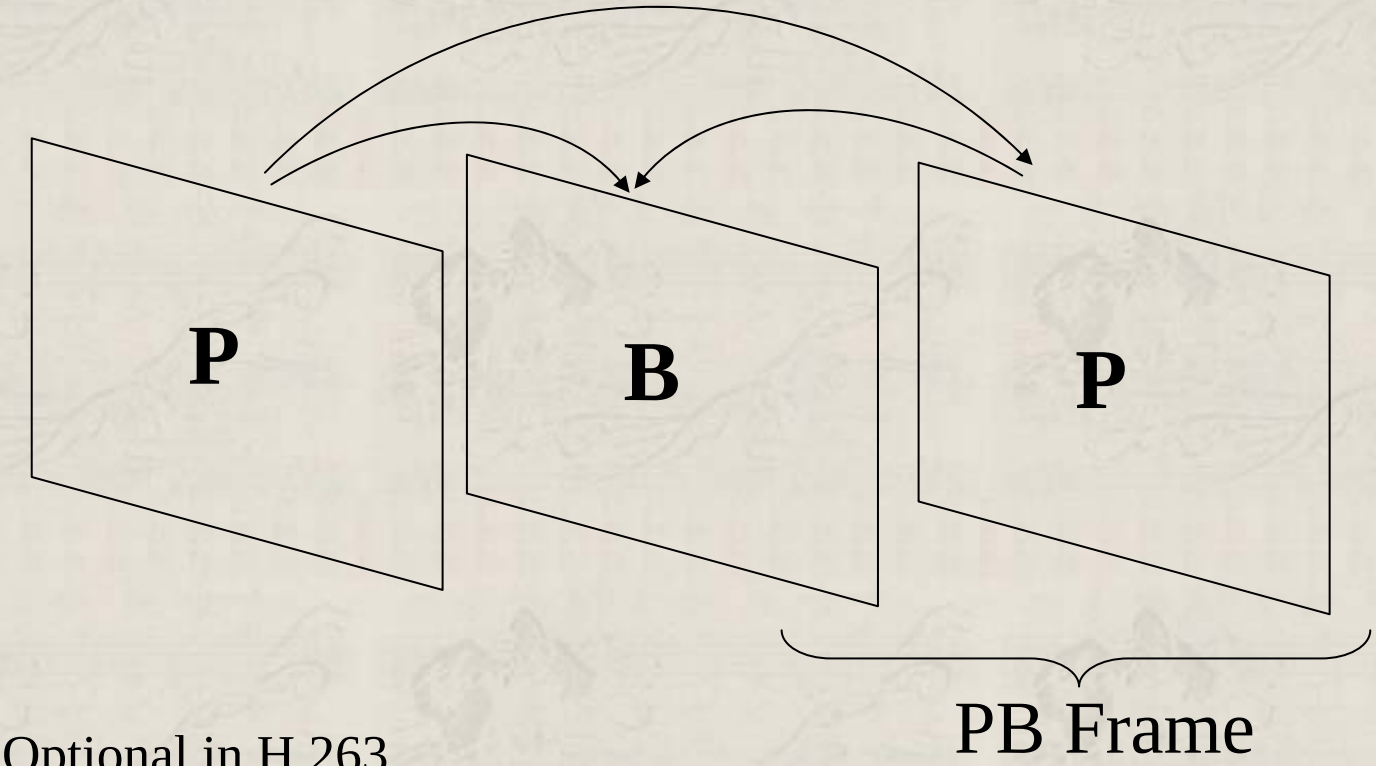
$$p = \frac{1}{8}\left(x_0 H_0 + x_1 H_1 + x_2 H_2 + 4\right)$$

MC prediction current block

Syntax-Based Arithmetic Coding

- Adaptive arithmetic coding based on appropriate syntax is used to replace all VLC operations
- Improves coding efficiency significantly
  - For inter-MB, AC yields 3-4% bit rate reduction
  - For intra-MB, AC yields ~10% bit rate reduction

PB-Frames Mode



- Optional in H.263
- Two frames are encoded as one unit: P and B
- P is predicted from a previously decoded P frame
- B is predicted from the P frame in the unit and another previously decoded P frame
- 12 blocks from a MB: 6 from P and 6 from B

MPEG

- Coding and communications of moving pictures and associated audio for digital storage and archival
- MPEG: Moving Picture Expert Group
- MPEG family
  - MPEG-1, Nov 1992
  - MPEG-2, Nov 1994
  - MPEG-4, Oct 1998
  - MPEG-7, ongoing work
- Main features of the MPEG video family
  - Bi-directional MEMC
  - I-frame, P-frame, B-frame
  - Structure: Group of Pictures (GOP), picture, slice, macro-block
  - Coding decisions

MPEG Goals and Applications

- MPEG-1
  - Optimized for applications that support a continuous transfer bit rate of about 1.5 Mbps (example, CD-ROM)
  - Target 1.2 Mbps for video and 250-300 kbps for audio, around analog VHS quality
  - Does not support interlaced sources
  - Main target source: SIF YCrCb 4:2:0 360 x 240 x 30 fps
  - VCD
- MPEG-2
  - The most commercially successful international coding standard
  - Wide range of bit rates: 4 – 80 Mbps; optimized for 4 Mbps
  - Target high-resolution, high-quality video broadcast & playback
  - DVD, Digital TV: DirecTV, HDTV…

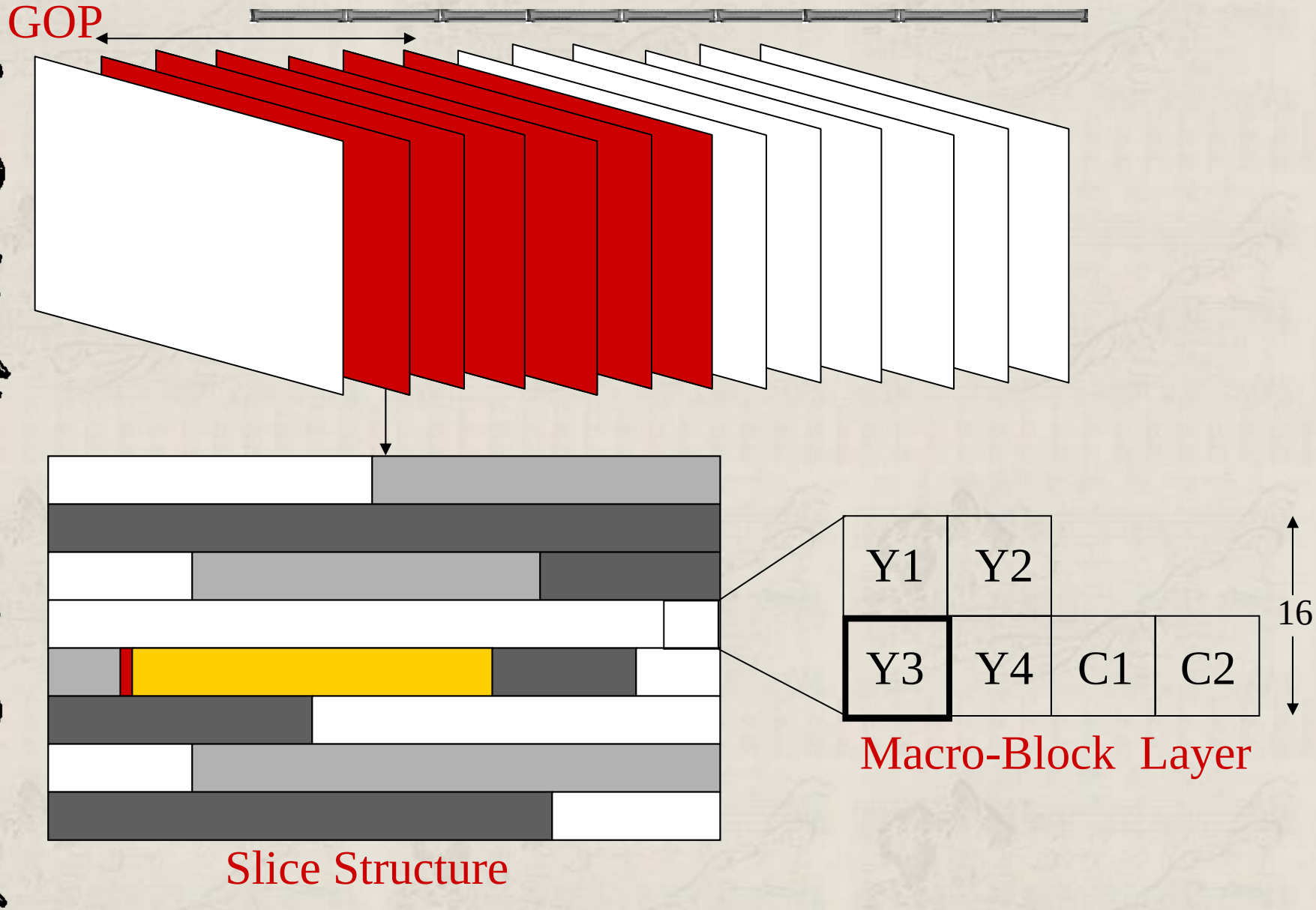
Requirements

- Coding of generic video at around 1.5 Mbps at reasonable quality (VHS)
- Random access capability, frequent access point
- Fast forward and fast rewind capability
- Audio-video synchronization during play and access
- Simple decoder
- Flexibility of data format
- Certain degree of robustness to communication errors
- Real-time encoder possibility

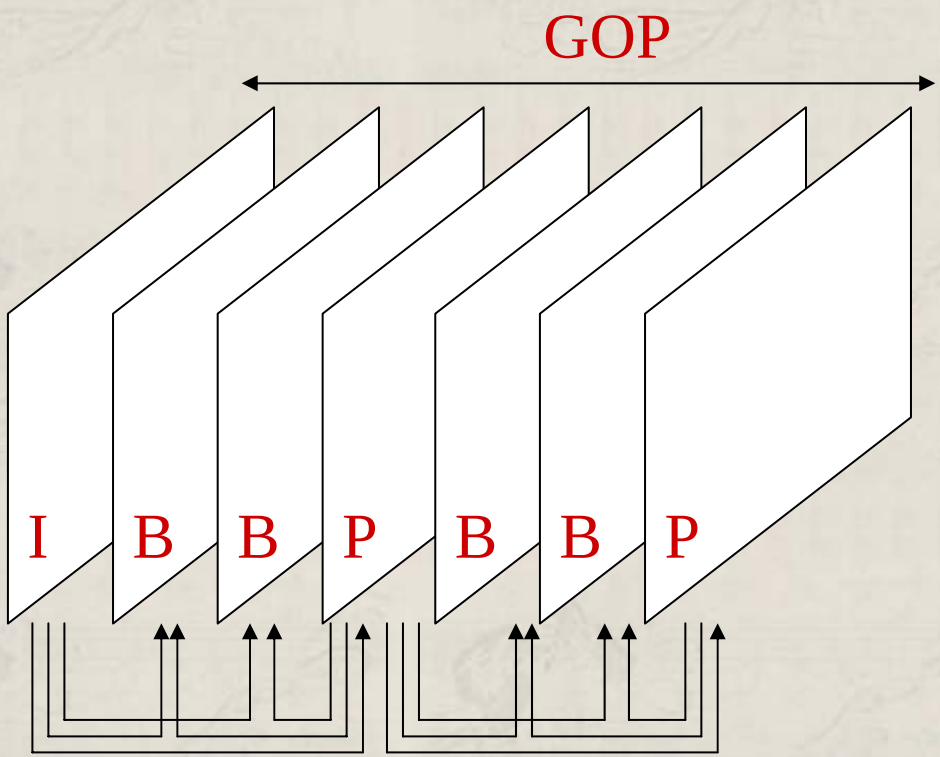
From H.261 to MPEG-1

- There are a few new features in MPEG-1 comparing to the pioneering H.261 codec
  - Flexible data sizes and frame rates
  - More flexible slice structure to replace the fixed GOB structure
  - Data structure: introducing Group of Picture (GOP) allowing frequent access points
  - Bi-directional motion compensation, B-frames
  - Half-pixel motion compensation
  - More finely tuned VLCs for different purposes
  - Quantization table (like JPEG) replaces single Q step size

Hierarchical Data Structure



GOP

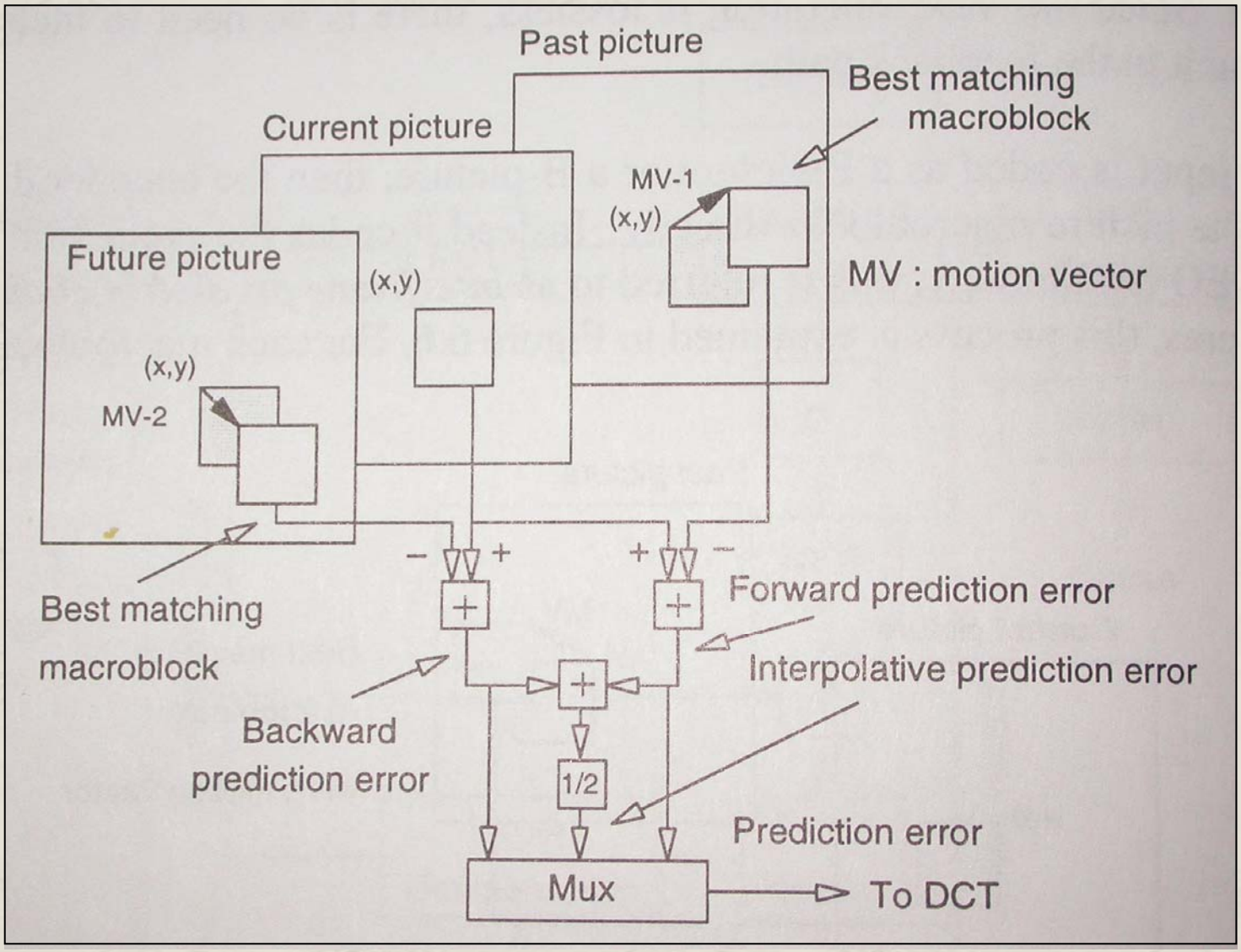


- N = number of frames (pictures) in a GOP
- M = number of B-frames between I- or P-frame + 1
- There is one I-frame for each GOP
- I-frame: intra coded only
- P-frame: forward prediction and MC
- B-frame: both forward and backward prediction and MC

Encode/Decode Sequence: I P B B P B B

Display Sequence: I B B P B B P

Bidirectional MEMC

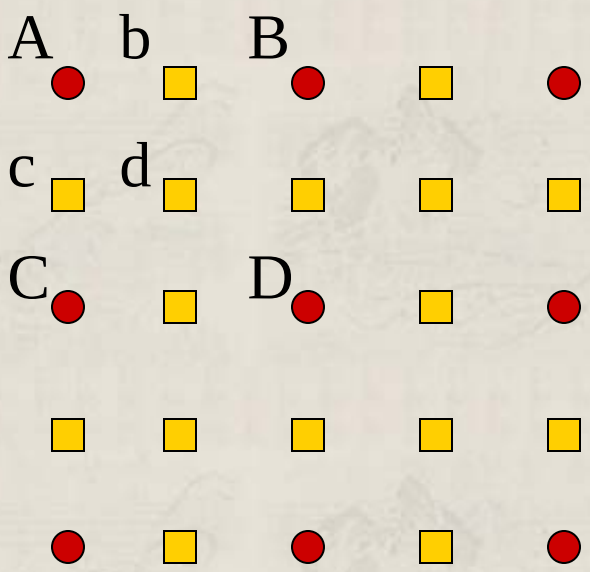


Bidirectional MC Properties

- Advantage
  - Higher coding efficiency, frame rate can be increased significantly with few bits
  - More accurate motion estimation & compensation
  - No error propagation
- Disadvantage
  - More memory buffer for frame storage (minimum of 3)
  - More end-to-end delay

Half-Pixel Motion Estimation

- Use linear/bilinear interpolation to fill in sub-pixels
- Trade-offs: motion accuracy versus MV bit-rate and complexity increase
- H.26L uses down to 1/4-MEMC, maybe even 1/8



integer pixel

half pixel

b = round[(A+B)/2]
c = round[(A+C)/2]
d = round[(A+B+C+D)/4]

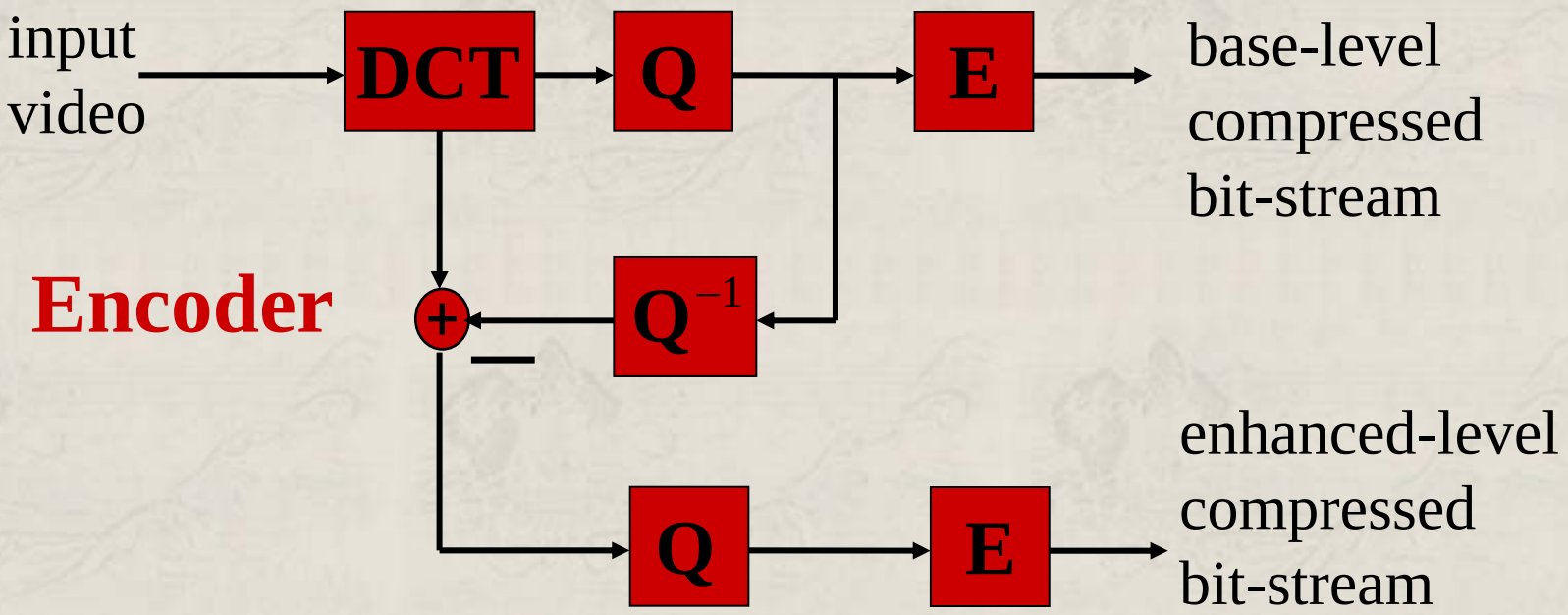
Computational Complexity

Decoding Function	Load %
Bit-stream header parsing	0.44
Huffman decoding and inverse Q	19.00
8 x 8 IDCT	22.10
Motion compensation	38.64
Color transformation and display	19.82

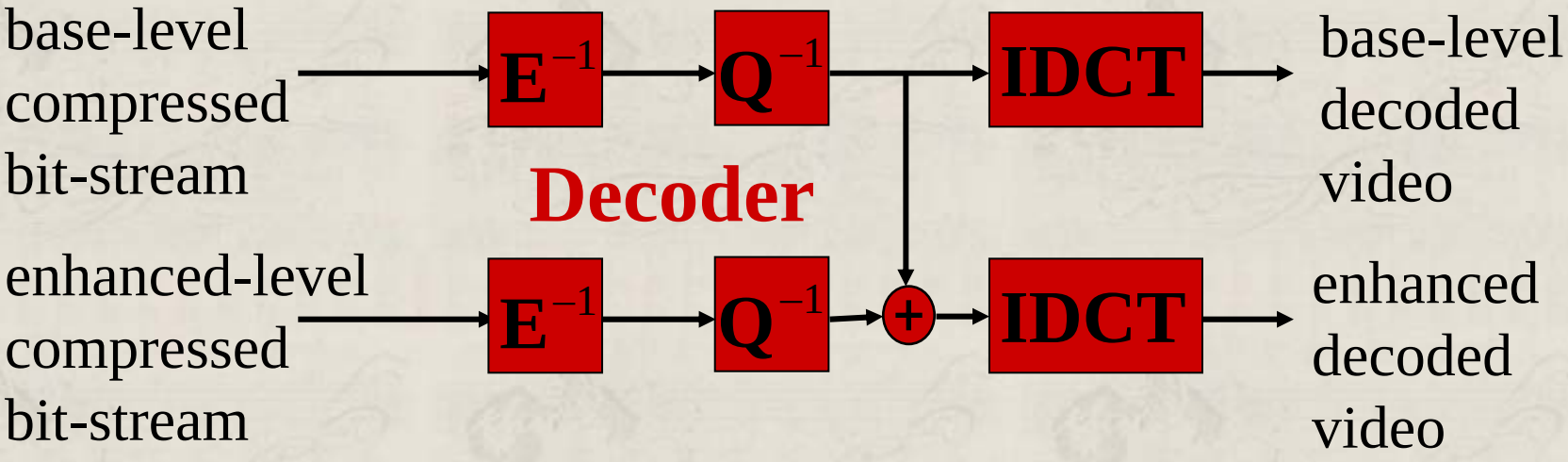
Video: Coarse- & Fine-Granularity

- Bit-plane coding schemes such as EZW & SPIHT are classified as fine-granularity scalability coding
  - Many layers can be added to improve quality. Each layer comes from a bit plane
  - Exact bit rate control
- Coarse-granularity scalability
  - Several bit planes can be combined together to yield a layer
  - For example, the top half of the bit planes can form the base layer whereas the remaining form the enhancement layer
  - Less flexibility but improved coding efficiency

Encoder: SNR Layer Scalability

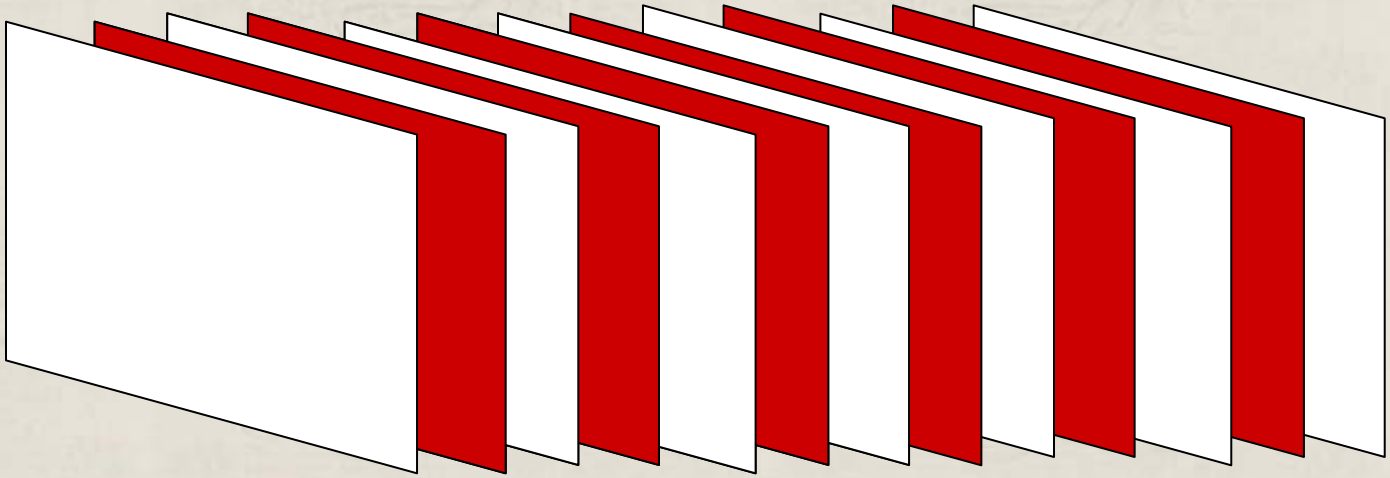


Decoder: SNR Layer Scalability

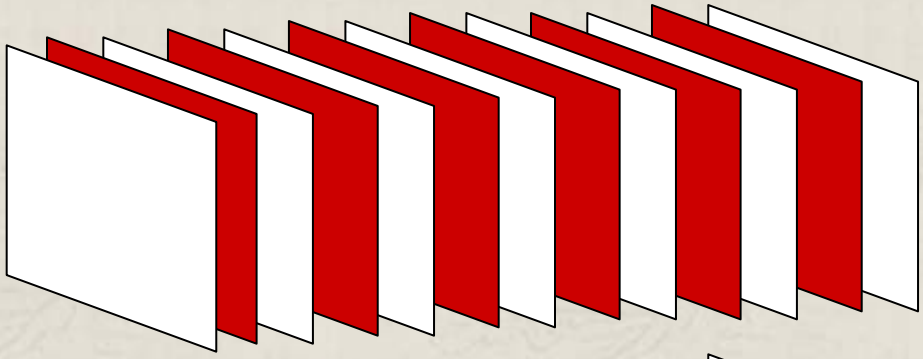


Spatial & Temporal Scaling

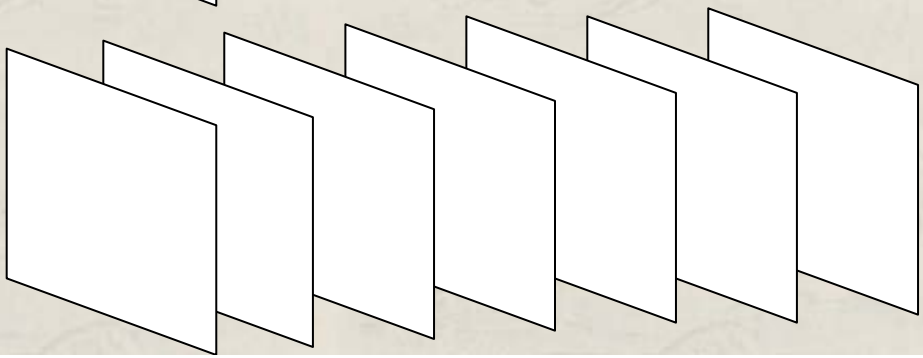
Original Video



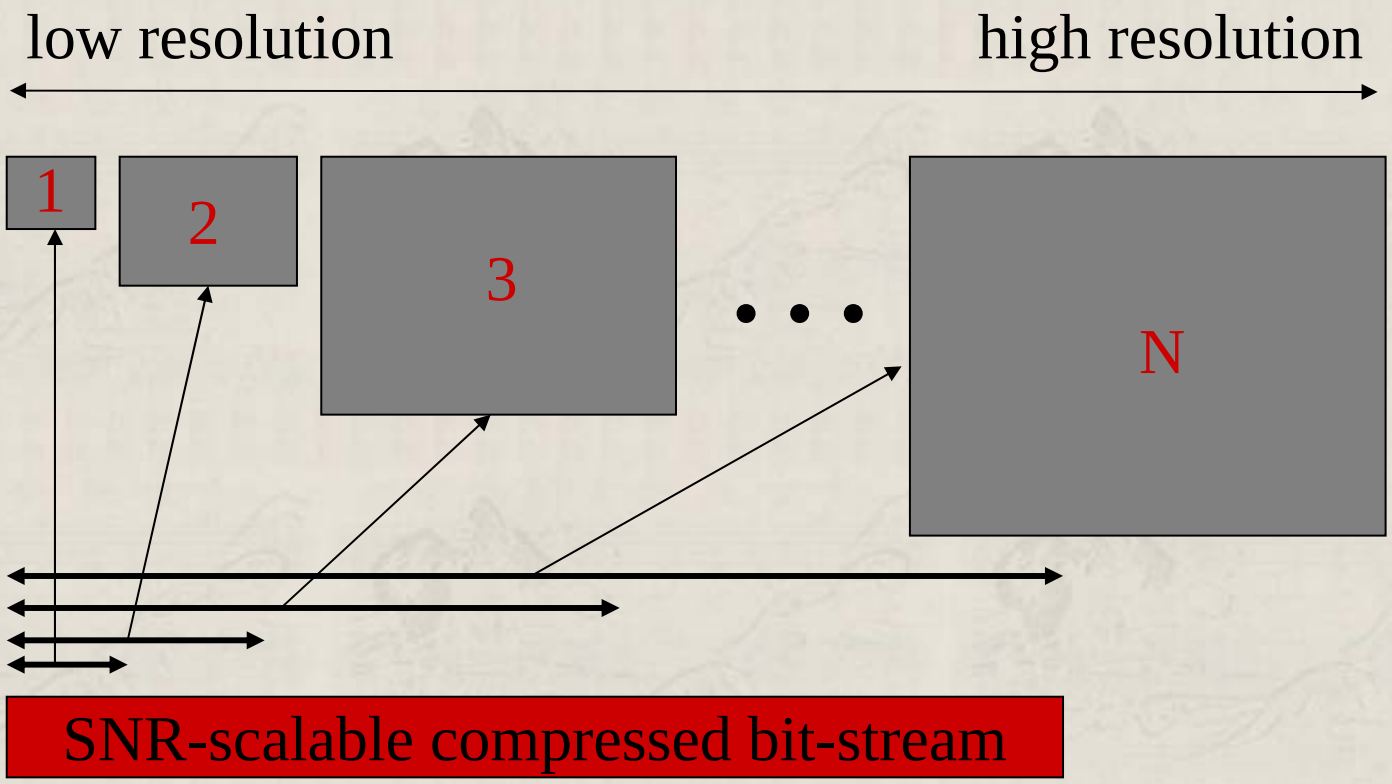
Spatial Scaling:
Half Resolution



Spatial & Temporal Scaling:
Half resolution
& Half frame rate

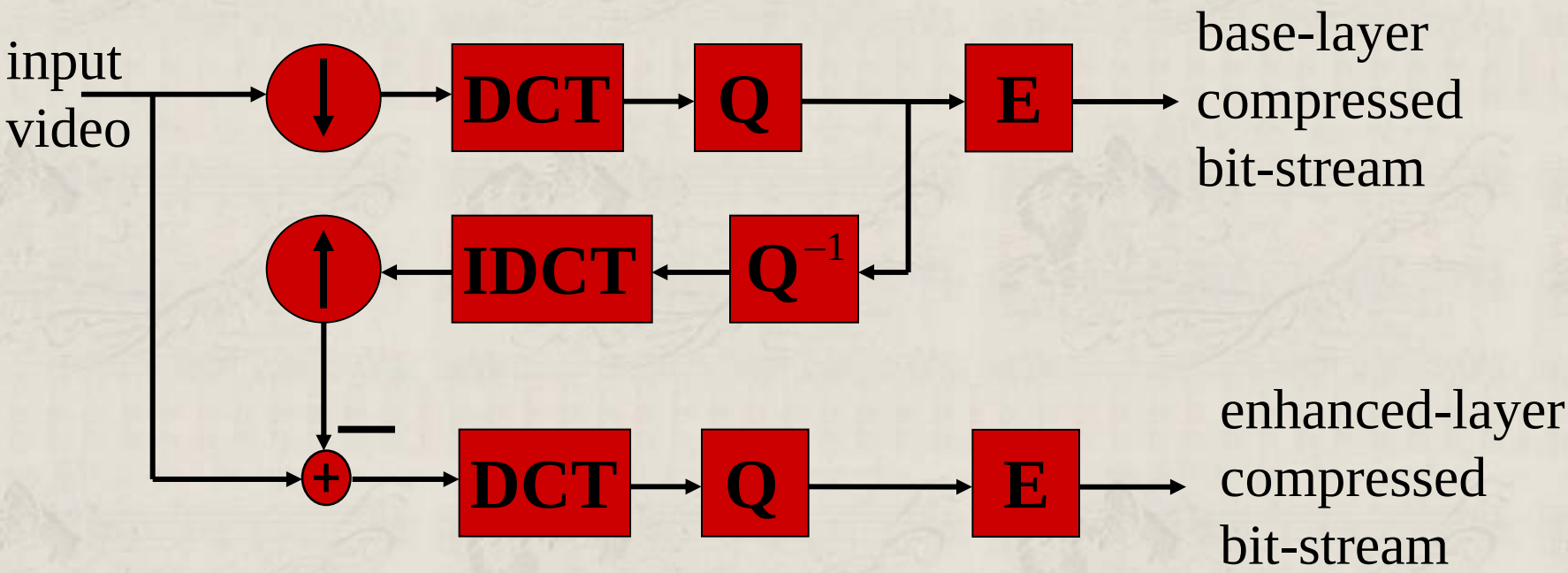


Spatial Scalability



- N layers of spatial scalability

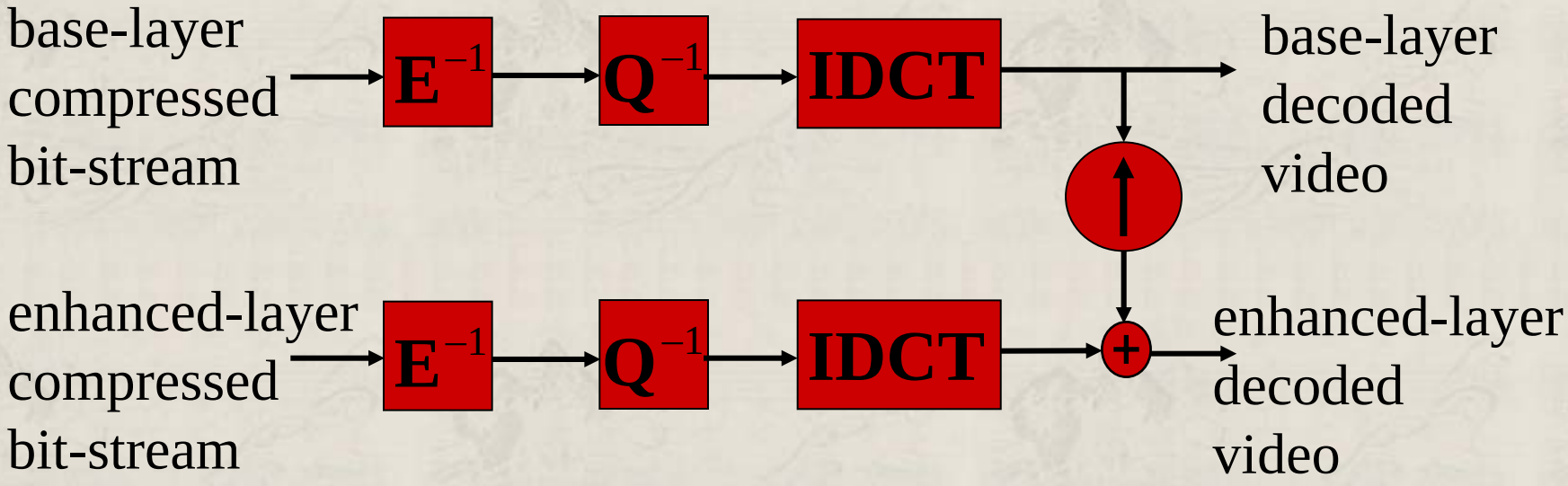
Encoder: Spatial/Temporal Scalability



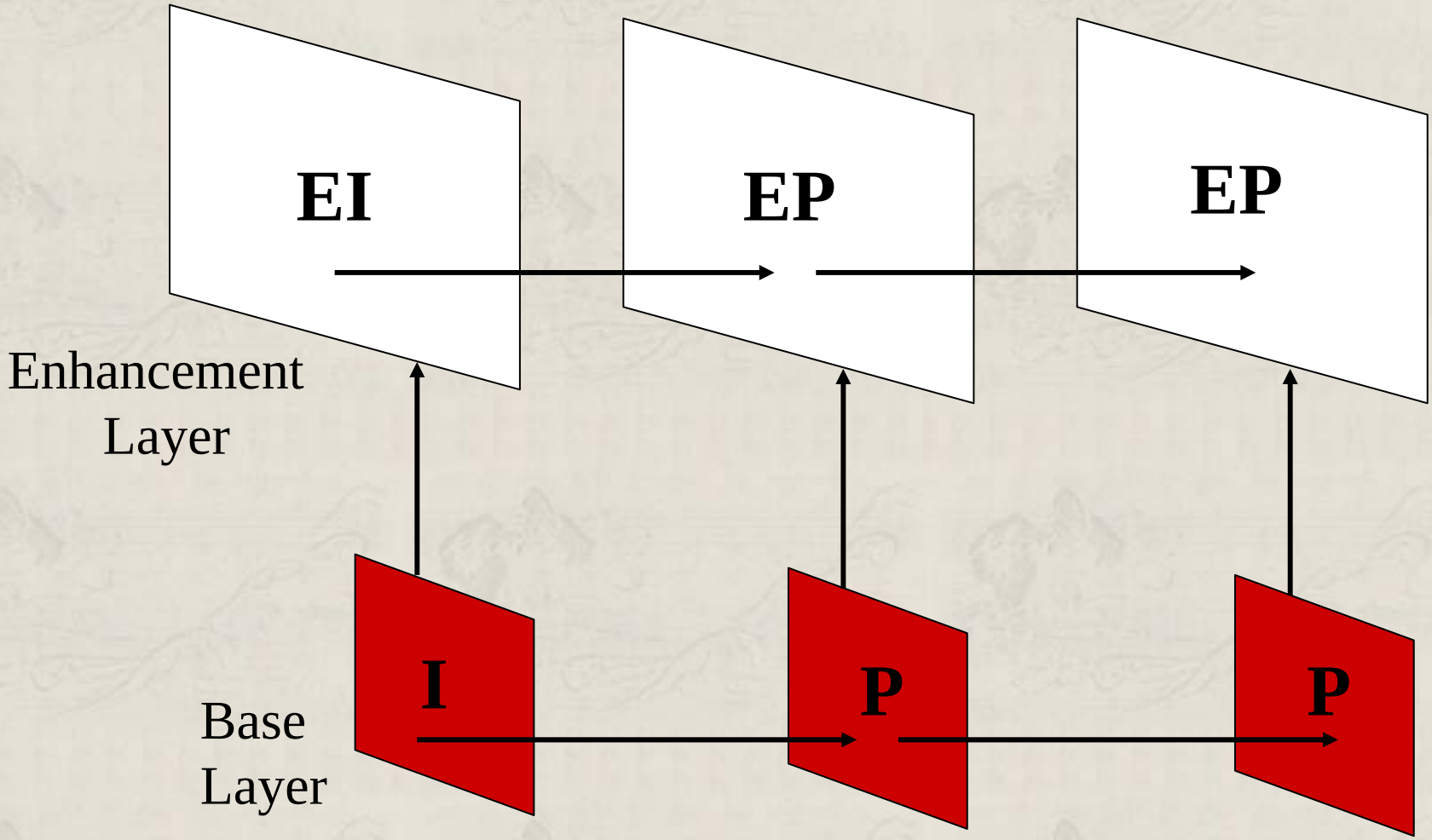
Spatial/temporal decimator

Spatial/temporal interpolator

Decoder: Spatial/Temporal Scalability

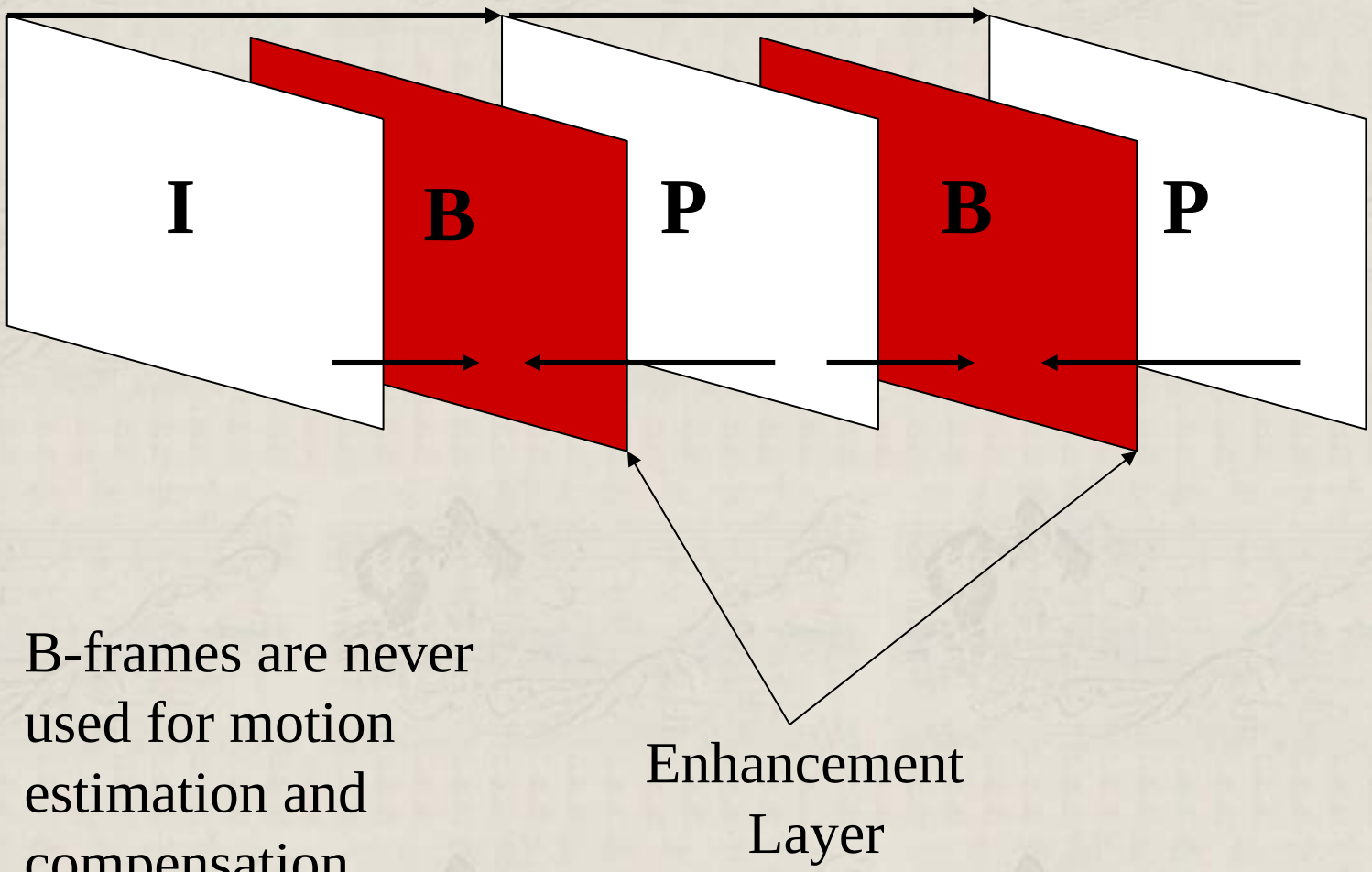


MEMC & Spatial Scalability



- Careful with encoder/decoder mismatch which causes drifting

MEMC & Temporal Scalability



- B-frames are never used for motion estimation and compensation

H.264 Advanced Video Coding

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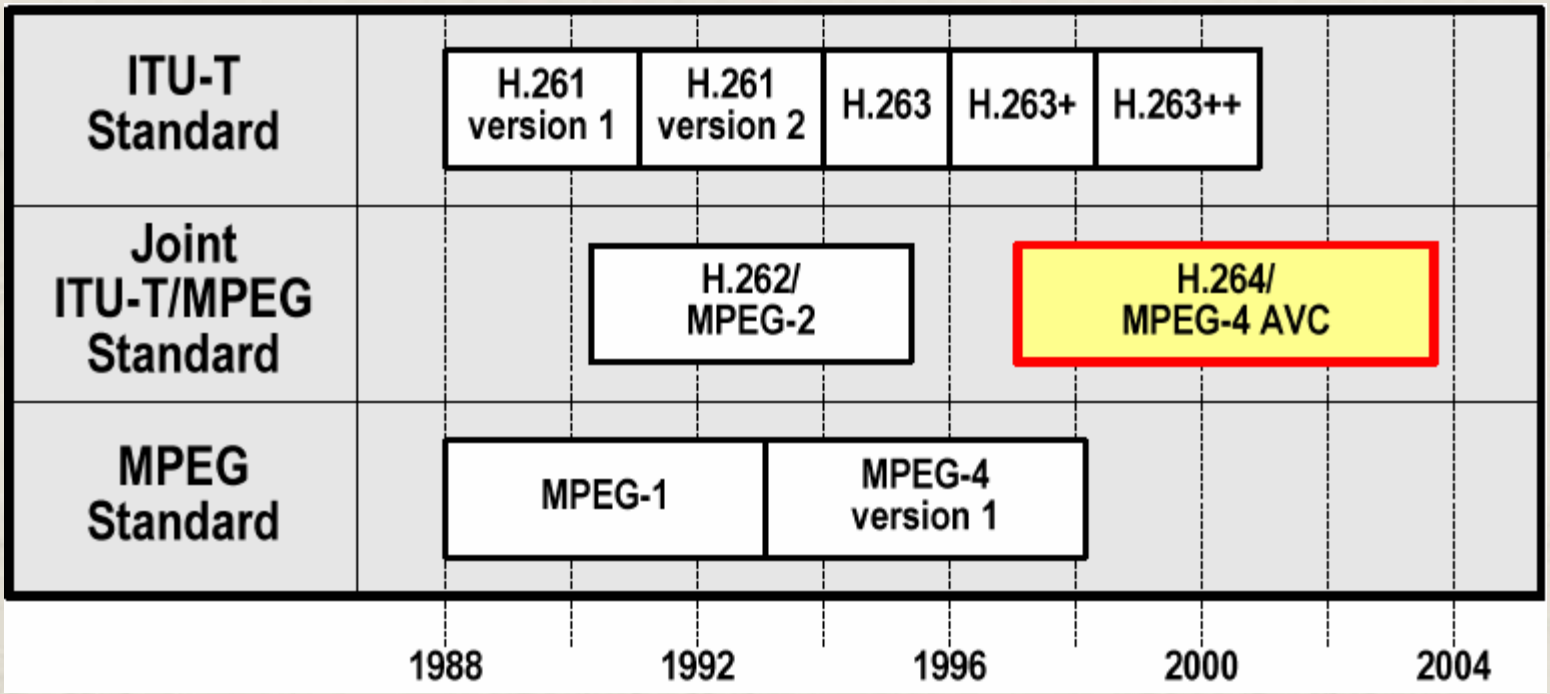
Baltimore MD 21218

History of Video Standards



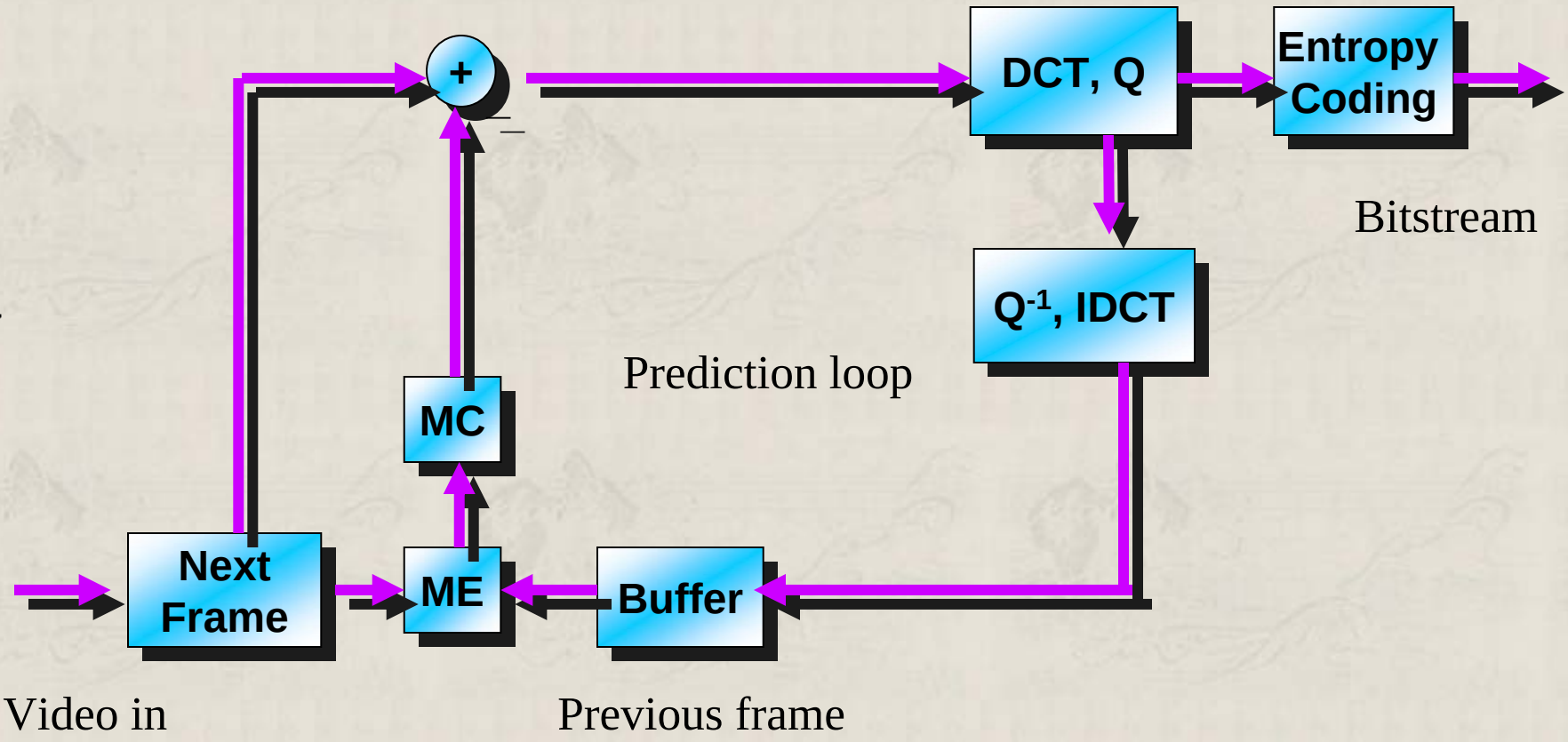
ITU H.26x History

- ITU H.26L: “long-term” solution for low bit-rate video coding for communication apps
- Predecessors include
  - H.261 (1990): “px64”, video conf. solution
  - H.263 (1995): next conf. solution, used in H.323
  - H.263+, H.263++, follow-on solutions
- H.26L project dates back to early ’90s
- Call for formal proposals January 1998
- First draft in August 1999
- Joining forces with MPEG: Dec. 2001
- H.264 (H.26L) completed in May 2003

MPEG History

- MPEG-1 (1993)
  - Video on CD (VCD)
- MPEG-2 (1994)
  - Broadcast, DVD, HD
- MPEG-4 (1999 -)
  - Cell phone, Interactive, high rate communication
  - Object-oriented
  - Over-ambitious ?
- AVC (2003)
  - Conventional to HD
  - Emphasis on compression performance and loss resilience

Generic Framework



* H.261, 263, 263+, MPEG-1/2/4

H.264 Video Coding

- Development history
- Main features
- Key compression techniques
  - Tools
  - Framework
- Performance
- Profiles
  - Basic and main profiles
  - High profile
  - Other new profiles

Development History

- Dec 01 – Start
  - Joint Video Team (JVT) formed between ITU/MPEG
- Dec 02 – Tech freeze
- May 03 – ITU-T Rec. H.264
- June 03 – ISO/IEC final draft (FDIS)
- July 03 – Launch of FRExt extension project
- Oct 03 – ISO/IEC (14496-10) AVC
- Dec 03 – Verification tests by MPEG

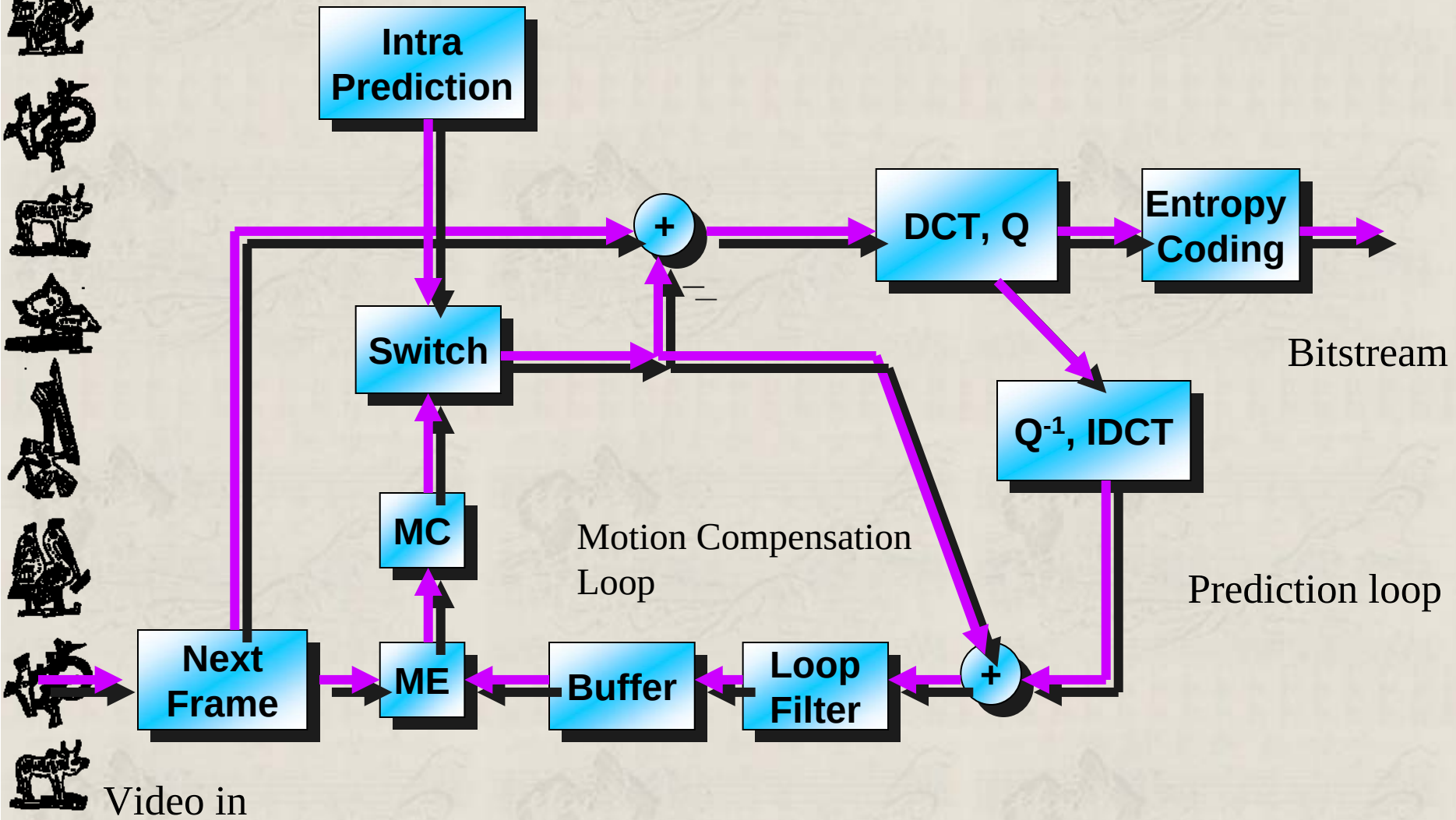
Main Features

- High compression performance
  - Advanced compression tools
  - Average 50% bit rate reduction given fixed fidelity compared to other standards
- Exact match decoding
  - Integer transform
- Improved perceptual quality
  - In-loop deblocking filter
- Network friendliness
  - NAL (network abstraction layer)
  - Enhanced error resilience

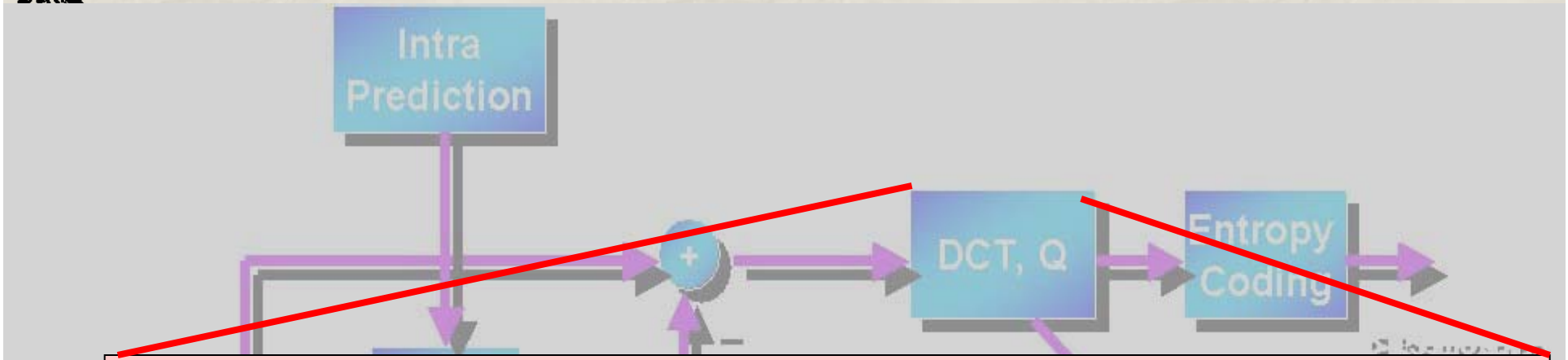
H.264 Technical Tools

- Structure
  - Sequence ->GOP->Picture->Slice->MB->Block
- Picture type: I, P, B, SI, SP
- Frame structure: interlaced, progressive
- Adaptive frame/field: per picture, per MB
- Deblocking filter – in loop
- MV resolution – ¼ pixel
- Tree-like motion segmentation – 16x16 to 4x4
- Entropy coding – CAVLC/CABAC
- Data partition – NAL unit, priority
- ASO (arbitrary slice order) – independently decodable
- FMO (flexible macroblock order) – map
- ABP (adaptive bi-prediction) – adaptive weighting

Block Diagram: H.264 Encoder



Innovation 1: Transform



$$\begin{bmatrix} 1 & 1 & 1 & 1 \\ 2 & 1 & -1 & -2 \\ 1 & -1 & -1 & 1 \\ 1 & -2 & 2 & -1 \end{bmatrix}$$

Quantization step size control is nonlinear: step sizes graduated by about 12% (double after 6 steps)

16-bit 4x4 DCT

- **EXACT MATCH** simplified transform
  - 4x4 transform

4x4 DCT

$$H = \begin{bmatrix} a & a & a & a \\ b & c & -c & -b \\ a & -a & -a & a \\ c & -b & b & -c \end{bmatrix}$$

H.264

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

where $a = 1/2$, $b = \sqrt{1/2} \times \cos(\pi / 8)$,

and $c = \sqrt{1/2} \times \cos(3\pi / 8)$.

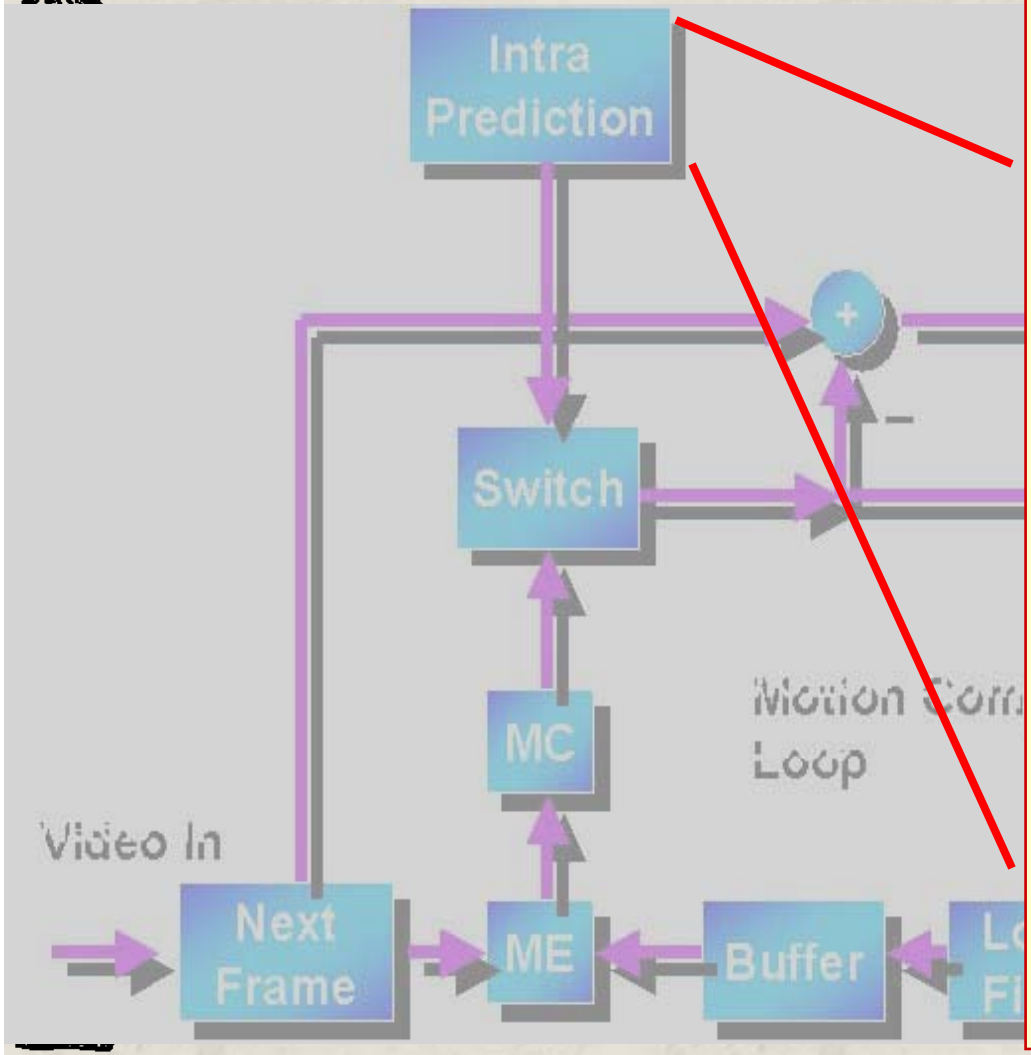
  - Non-orthonormality of the integer transform, i.e., position dependent scaling
  - Requires only 16 bit arithmetic (including intermediate values)
  - Expanded to 8x8 for Chroma by 2x2 transform of the DC values

Quantization

- Quantization of transform coefficients
  - Logarithmic step size control
  - Extended range of step sizes
  - Smaller step size for chroma
  - 16-bit multiply, add and shift
  - Table-driven: 2 times in Qstep for every 6th increment in Qp

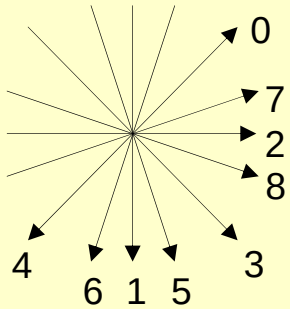
QP	0	1	2	3	4	5	6	7	8	9	10	11	12	...
qStep	0.625	0.6875	0.8125	0.875	1	1.125	1.25	1.675	1.625	1.75	2	2.25	2.5	...
QP	...	18	...	24	...	30	...	36	...	42	...	48	...	51
qStep	...	5	...	10	...	20	...	40	...	80	...	160	...	224

Innovation 2: Intra Prediction



- Directional spatial prediction
  (9 types for luma, 1 for 4x4 chroma)

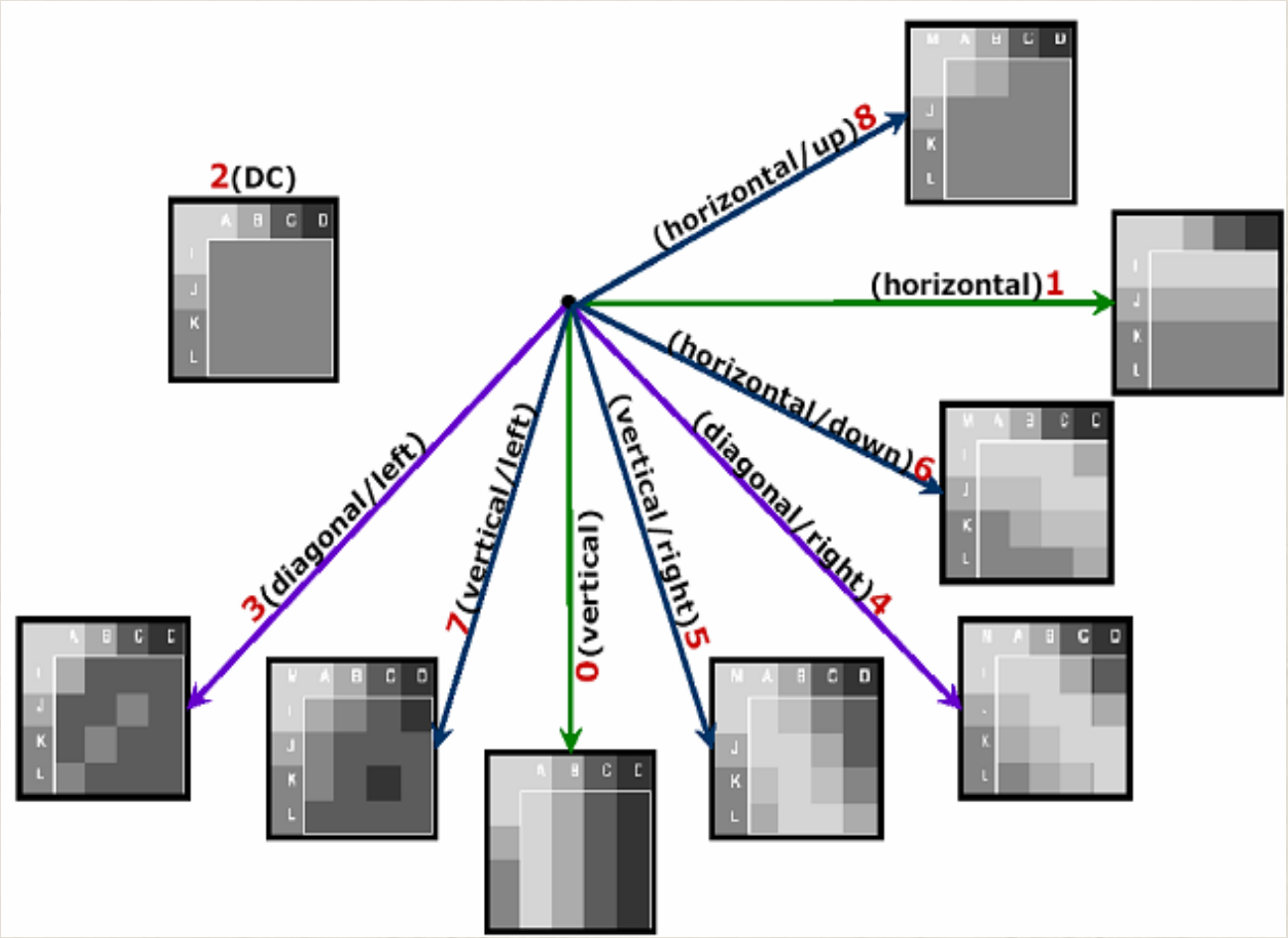
```
Q A B C D E F G H
I a b c d
J e f g h
K i j k l
L m n o p
M
N
O
P
```



- e.g., Mode 3:
  diagonal down/right prediction
  a, f, k, p are predicted by
  (A + 2Q + I + 2) >> 2

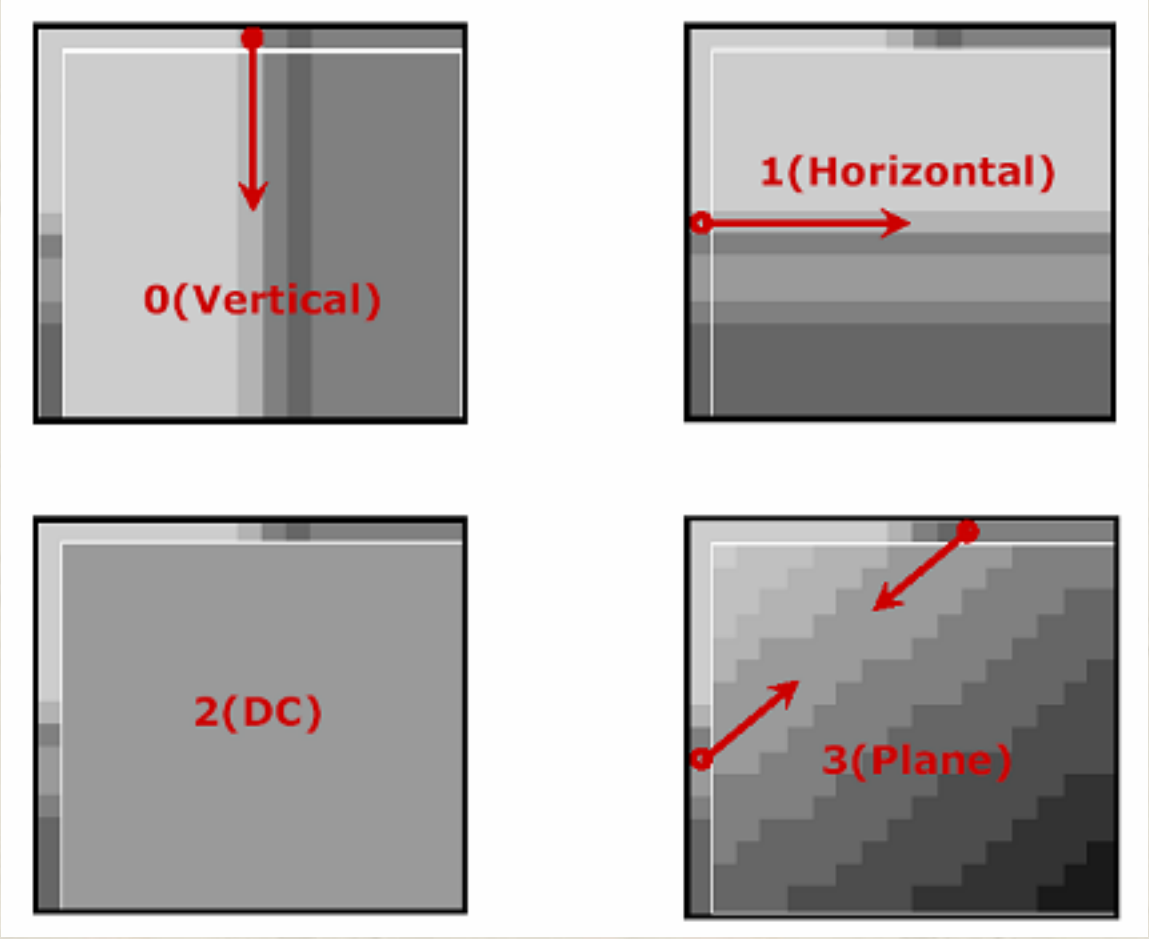
4x4 Intra Block Prediction Modes

- Nine 4x4 block prediction modes

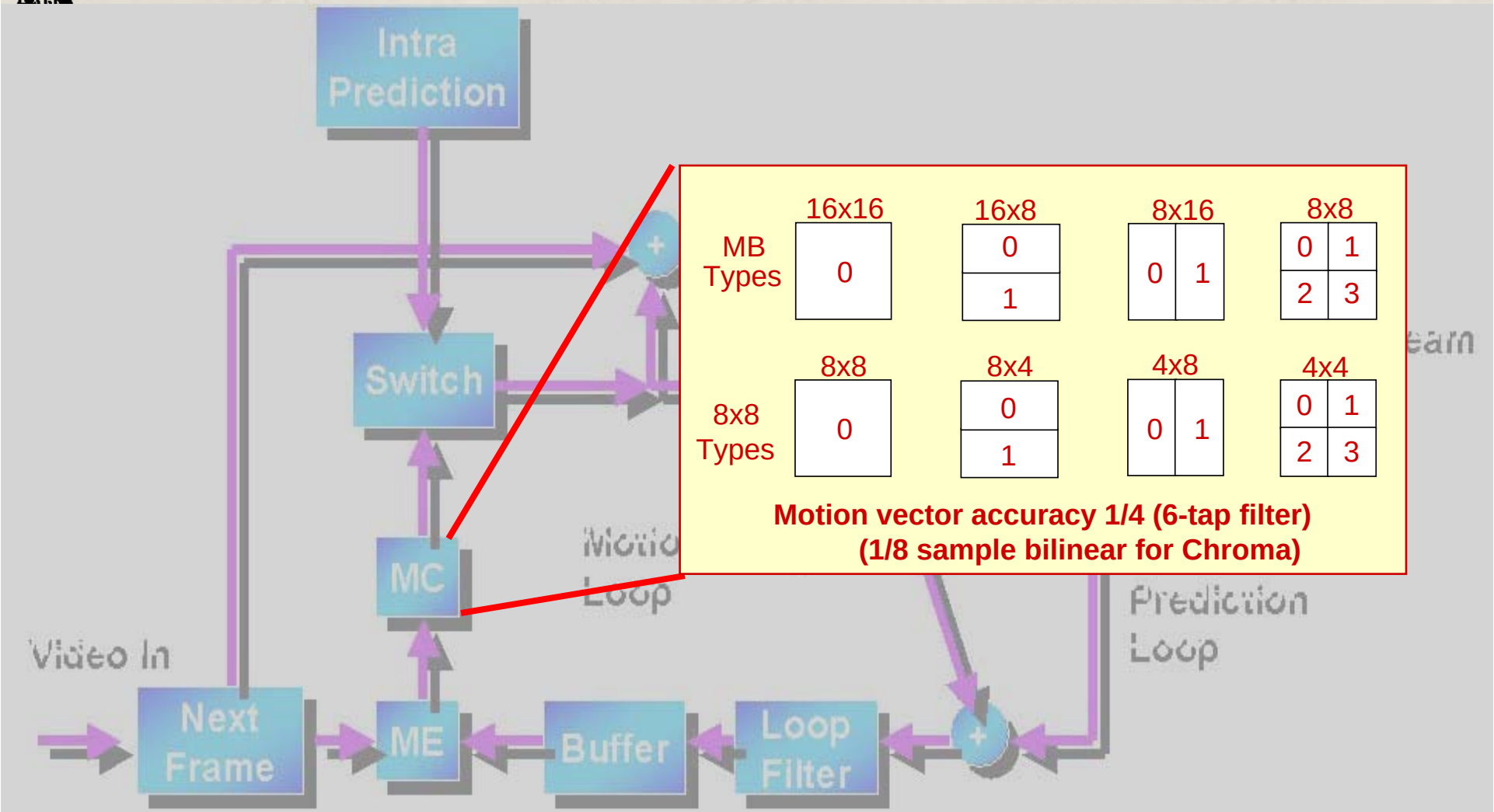


16x16 Luma (8x8 Chroma) Intra Prediction

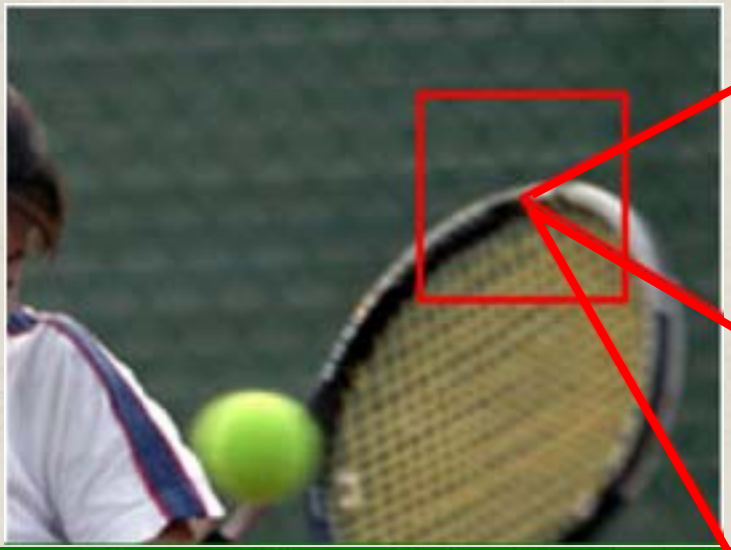
- Four 16x16 Luma (8x8 chrominance) intra predication modes



Innovation 3: Flexible Block MC



Example: H.264 MC



MPEG-2
- 16x16 block size
- Square shape
- ½ pel motion vector

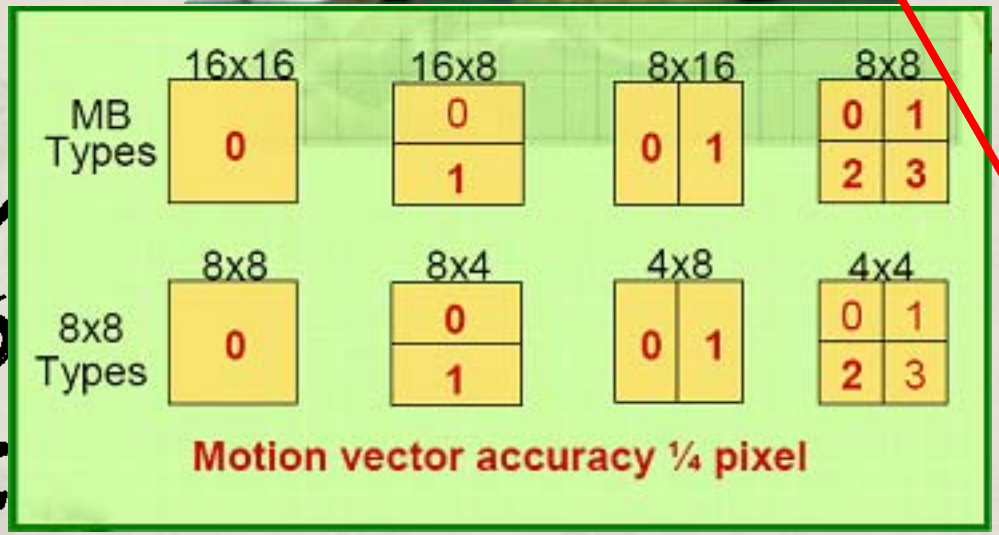
➔ Weak Motion Isolation !

MPEG-4
- 8x8 block size
- Square shapes
- ½ pel motion vector

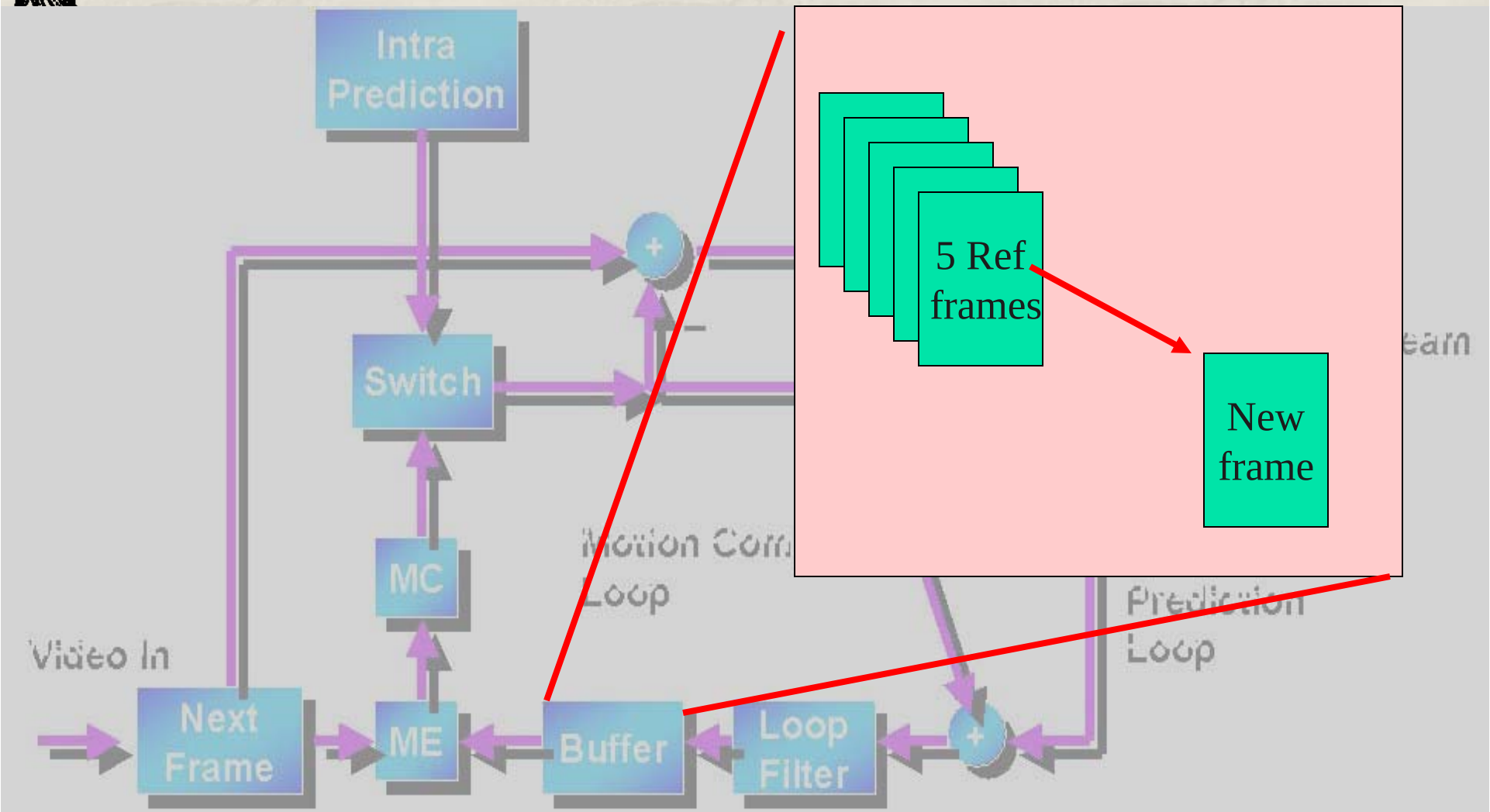
➔ Moderate Motion Isolation !!

H.264
- 4x4 block size
- Arbitrary shapes
- ¼ pel motion vector

➔ Strong Motion Isolation !!!

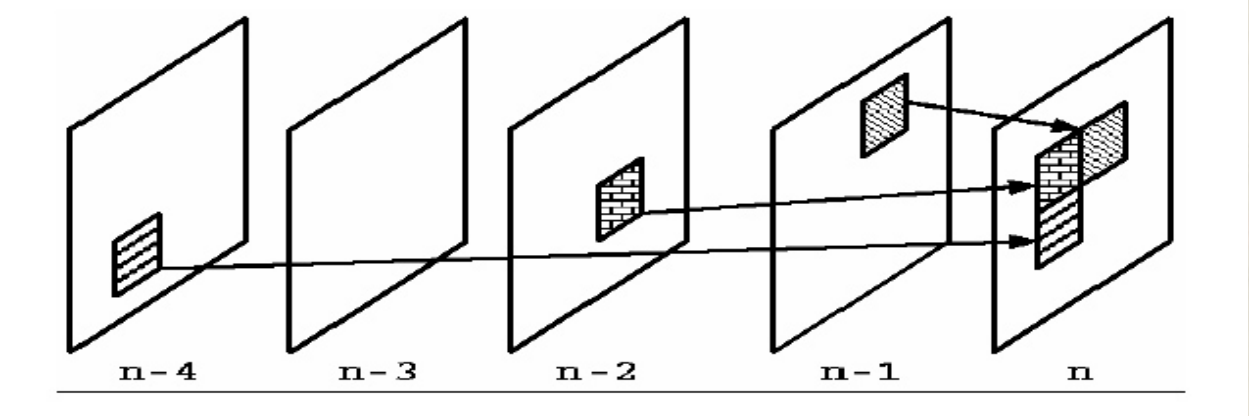


Innovation 4: Multiple Reference Frames

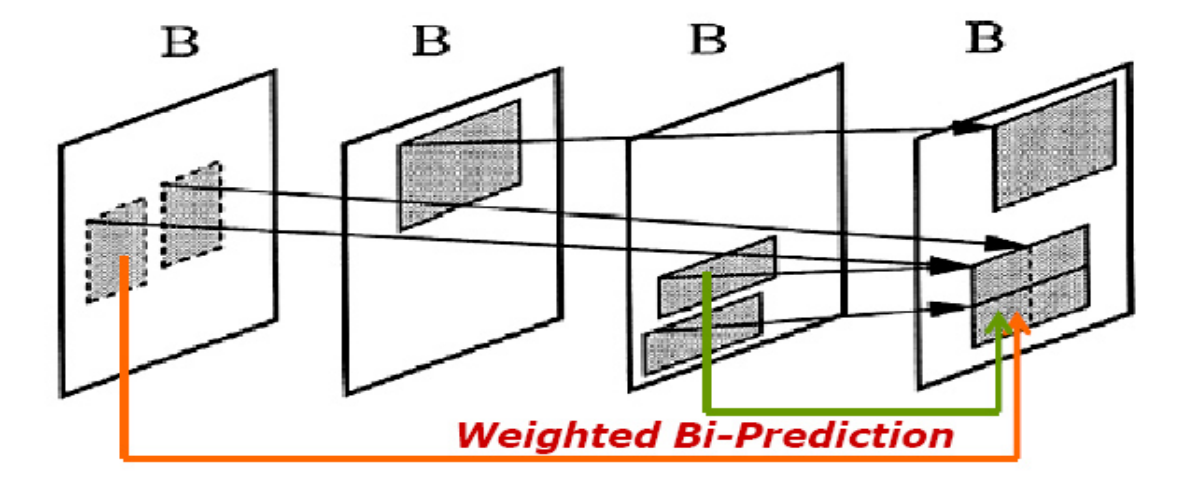


Multiple Reference Frames

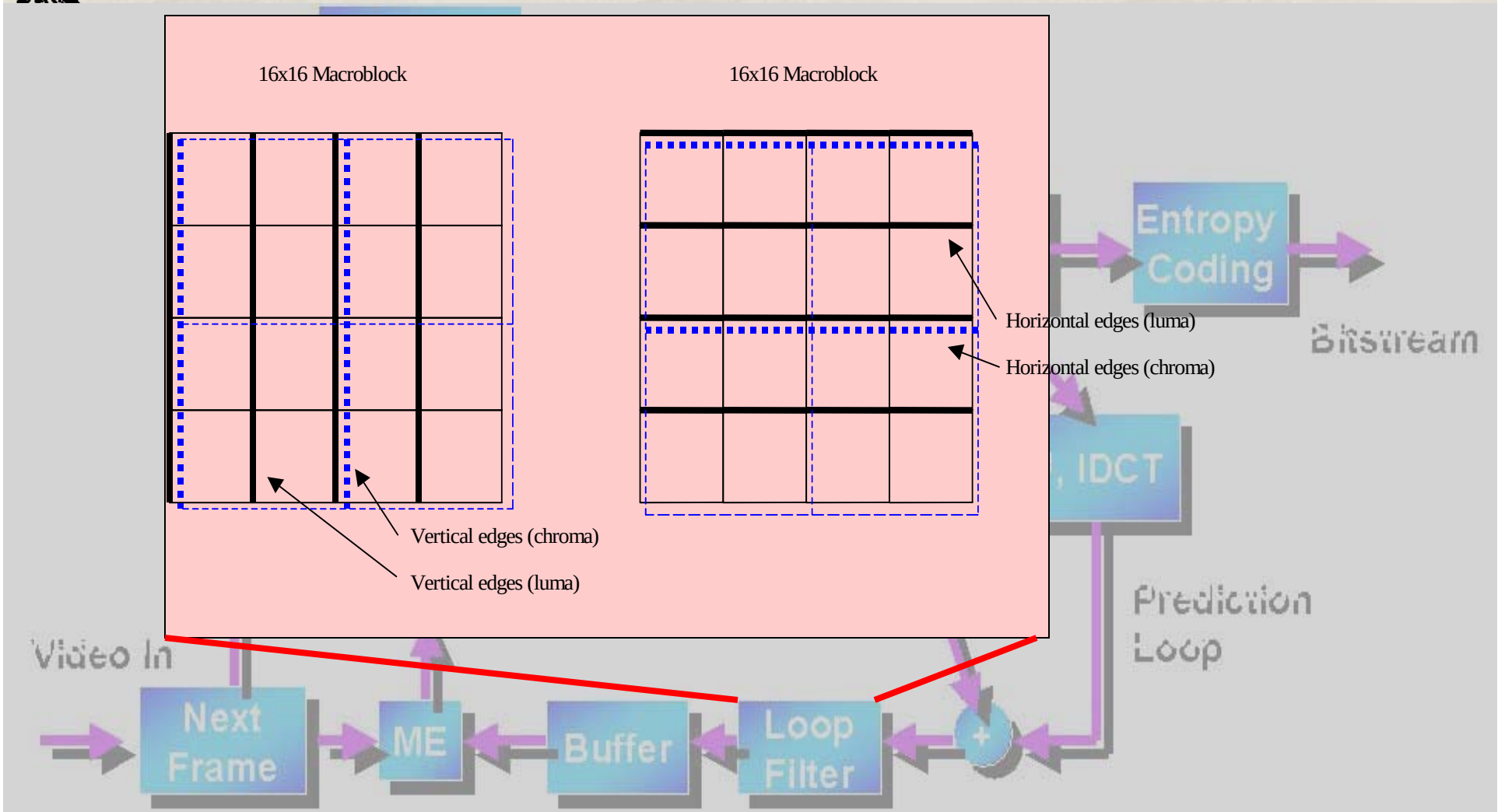
- Reference blocks



- Weighted bi-prediction



Innovation 5: In-Loop Deblocking



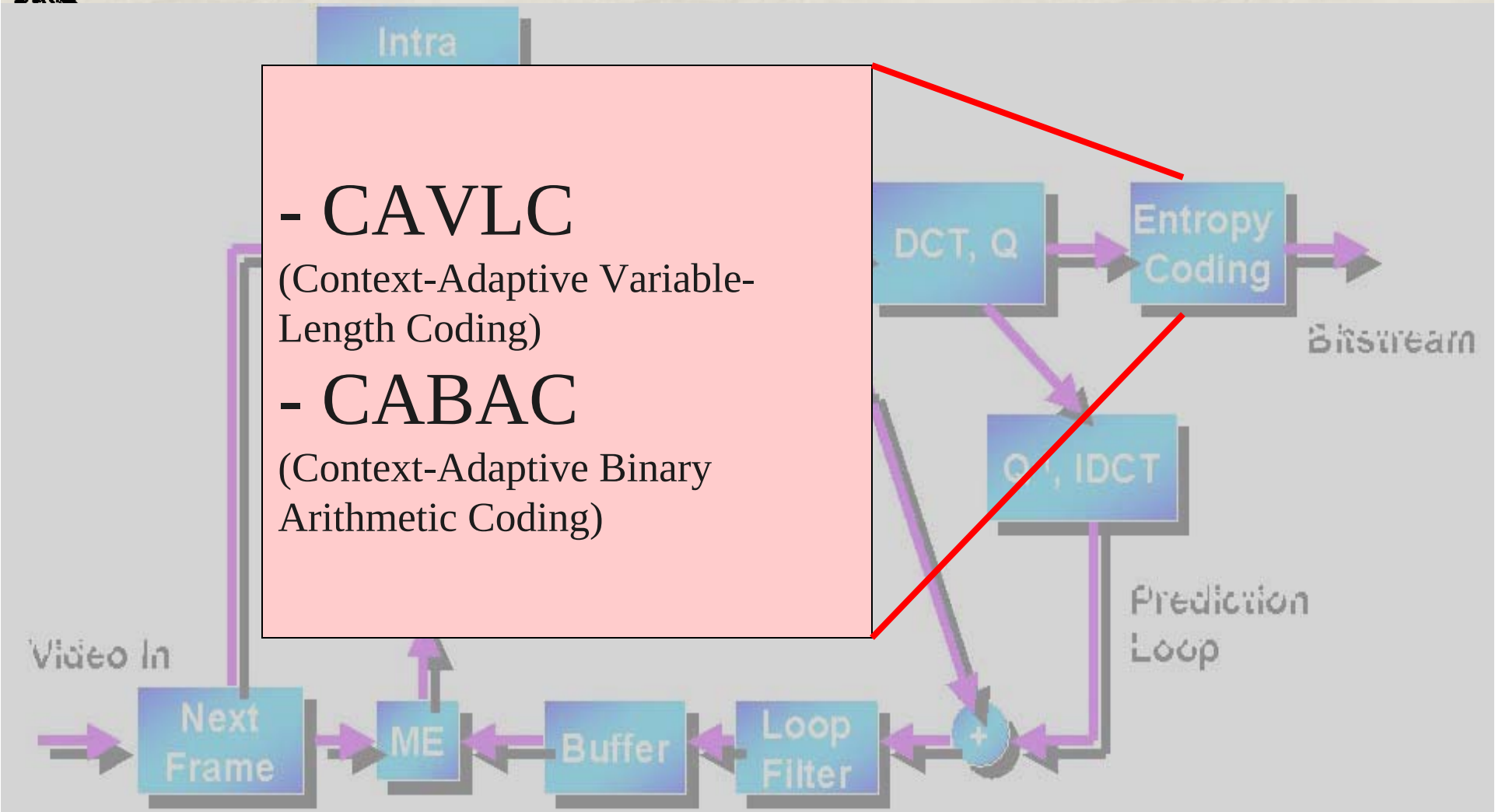
In-Loop Deblocking Filter

- Improves subjective visual quality
- Much better than post-filtering
- Highly context adaptive

Without loop filter

With H.264/AVC loop filter

Innovation 6: Two Entropy Coding Methods



- CAVLC

(Context-Adaptive Variable-Length Coding)

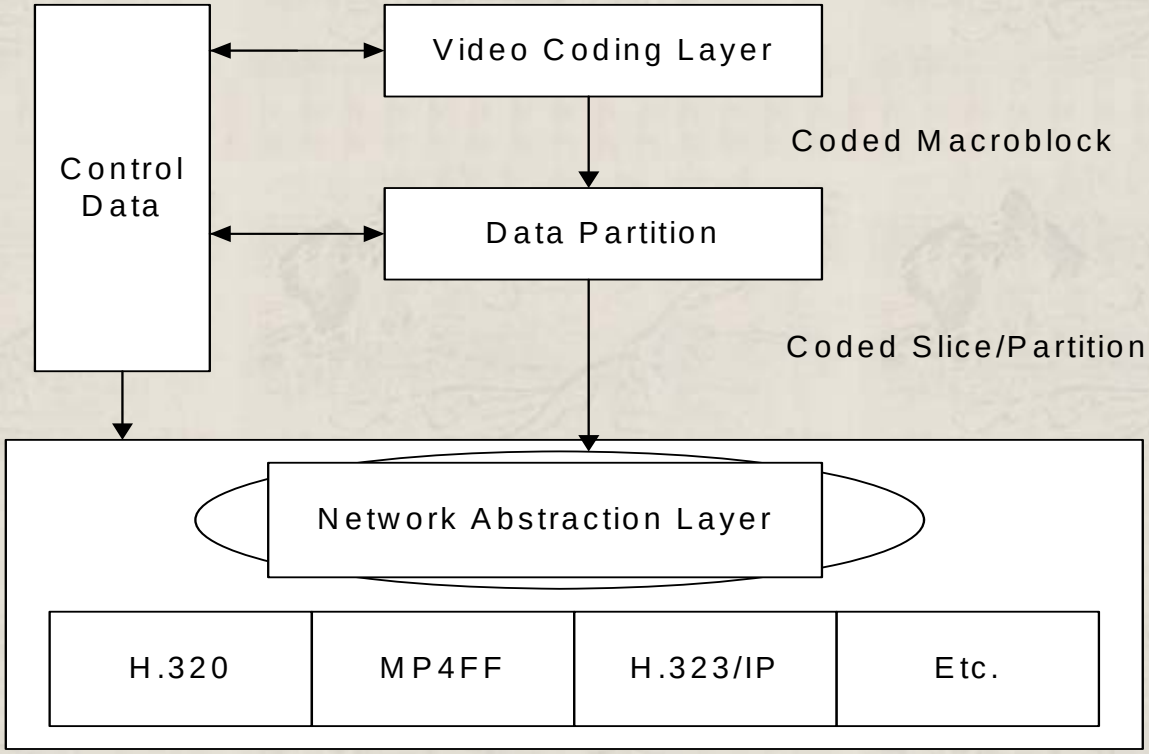
- CABAC

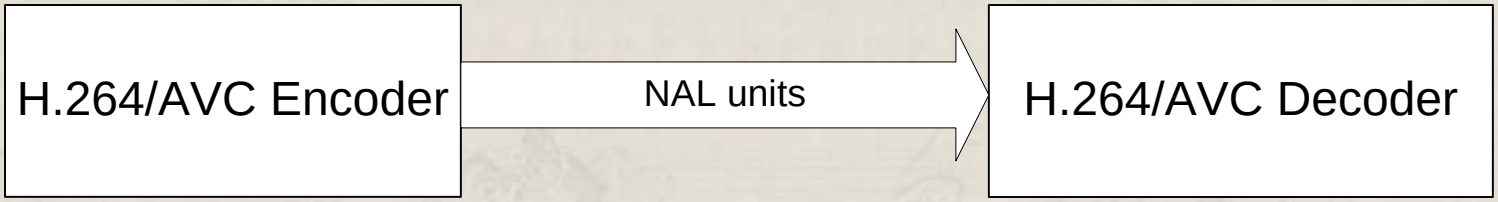
(Context-Adaptive Binary Arithmetic Coding)

H.264 Entropy Coding

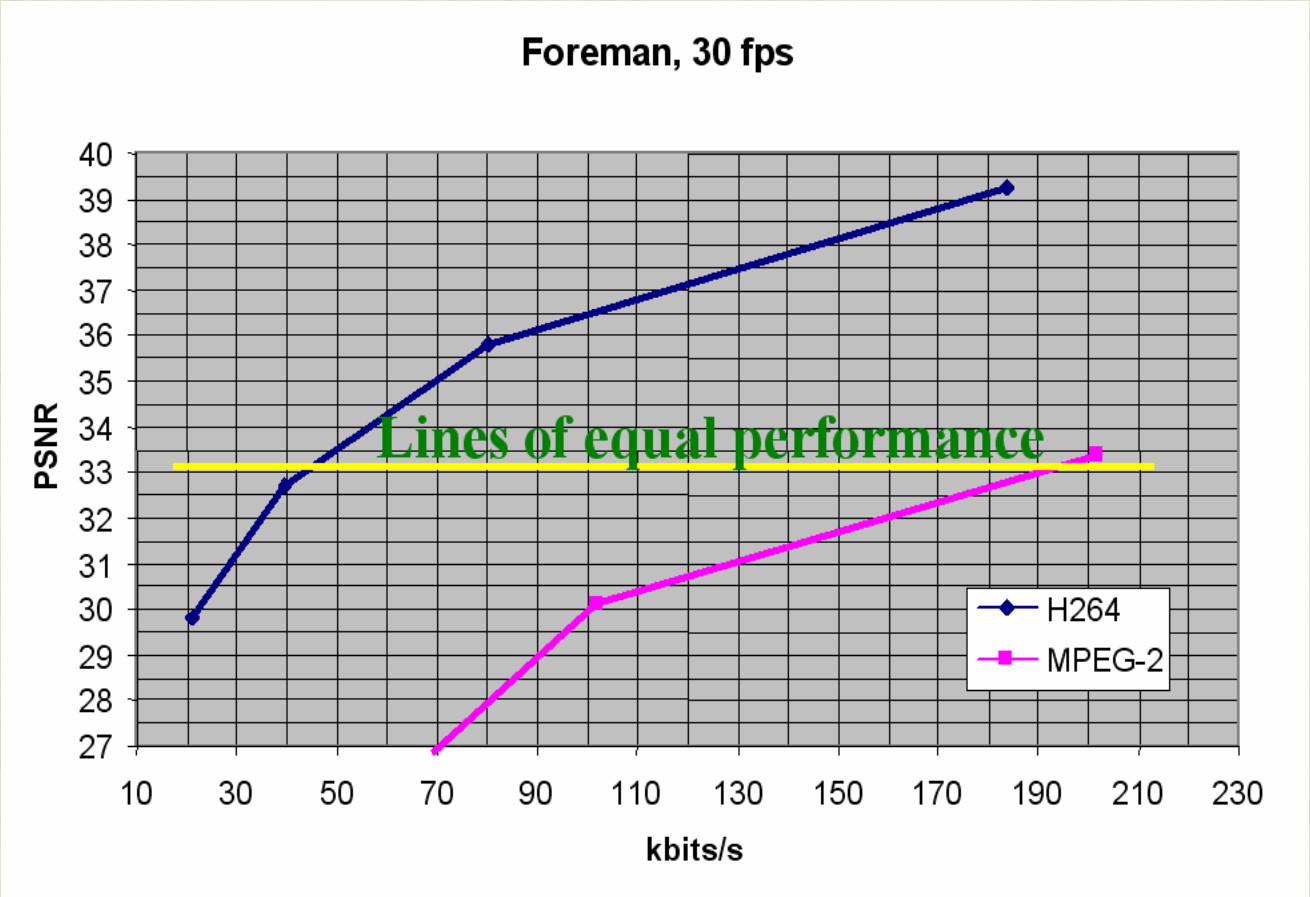
- Exp-Golomb Code
  - For all symbols except transform coefficients
  - Variable length codes with a regular construction, e.g.,
    0 -> 1; 1-> 010; 2 -> 011; 3 -> 00100; 4 -> 00101; 5 -> 00110
    6 -> 00111; 7 -> 0001000; 8 -> 0001001 …
- CAVLC (Context adaptive VLC)
  - For transform coefficients
  - No end-of-block, but the number of coefficients is encoded
  - Coefficients are scanned backwards
  - Contexts are built dependent on transform coefficients
- CABAC (Context-based binary arithmetic coding)
  - For transform coefficients
  - Uses adaptive probability models for most symbols
  - Exploiting symbol correlations by using contexts
  - Average bi-rate saving over CAVLC 10-15%

Innovation 7: Network Abstraction Layer





H.264 vs. MPEG-2: Low bitrate (1)

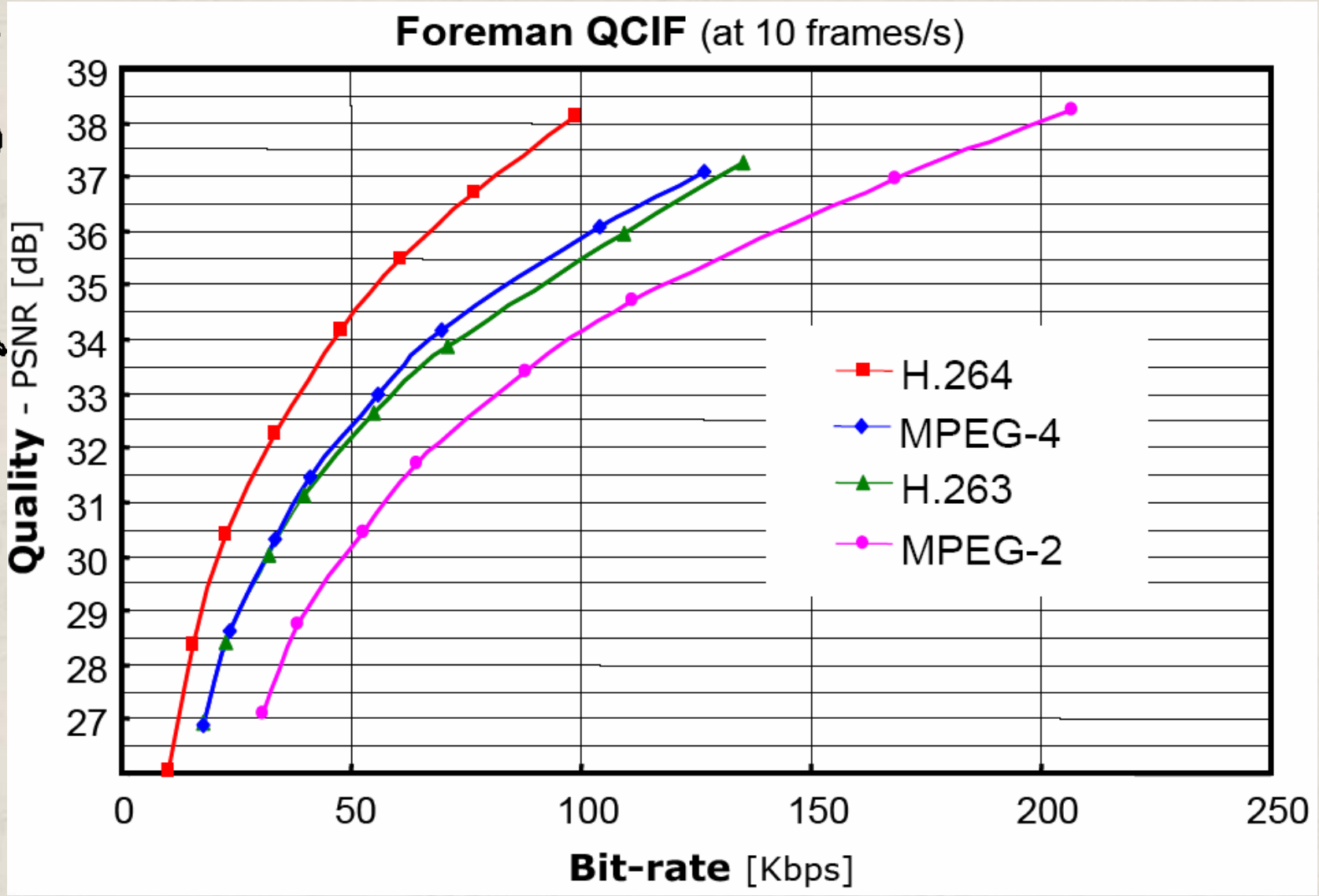


H.264 vs. MPEG-2: Low bitrate (2)

MPEG-2 203kbps

H.264 39 kbps

Comparison to Other Standards



Basic H.264 Profiles

- Baseline (Videoconferencing & Wireless)
  - I and P frames (no B frame)
  - Interlace
  - Adaptive frame/field
  - In-loop deblocking filter
  - ¼ -sample motion compensation
  - Variable block motion estimation
  - CAVLC
  - Some error resilience features, e.g., ASO, FMO
- Main profile (Broadcast)
  - All baseline features except enhanced error resilience features
  - B frame
  - CABAC
  - MB-level frame/field switching
  - Adaptive weighting for B and P picture prediction

Enhanced H.264 Profiles

- Extended Profiles (Streaming)
  - Main profiles + Error resilience - CABAC
  - More error resilience: data partition
  - SP/SI switching pictures
- High profile
  - Old name: *Fidelity-Range Extensions* (**FRExt**)
  - Main profile
  - Switchable 8x8 transform
  - Scaling matrix for subjective quality optimization
  - Implementation beyond Main Profile affects Intra prediction, transform, deblocking filter control, CABAC decoding

High Profile

- H.264/AVC standard finished 2003
  - ITU-T/H.264 finalized May, 2003
  - MPEG-4 AVC finalized July, 2003
- High profile
  - Initiated in July 2003 and finished in July 2004
  - Motivation: higher quality and higher rates
  - Consider more than 8 bits sequences, and various color spaces
  - Improved coding efficiency (bit-rate reduction): e.g., 12% for HD films and progressive HD video
  - Complexity issues:
    - No increase in computational requirements
    - Slight increase in memory requirements (CABAC, transform)
  - *No reason not to move to High profile !*

New Features in High Profile

- Larger transforms
  - 8x8 transform
  - Drop 4x8, 8x4, and larger transforms
- Quantization matrix
  - 4x4, 8x8, intra, inter trans. coefficients weighted differently
  - Full capabilities not yet explored (visual weighting)
- Coding in various space
  - 4:4:4, 4:2:2, 4:2:0, and monochrome
  - New integer color transform
- Efficient lossless interframe coding
- Film grain characterization for analysis/synthesis representation
- Stereo-view video support
- De-blocking filter display preference

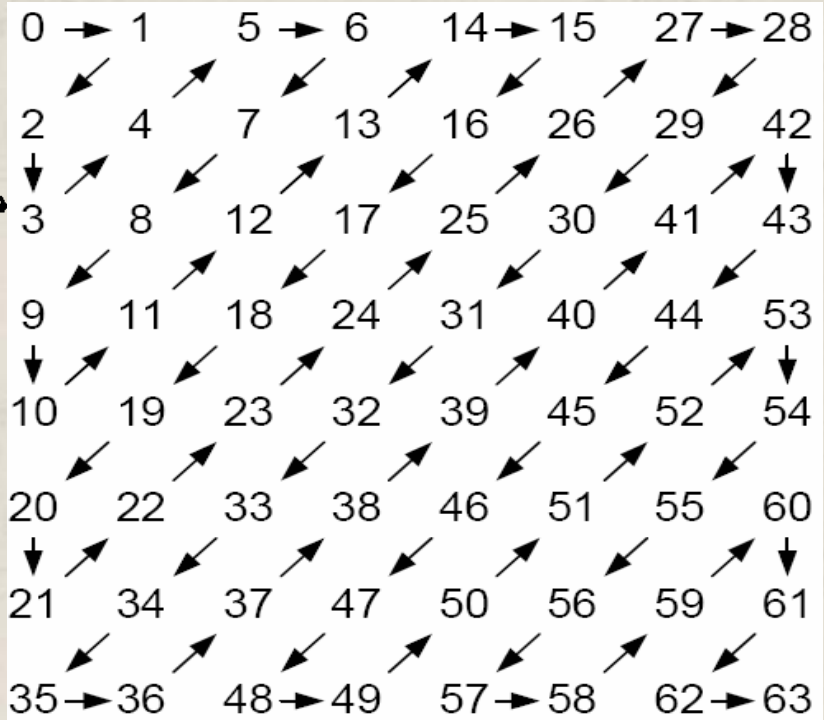
8x8 16-bit Transform

$$\begin{bmatrix} 8 & 8 & 8 & 8 & 8 & 8 & 8 & 8 \\ 12 & 10 & 6 & 3 & -3 & -6 & -10 & -12 \\ 8 & 4 & -4 & -8 & -8 & -4 & 4 & 8 \\ 10 & -3 & -12 & -6 & 6 & 12 & 3 & -10 \\ 8 & -8 & -8 & 8 & 8 & -8 & -8 & 8 \\ 6 & -12 & 3 & 10 & -10 & -3 & 12 & -6 \\ 4 & -8 & 8 & -4 & -4 & 8 & -8 & 4 \\ 3 & -6 & 10 & -12 & 12 & -10 & 6 & -3 \end{bmatrix} \cdot 1/8$$

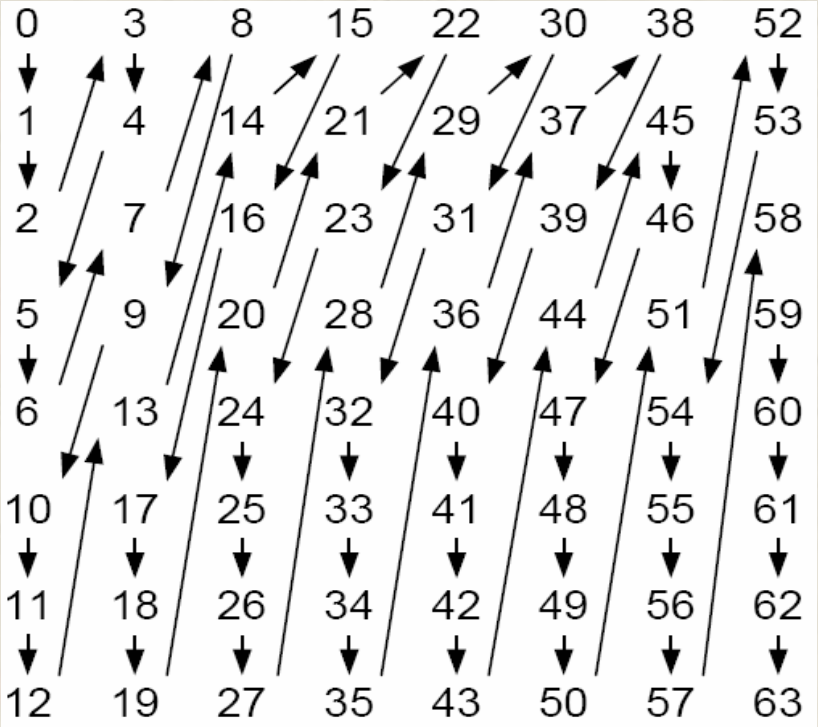
- Computational complexity
  - One 8x8 block has the same number of adds (64) and 4 extra shifts (20 vs. 16) compared with four 4x4 transform

8x8 Transform Coefficients Scan

- Two Scans
  - Different scan for frame/field coding



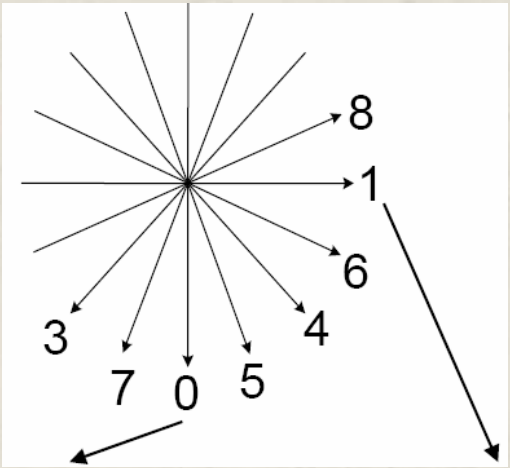
Frame scan



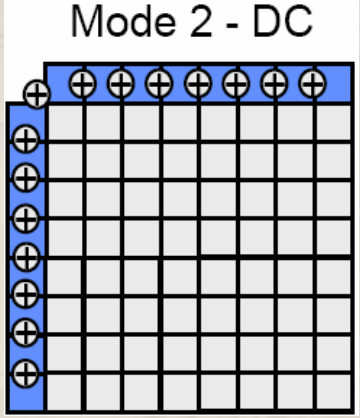
Field scan

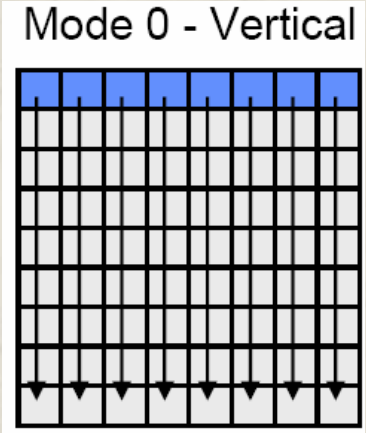
8x8 Intra Block Prediction

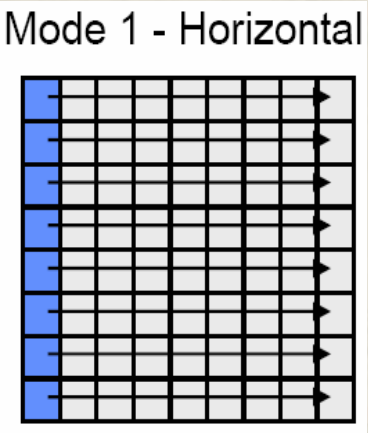
- Nine intra-prediction modes similar to the nine modes for 4x4 block prediction



&







Quantization Matrix

- Similar concept to MPEG-2 design
- Vary step size based on frequency
- Adapted to modified transform structure
- More efficient representation of weights
- Separate matrix for inter and intra
- Matrix can be included in picture/slice head information
- Eight downloadable matrices (at least for 4:2:0)
  - Intra 4x4 Y, Cb, Cr
  - Intra 8x8 Y
  - Inter 4x4 Y, Cb, Cr
  - Inter 8x8 Y

Reversible Integer Color Transform

- Color transform for YUV

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} .299 & .587 & .114 \\ -.147 & -.289 & .436 \\ .615 & -.515 & .100 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

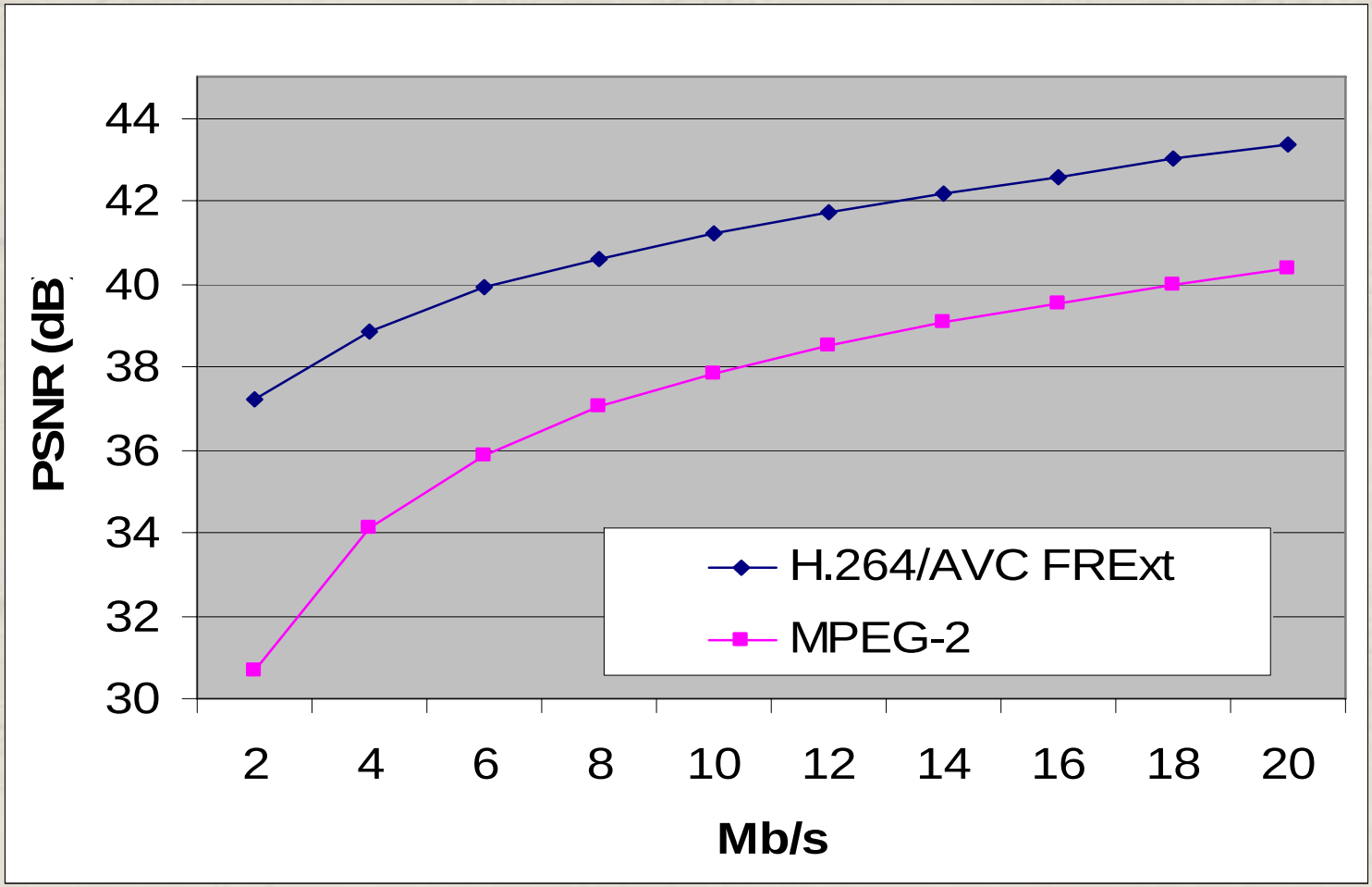
- Integer color transform (YCoCg)

$$\begin{bmatrix} Y \\ Co \\ Cg \end{bmatrix} = \begin{bmatrix} 1/4 & 1/2 & 1/4 \\ 1 & 0 & -1 \\ -1/2 & 1 & -1/2 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Other High Profile Details

- Deblocking filters:
  - Only control of filter is adjusted: do not filter for 4x4 blocks
  - Filter operation itself does not change
- CABAC
  - 61 contexts and their corresponding initial values
  - No change to CABAC engine
- Information signaling
  - 8x8 transform on/off flag at the picture head information
  - 8x8 transform on/off flag at per macroblock allows adaptive use

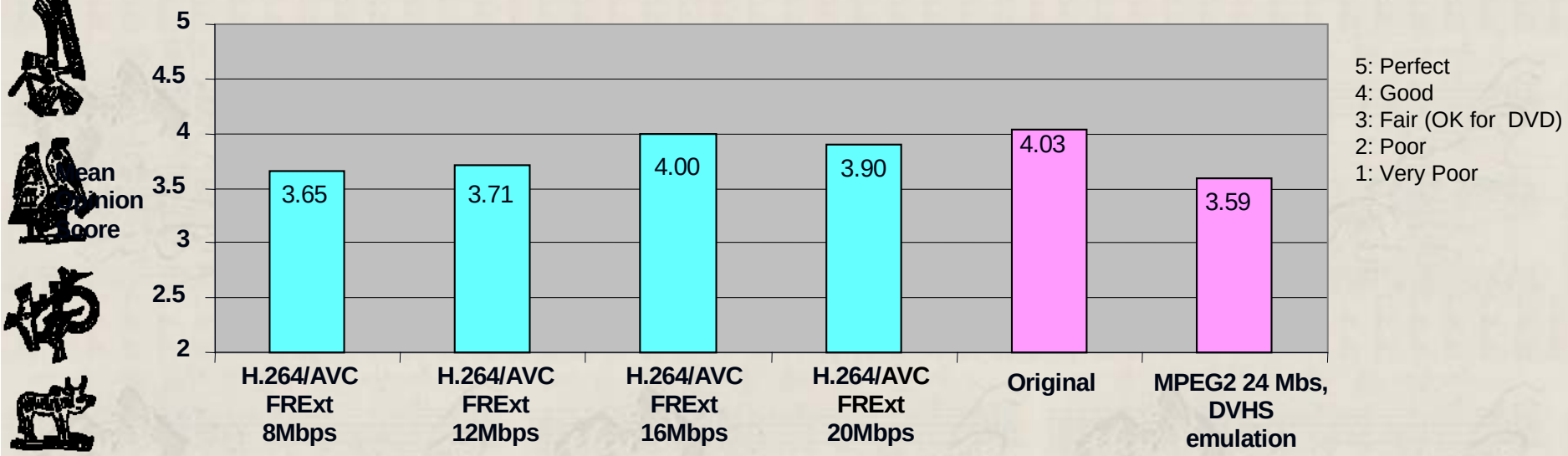
H.264 High Profile vs. MPEG2



BigShip HD sequence (1280x720, 720p)

Subjective Performance

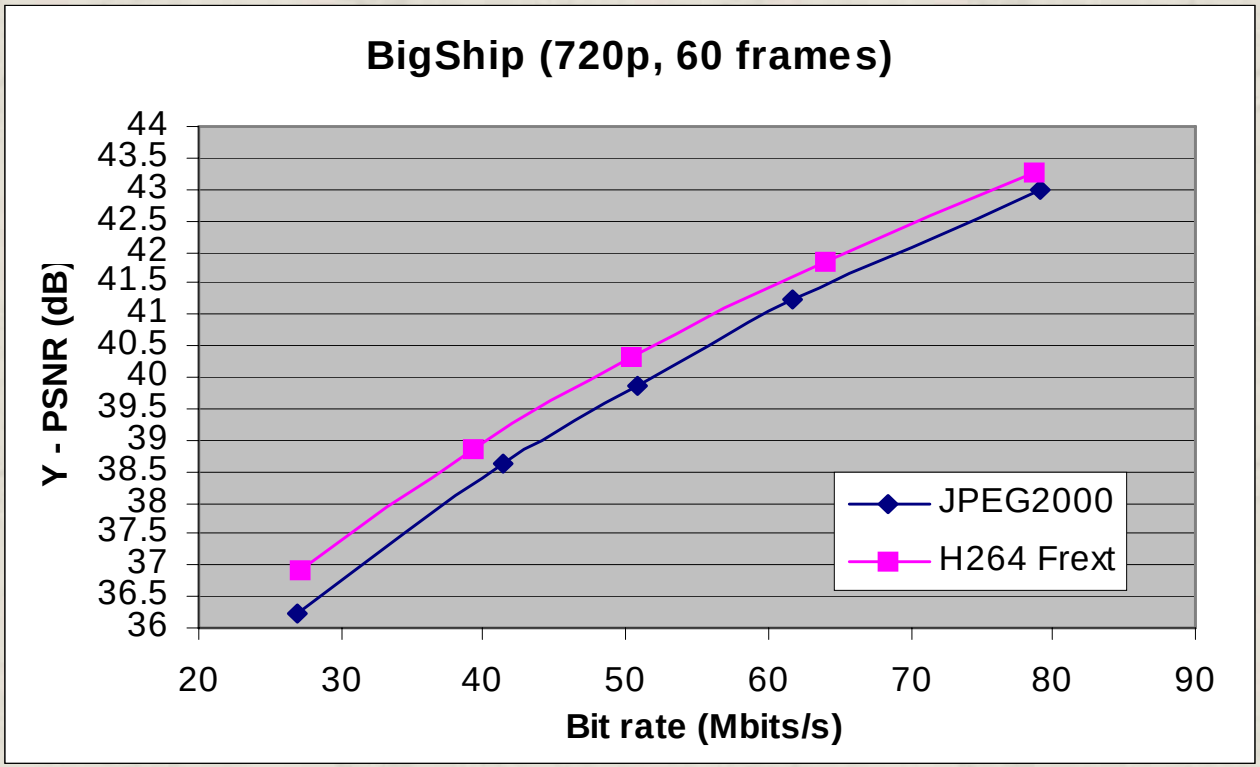
- Subjective tests by Blu-Ray Disk Founders of FRExt HP
  - 4:2:0/8 (HP) 1920x1080x24p (1080p), 3 clips.
  - Notional 3:1 advantage to MPEG-2
    - 8 Mbps HP scored better than 24 Mbps MPEG-2!
  - Apparent transparency at 16 Mbps!



*JVT-L033, M1116, Draft JVT Redmond report

High Profile I-Frame Coding vs. JPEG2000

- High profile I frame coding with RD-optimization model selection
- RD-optimized JPEG2000 coder used



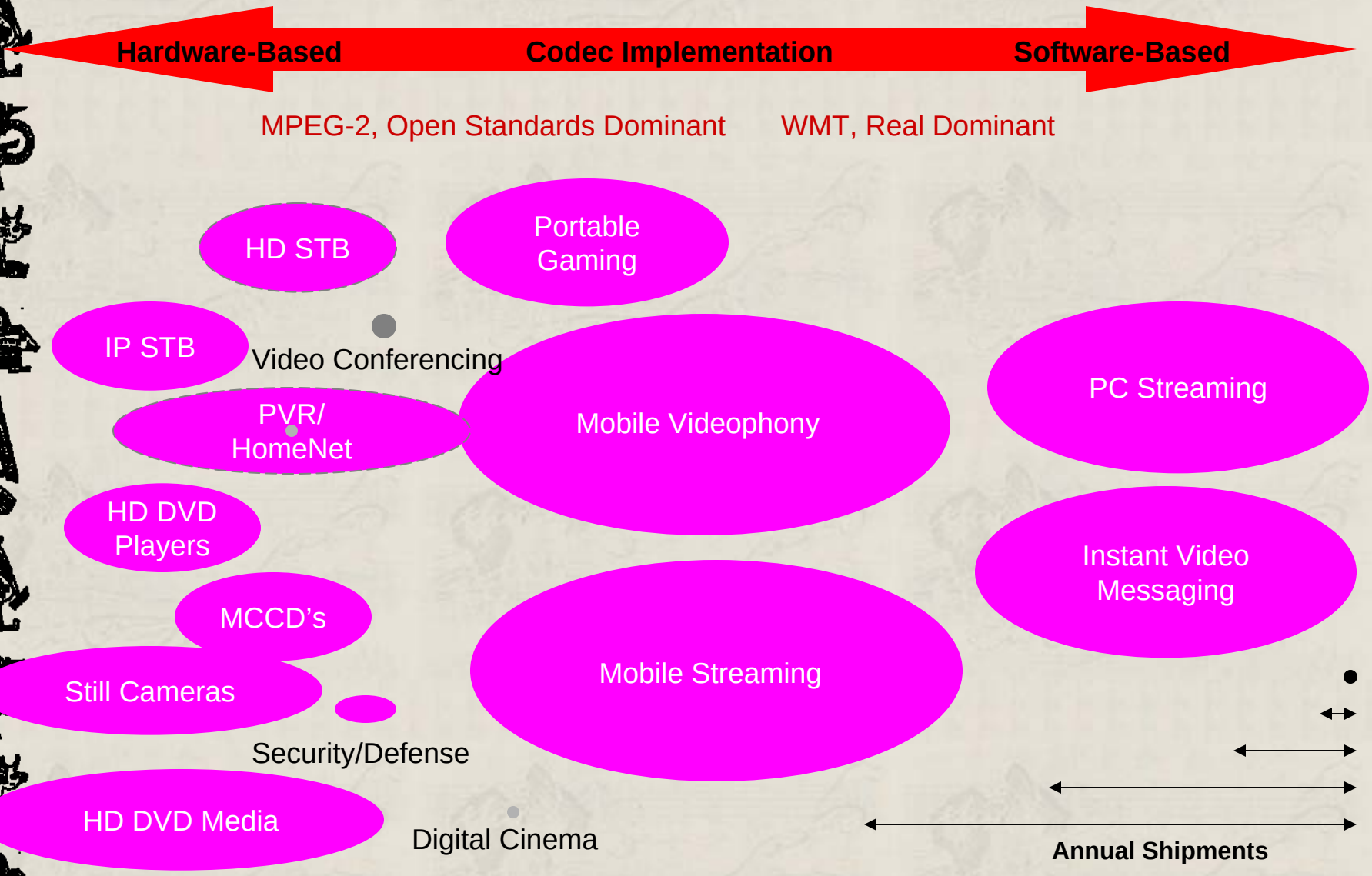
Challenging Problems

- Major problem: reduce the computational complexity without sacrificing the performance
  - Motion estimation
    - Fast motion search
    - Reference frames selection
  - Macroblock mode decisions
    - Seven inter modes, intra mode with prediction
    - Try all and select the best ?
    - Mode decision criterion needed
  - Etc.
- Implementation issues
  - Read time h.264 encoding and decoding
  - Hardware implementations
  - Etc.

Applications and Markets

- Storage
  - Video CD, DVD, Hard Disk, Web publishing
- Broadcast
  - Satellite, Cable, Terrestrial
- Conversational
  - Videoconferencing, Cell phones, PDAs
- Streaming
  - Video-on-demand, music video, streaming ads
- Future Applications! – unknown

H.264 Opportunities Map



Example: HD DVD Multimedia

- With H.264, put 2 hours of HD on DVD-9
  - Note: a 100-min HD movie fits in 8.25 GB @ 11 Mb/s
- Keep MPEG-2 skin
  - Systems, audio… minor change to DVD player
  - Small cost, big quality jump
- Even better with blue-ray when ready
  - Tech is "laser-agnostic"
- Studios can recycle catalog in HD
  - Double the money!!

Source: DVD-FAQ (Jim Taylor)

Format	Laser	Density	Data Rate	Encoding	Supporters
HD-DVD9	Red	9 GB	6-11 Mb/s*	H264/WM9	Warner
AOD	Blue	15 GB	10-20 Mb/s	MPEG2, …	Toshiba/NEC
Blue 1	Blue	17 GB	25 Mb/s	H264?	ITRI (Korea)
Blue-Ray	Blue	27 GB	10-30 Mb/s	MPEG2, …	LG, Philips, Pan., Sony, Sharp…
Blue 2	Blue	17 GB	10-30 Mb/s	H264?	Matsushita(Panosonic)?

H.264/AVC Organization Adoptions

- ITU-T systems adoption completed
- MPEG-2 and MPEG-4 systems & file format adoption completed
- IETF WG last call for RTP payload
- 3GPP2
  - adopted Baseline (restricted) for streaming and MMS
- HD DVD in DVD Forum: Mandatory player support
- Blue-Ray Disc Founders (BDF)
  - High Profile (HP) is their first choice beyond MPEG-2
- Digital Multimedia Broadcast in Rep. of Korea
- Mobile broadcast announcement in Japan
- France Terrestrial Broadcast announcement
  - H.264/AVC HD instead of MPEG-2
- Etc.

Companies Publicly Known to Implement the Standard

- Ahead Software / ATEME
- Amphion
- Apple Computer
- British Telecom
- Broadcom / Sand Video (chips)
- Conexant (chipset for STB)
- Cradle
- Deutsche Telekom
- DG2L
- Dicas
- DSP Research / W&W Communications
- Emblaze Group
- Envivio
- Equator
- FastVDO
- France Telecom
- Hantro
- Harmonic (filtering and motion estimation)
- HHI (PC & DSP encode & decode; demos)
- i3 Micro Technology
- iVast
- Intel
- KDDI R&D Labs
- Ligos
- LSI Logic / Videolocus
- Mainconcept
- Mcubeworks
- Media Excel
- Mobile Video Imaging
- Mobilygen
- Modulus Video (main profile levels 3 & 4 b'cast encoders & professional-use decoders)
- Moonlight Cordless
- Motorola
- Neomagic
- Nokia
- Oki Electric
- Optibase
- Packetvideo
- PixelTools
- PixSil Technology
- Polycom (videoconferencing & MCUs)
- Prodys
- Radvision (videoconferencing)
- Richcore
- Samsung (Terrestrial DMB receiver)
- Scientific Atlanta
- Setabox
- SkyStream Networks
- Sony (encode & decode, software & hardware, including PlayStation Portable 2004 & videoconferencing systems)
- ST Micro (decoder chip in '03)
- Tandberg (shipping with all videoconferencing endpoints since July '03, GW and MCU since Oct.)
- TandbergTV
- Tektronix
- Techno Mathematical
- Telesuite
- thin multimedia
- Thomson
- TI (DSP partner with UBV for one of two UBV real-time implementations)
- Toshiba
- Tuxia
- UB Video (demoed real-time encode and decode, software and DSP implementations)
- Videosoft / Vanguard Software Solutions (s/w, enc/dec)
- VideoTele.com (a division of Tut Systems)
- VCON
- Vqual
- W&W Communications / DSP Research

CAUTION: This information should be considered preliminary and should not be considered to be product announcements – only preliminary implementation work. It may be a while before robust interoperable implementations are well-established.

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