Digital Video Image Quality and Perceptual Coding

H. R. Wu and K. R. Rao

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I. Picture Coding and Human Visual System Fundamentals

1. Picture Coding and Human Visual System Fundamentals

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Chapter 1 Outline

1.1 Introduction to Digital Picture Coding
1.2 Characteristics of Picture Data
1.3 Compression and Coding Techniques
1.4 Picture Quantization
1.5 Rate-Distortion Theory
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1.1 Introduction to Digital Picture Coding

- Digital versus Analogue
  - Advantages
    - High Picture Quality
    - Portability/mobility
      - Storage and transmission over existing networks
  - Disadvantages
    - Large storage and transmission requirements
      - e.g. NTSC motion video 720 x 480 pixels @ 30 fps with 4:2:2 format requires 20.8 Mb/s bandwidth.
      - A 30 second video clip occupies 624 Mb (standard CD).

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- Compression: a practical necessity for digital pictures
  - Reduces storage and transmission requirements
- How?
  - Compression reduces redundancies in digital pictures

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- Statistical redundancies may appear
  - Spatially in adjacent pixels
  - Temporally in adjacent picture frames
  - Spectrally in different frequency and orientation bands
- Psychovisual Irrelevancy
  - Exists due to the limitations of the Human Visual System (HVS)
    - Optical (human eyes)
    - Cortical (the human brain)

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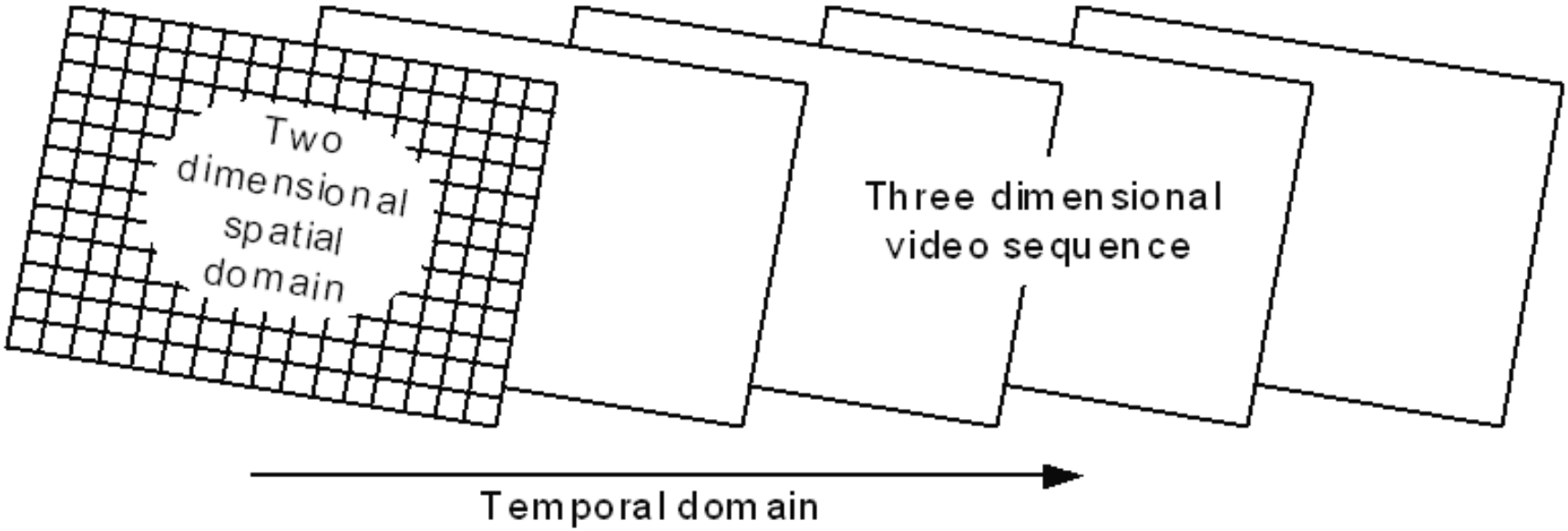
Spatial and Temporal Domains



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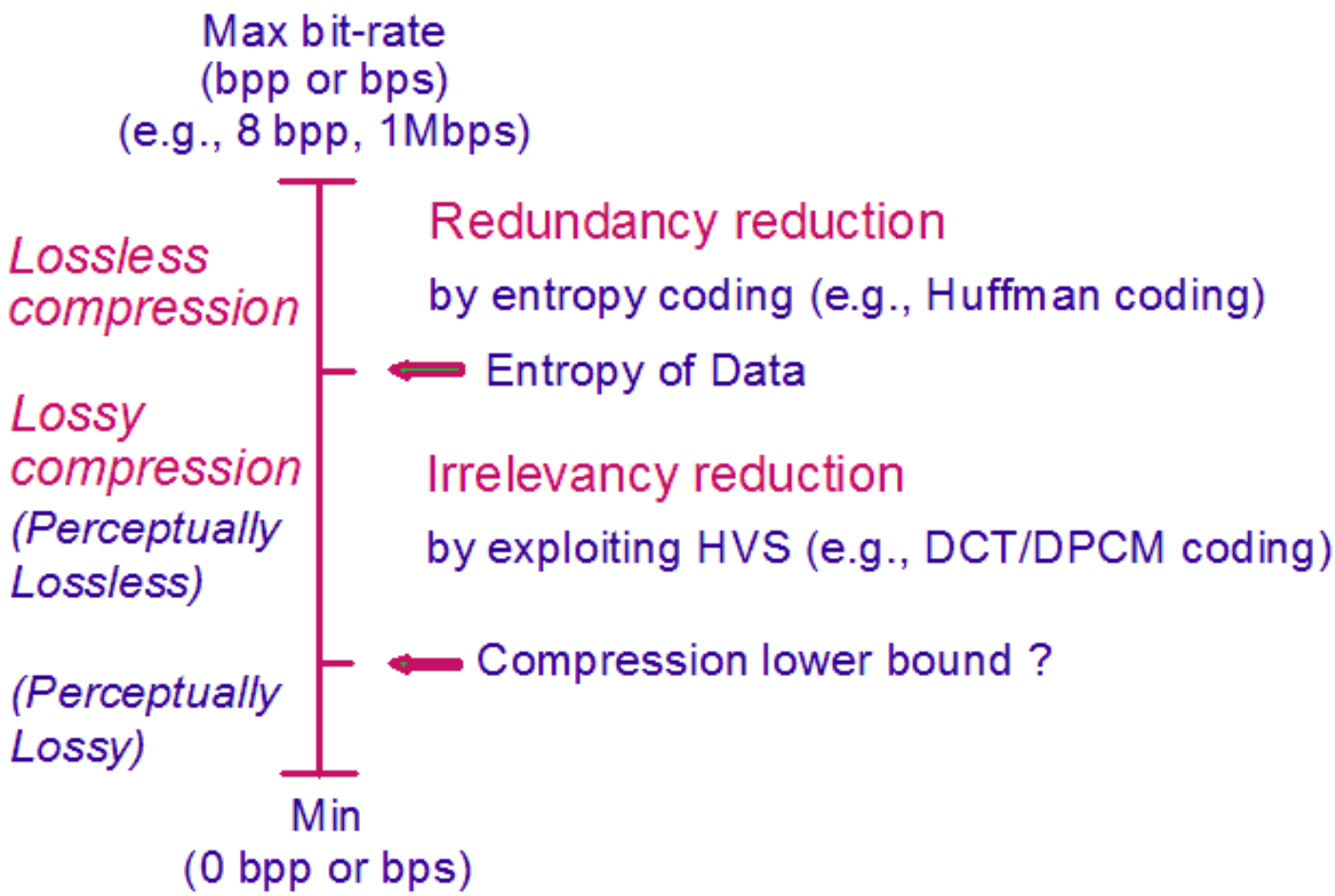
Digital Picture Compression Fundamental Concepts



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- Lossy and Lossless Compression
  - Lossless
    - ***No*** information loss, ***low*** compression
  - Lossy
    - ***Some*** information loss, ***high*** compression
- Quality/Distortion measures
  - Quantify coding quality/errors in lossy compression schemes
  - Objective and subjective measures

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- Subjective distortion measure
  - Employs human observers, gauges perceived quality/distortions
  - Impractical for general purposes
- Objective distortion measure
  - Utilises functional metric to determine quality/distortions
  - Statistical metric. e.g. MSE, PSNR
  - HVS bases metric. e.g. PBIM, VQM

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1.2 Characteristics of Picture Data

- Digital Image Data
  - Derived from sampling continuous image field data over an area of *M x N*
  - Individual digitized element is referred to as a pixel (or pel)
  - Each pixel has 2^q discrete levels per colour channel
  - q is typically 8 which corresponds to one byte (256 levels) per colour channel per sample

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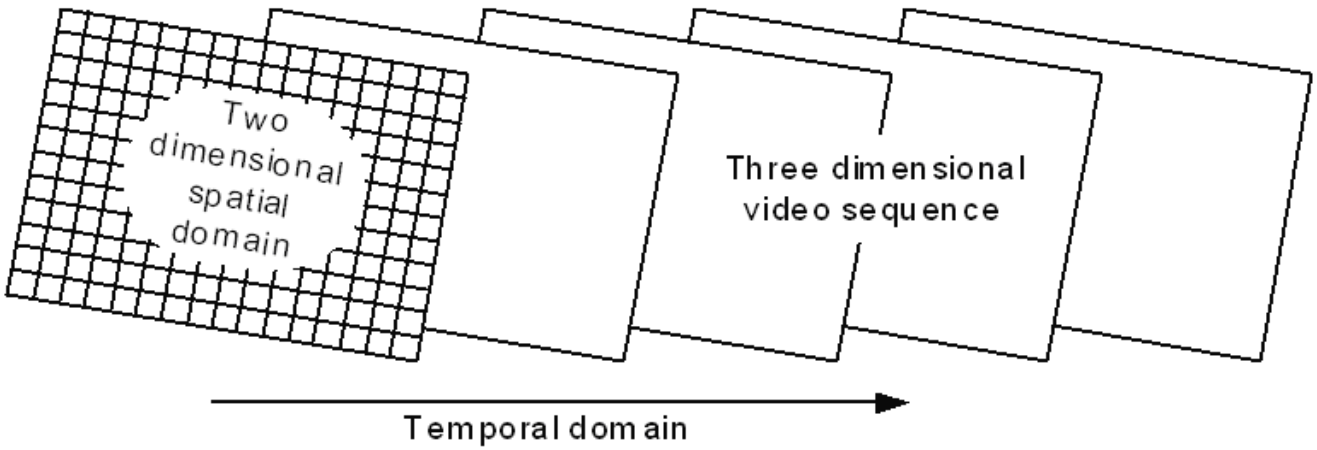
1.2.2 Digital Video Data

- Digitization of video
  - Sampled spatially as with digital image
  - Sampled at regular temporal interval to obtain multiple image frames



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- Colour Spaces
  - *RGB* (Red, Blue and Green)
  - $Y_d C_b C_r$ (1 Luminance, 2 Chrominance)
- RGB Colour Space
  - For source capture and display
  - Corresponds to the Red, Blue and Green elements in display devices. e.g. CRT, LCD
  - Each channel has equal bandwidth – inefficient for transmission and storage

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- $Y_d C_b C_r$ Colour Space
  - For storage, transmission and processing
  - Isolates luminance component (Y)
    - Human vision is more sensitive to luminance than colour

$$
\begin{aligned}
Y_d &= 219[0.229R' + 0.587G' + 0.144B'] + 16 \\
C_b &= 224[-0.169R' - 0.331G' + 0.500B'] + 128 \\
C_r &= 224[0.500R' - 0.419G' + 0.081B'] + 128
\end{aligned}
$$

R', ***G'*** and ***B'*** are normalised to 1

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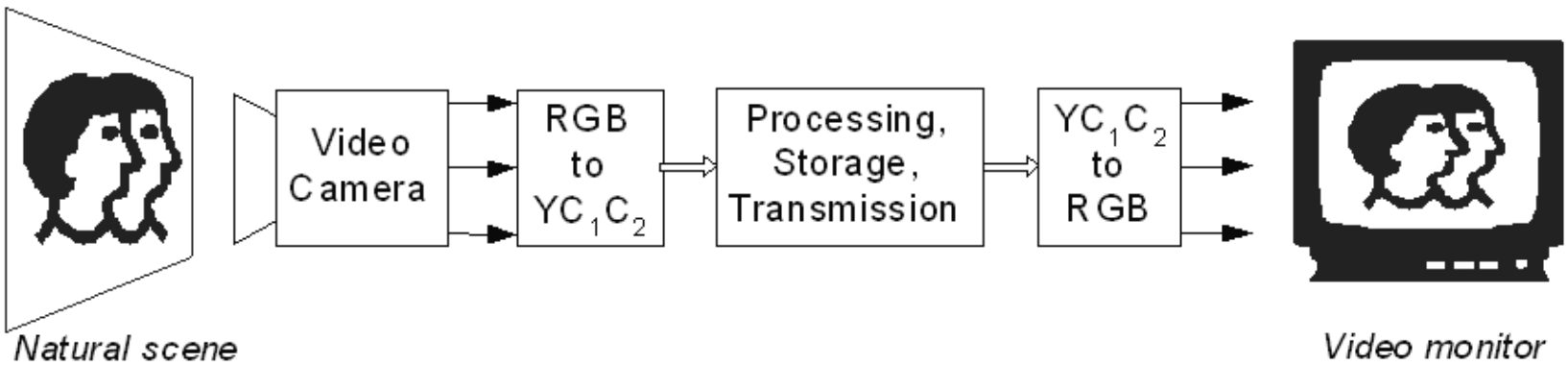
Digital representation of colour format conversion of natural video stream



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- $Y_d C_b C_r$ Operational Ranges
  - $16 \leq Y_d \leq 235$
  - $-112 \leq C_b, C_r \leq 112$
- $Y_d C_b C_r$ Component Resolutions
  - Full resolution (4:4:4)
  - Half resolution (4:2:2)
  - Quarter resolution (4:2:0)

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1.2.2 Statistical Analysis

- Design of coding system is dependent on statistical property of target images
- Correlation implies similarity
  - High correlation in data → high compression
- Variance implies difference
  - High variance in data → low compression

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1.3 Compression and Coding Techniques

- Entropy Coding
  - Shannon's first theorem
    - Describes the minimum bits required, ***H(x)***, to represent some source data, ***x***, with ***m*** number of symbols having a probability distribution, ***p***.

$$H(x) = -\sum_{i=1}^{m} p(x_i) \log_2 p(x_i)$$

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- Entropy coders
  - Huffman – block oriented
  - Arithmetic – stream oriented
  - Utilise variable length codes
    - More efficient than fixed length codes

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1.3.2 Predictive Coding

- Rationalè for predictive coding
  - high correlation → low prediction errors
  - low prediction errors → lower entropy
- Applicable to lossy and lossless coding
  - Lossless coder
    - LOCO (JPEG-LS core), CALIC
  - Lossy coder
    - Differential Pulse Code Modulation (DPCM) for motion compensated video
    - Pulse coding of DC coefficients in JPEG/MPEG

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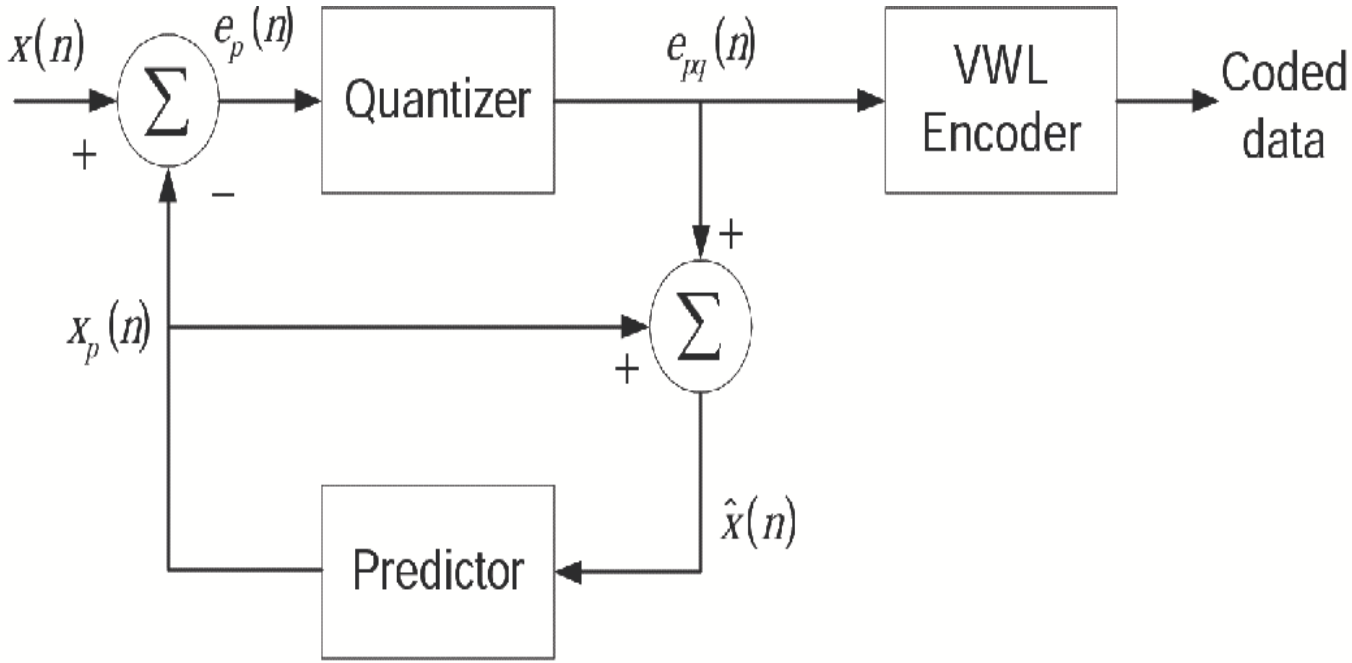

Closed loop DPCM encoder with Variable Word Length (VWL) coding

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1.3.3 Transform Coding

- Discrete Cosine Transform (DCT)
  - Derived from DFT
  - N-point can be extended to 2N-point (Mirroring)
  - Functional definition of 2-D DCT

$$X_{DCT}[u,v] = \frac{4}{N \times M} c[u]c[v] \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} x[n,m] \cos\left[\frac{(2n+1)u\pi}{2N}\right] \cos\left[\frac{(2m+1)v\pi}{2M}\right]$$

$$c[u], c[v] = \begin{cases} \frac{1}{\sqrt{2}} & u, v = 0; \\ 1 & otherwise. \end{cases}$$

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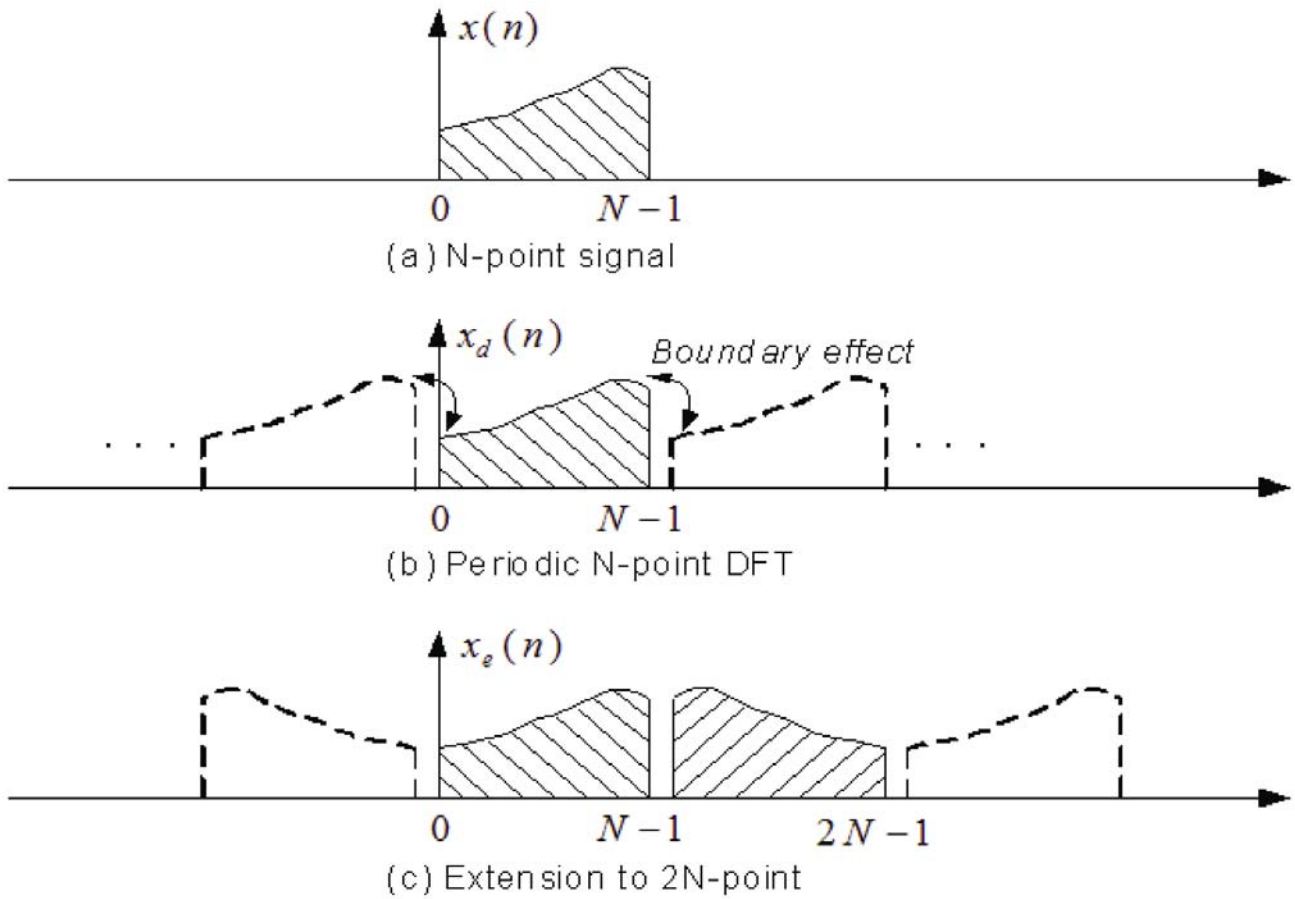
Signal extension. *A)* input signal. *B)* N-point DFT boundary effect. *C)* symmetric even extension (mirroring)



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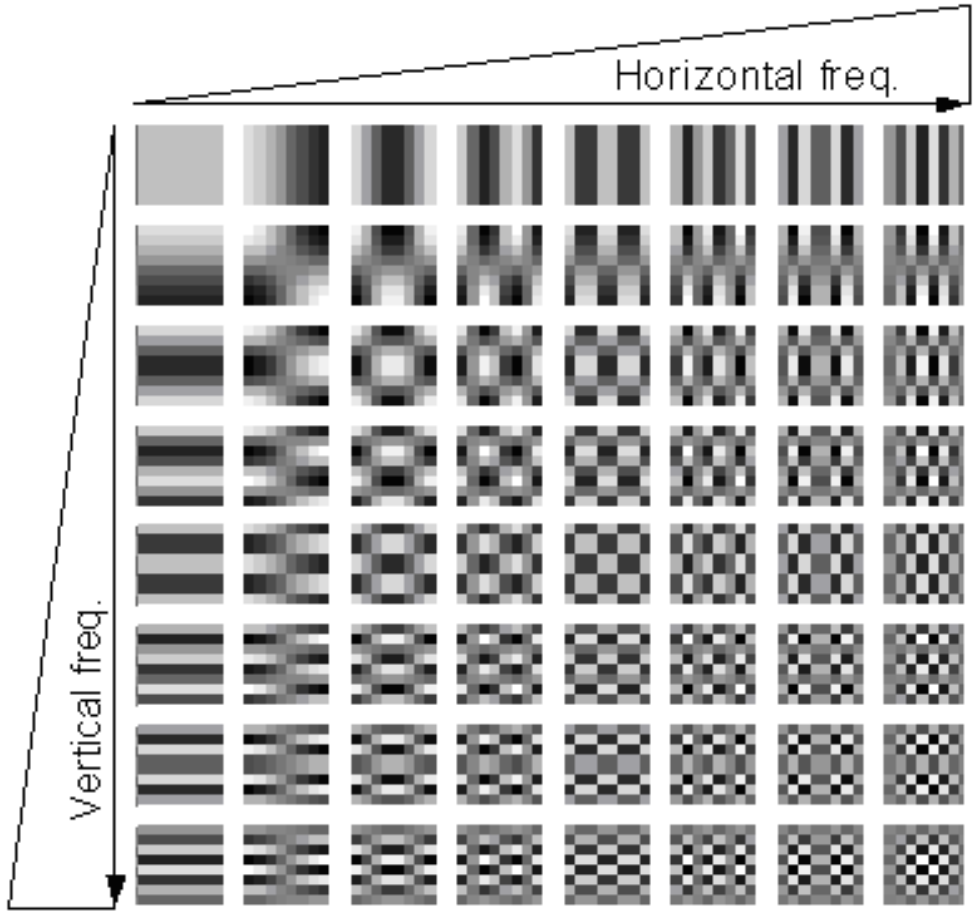
8x8 DCT Basis Image



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- Separable transform
  - 2-D DCT obtained through cascade of 1-D DCT
- Fast algorithm implementation
  - Only for 2^n-point DCTs
- Produces visually undesirable blocking artifacts at low bitrates.

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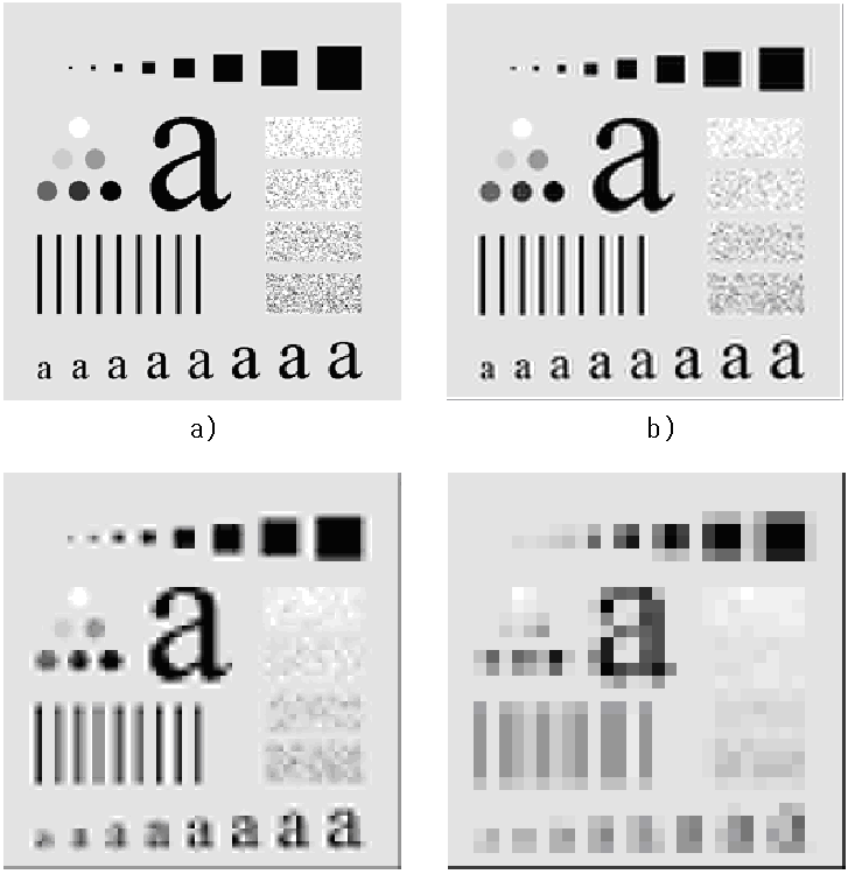
Blocking artifacts from DCT



a) Test image

b) Inverse DCT with 4x4 low frequency coefficients

c) Inverse DCT with 2x2 low frequency coefficients

d) Inverse DCT with DC coefficients only

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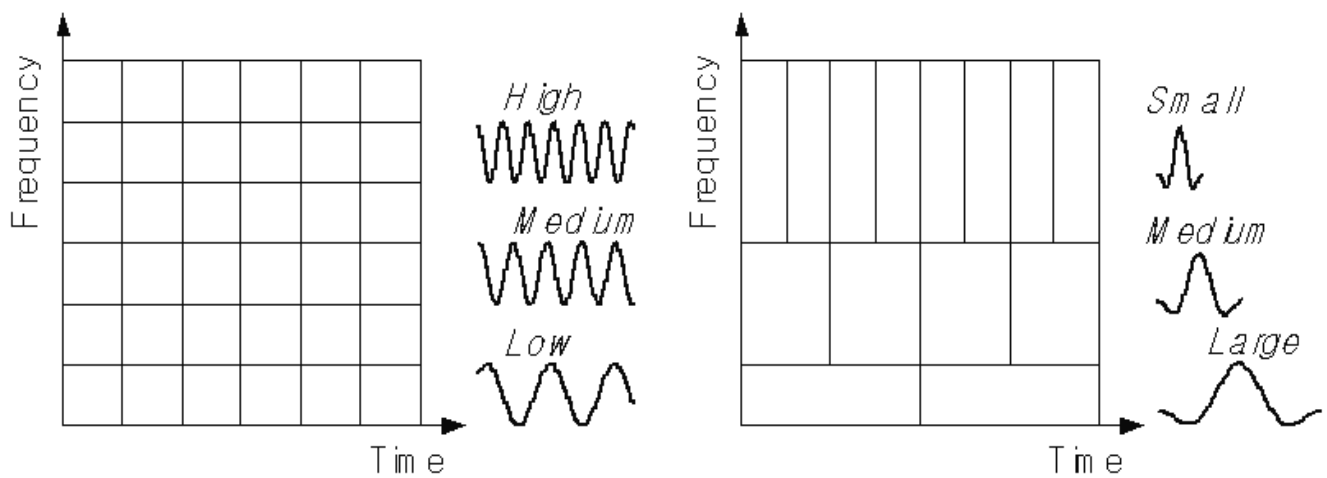
1.3.3.2 Discrete Wavelet Transform

- DWT is localised in space
- DWT more suited than DFT in dealing with non-stationary signals

Below: time-frequency resolution of DFT and DWT



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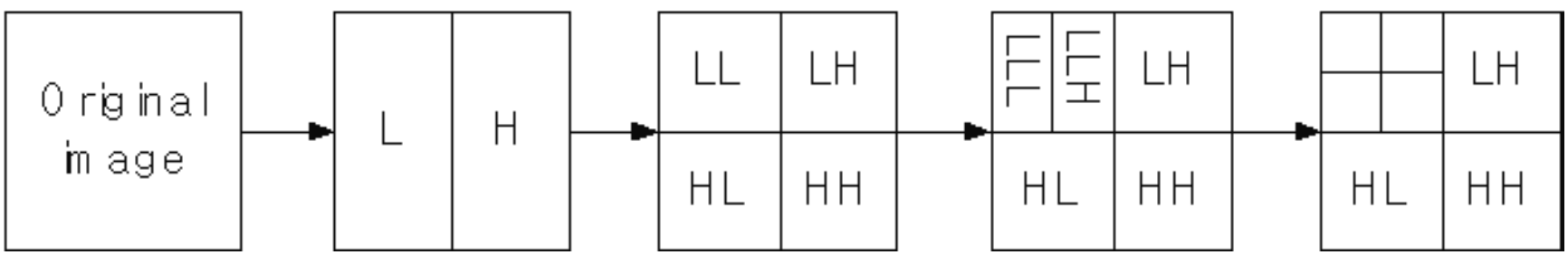
DWT

- Generally implemented in dyadic structure
  - 2 band filters, high-pass and low-pass
- Multi-resolution representation
  - Obtained through successive Iterative filtering of low-pass band



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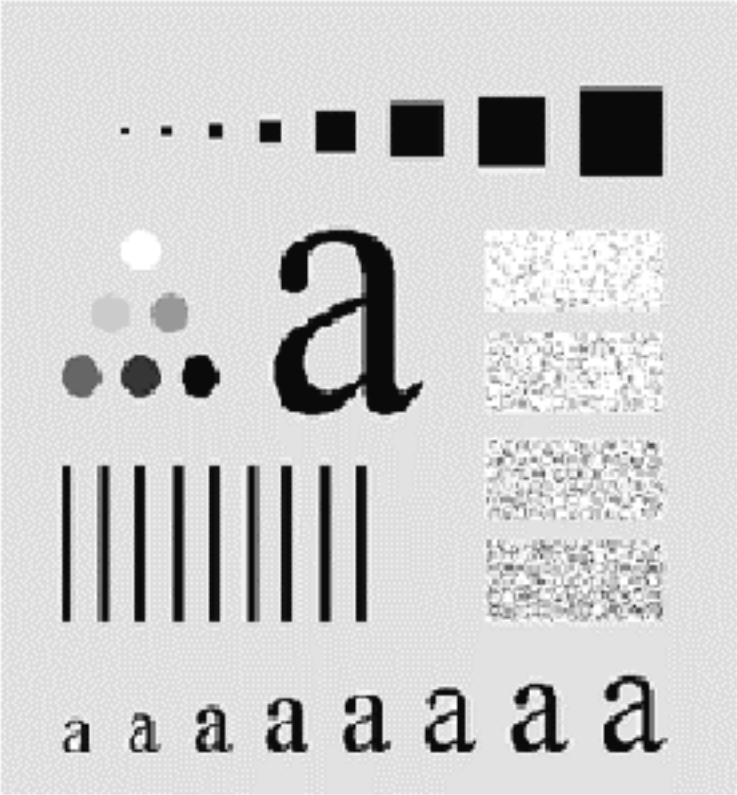

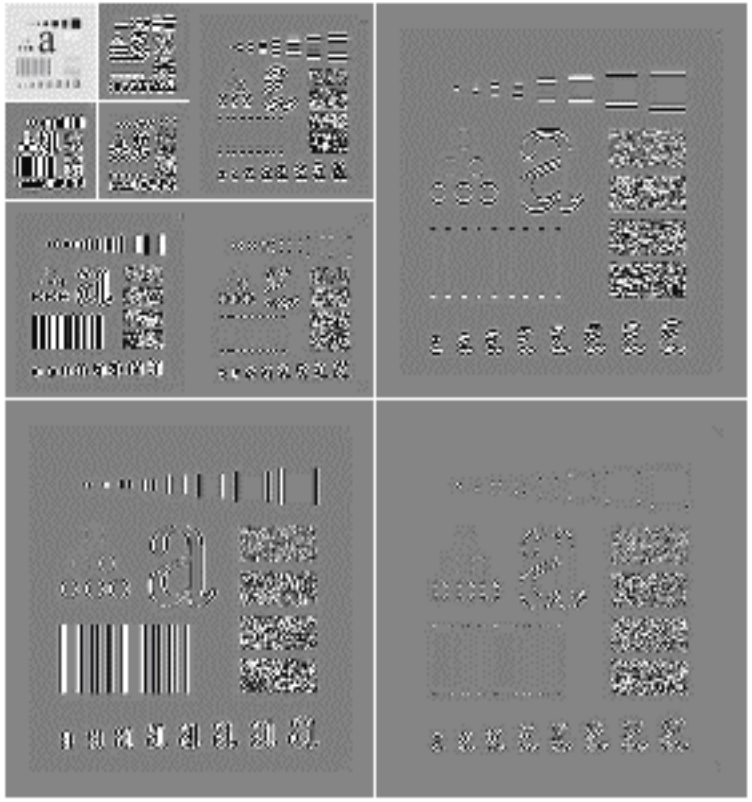

Left: Test Image
Right: 3 level spectral image

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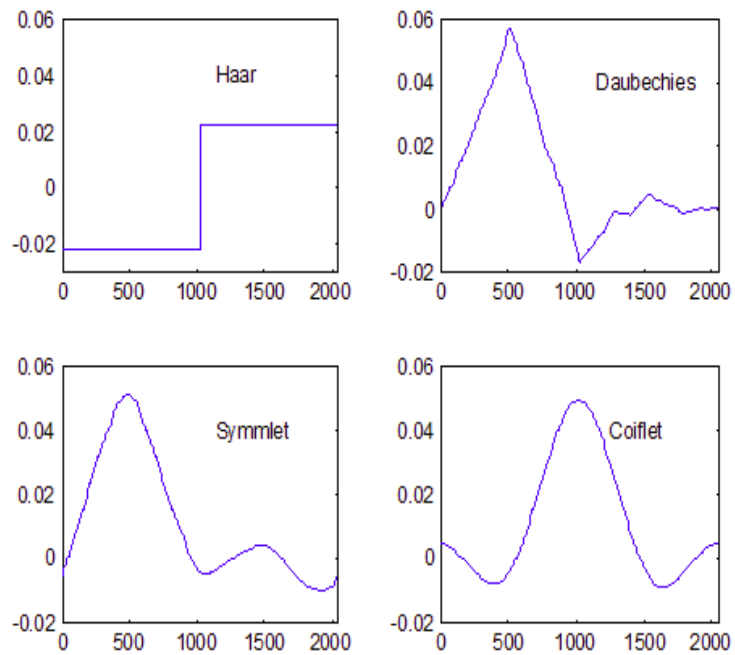
DWT

- DWT may use any number of filters (right)
- *Haar* filters - Simplest filter set
- For picture coding, spline filters are commonly employed



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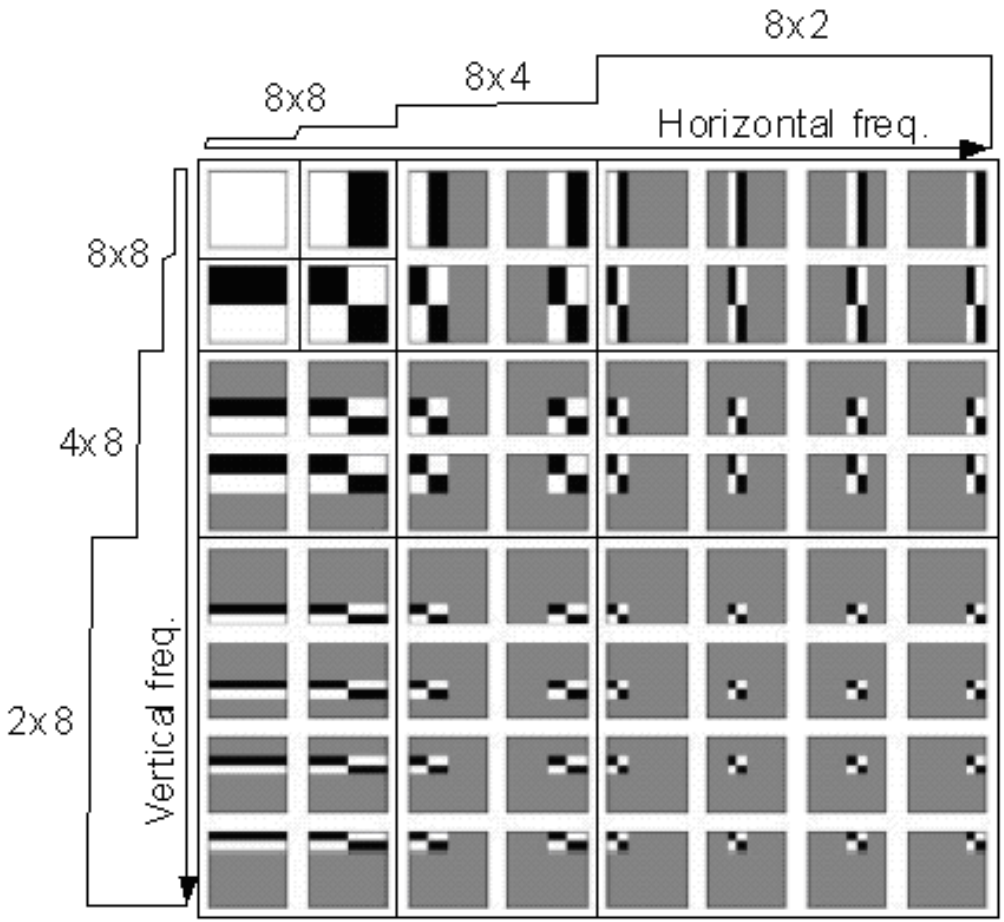
Discrete Haar Transform 8x8 basis image



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- Dyadic wavelet transform matches well with psychoviual models
  - Produces coded images with superior visual quality at medium and high bitrate
- Distortions in DWT coded images
  - blurring and ringing artifacts at low bitrates

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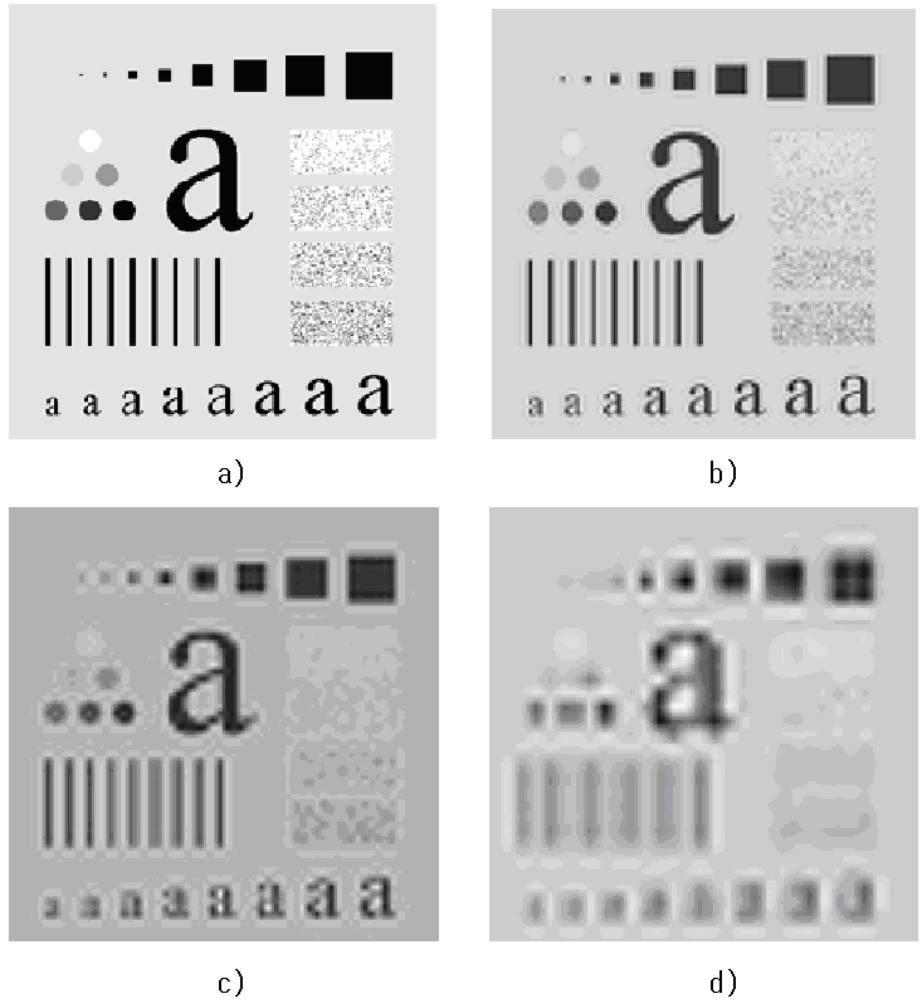
Blurring artifacts in 3 level wavelet transform

a) Test image
b) DWT image without level 1 coefficients
c) DWT images without levels 1 and 2 coefficients
d) DWT images with only the low-pass (LL) band coefficients



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1.4 Picture Quantization

- Maps *K* inputs to *L* outputs
- Memory and Memoryless
  - Quantization is dependent and independent of other causal sample data, respectively
- Deadzone quantiser
  - Located about the mean value of an image, typically zero
  - Larger step size within the deadzone reduces variance and improves entropy coding

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- Uniform Quantizer
  - Constant step size
  - Mid-rise or mid-tread
- Non-uniform quantizer
  - Variable step size
  - Outputs are dependent on the PDF of inputs

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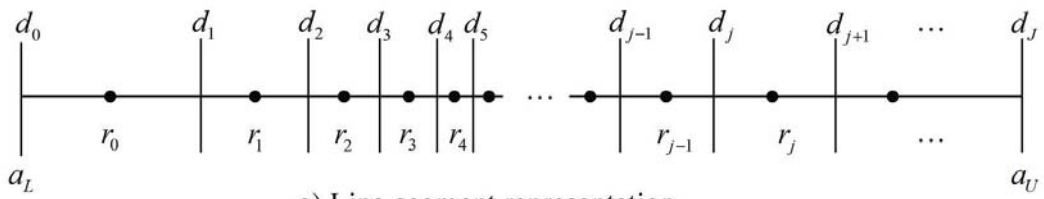
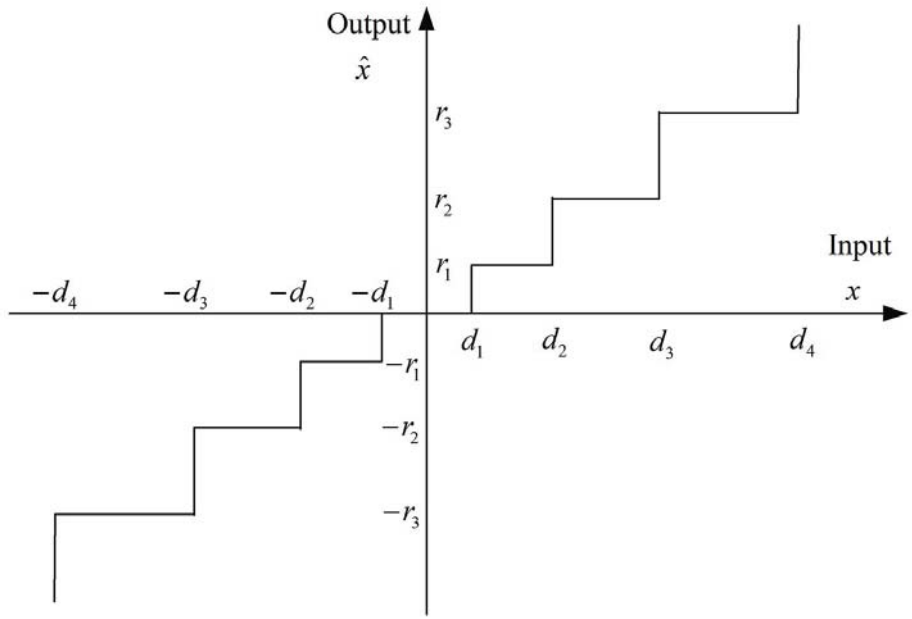
Non-uniform quantizer



a) Line-segment representation



b) Staircase representation

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1.4.2 Optimal Quantizer Design

- Minimize quantization errors
  - For K number of inputs (d) and L number of outputs (r)
  - $q_{L-1} \leq d < q_L \rightarrow r_L$
  - Determine the best set of quantization intervals, $q = \{q_0, q_1, q_2, \ldots, q_L\}$, that produces minimal quantization errors.

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1.4.3 Vector Quantizer

- Input vector is represented by a symbol within a codebook
- Minimal distortion criteria for selecting symbol
- Optimal vector quantizers are impractical
  - Require large codebooks
- Scalar quantizers are vector quantizers of dimension 1

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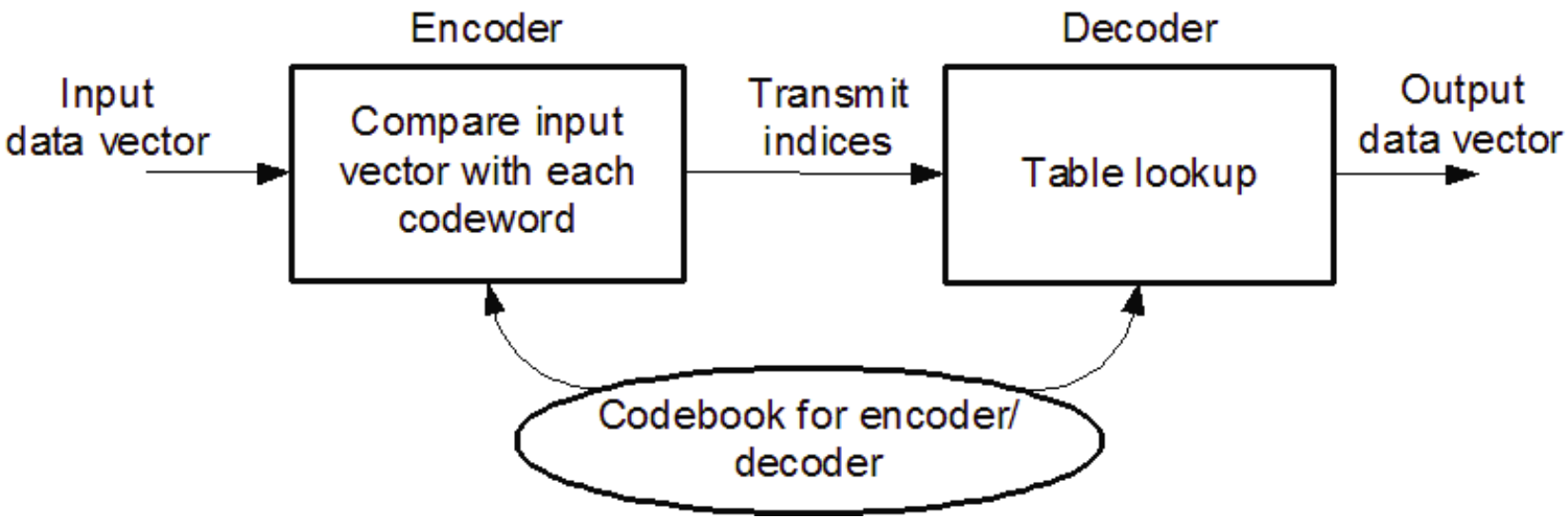
Block diagram of a simple vector quantizer



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1.5 Rate-Distortion Theory

- Minimum bitrate required to reproduce a source at various distortion levels
- May utilise different error measures
  - MSE, MAD, etc
- Employed to control quality of digitally coded pictures
- Accuracy of R-D estimation increases with the sophistication of algorithms

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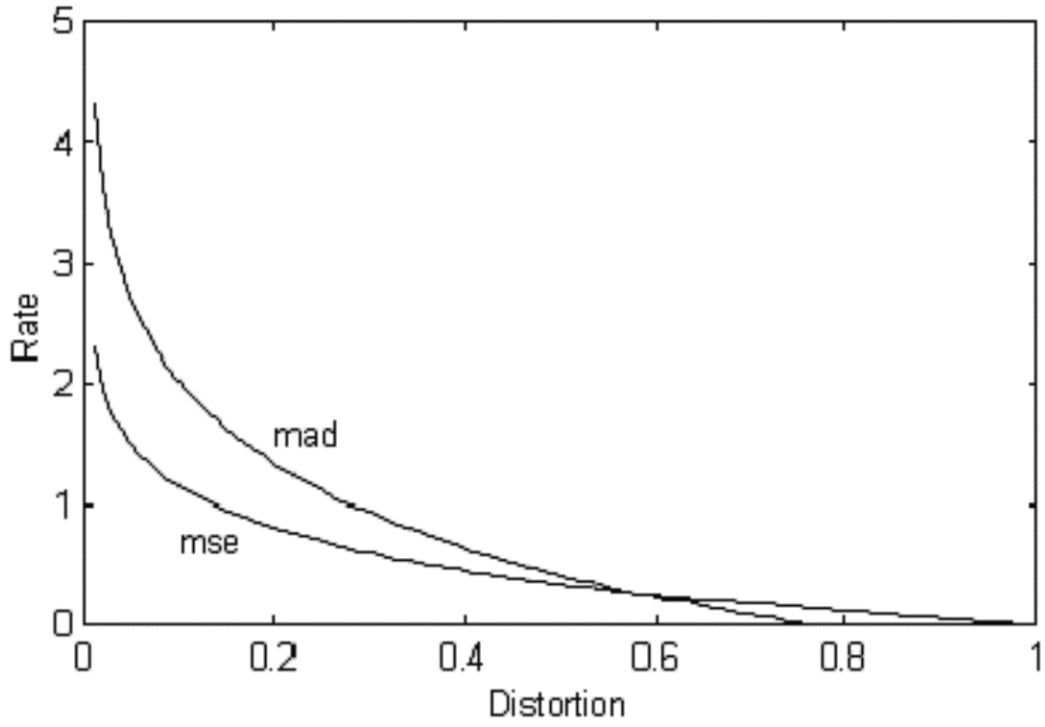
Rate-Distortion curve for MSE and MAE



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1.6 Human Visual System

- HVS Physiological make-up
  - Eyes
    - Cornea and lens for focusing
    - Photoreceptors in retina (cornea) to capture light
    - Optic nerve for transmission of receptor signals
  - Visual pathway
    - Connects the eye to the cortex
  - Visual cortex
    - Processing centre – detection, recognition, etc

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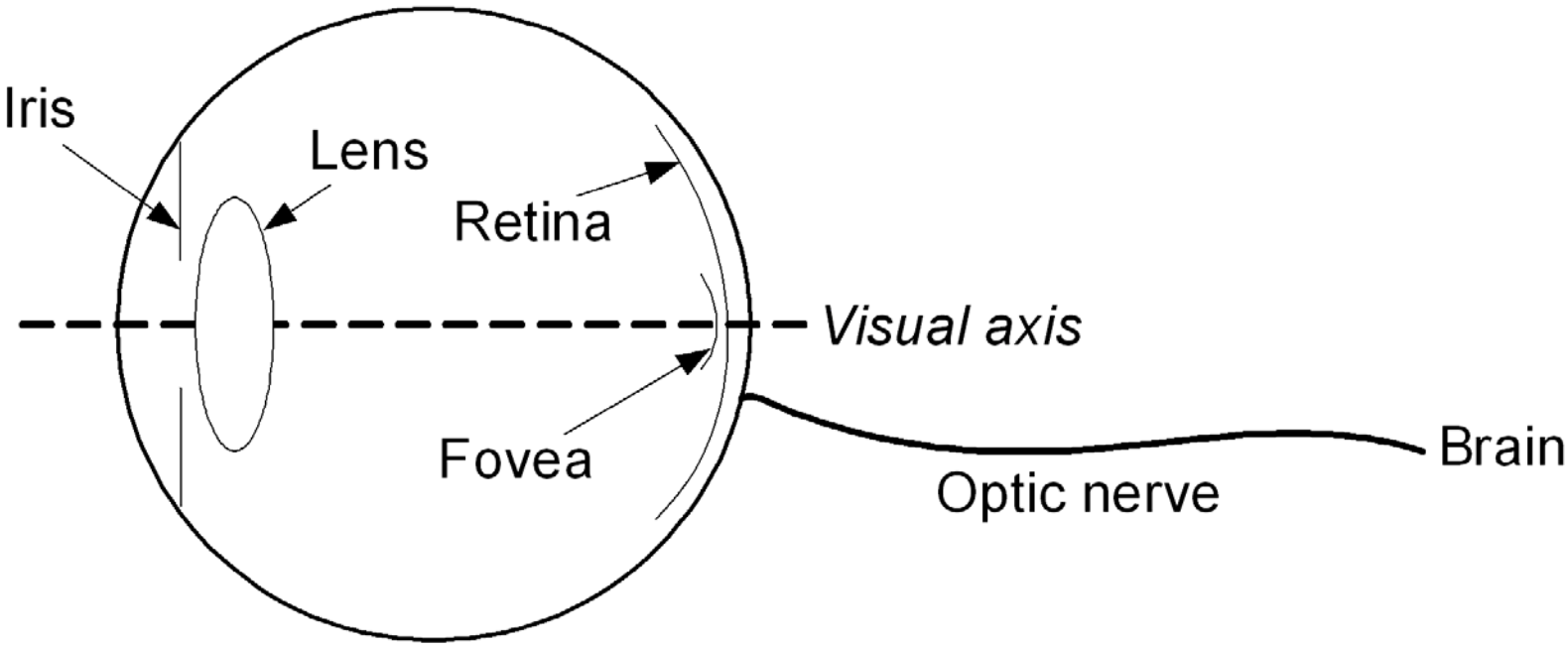
Simplified human eye – cross section



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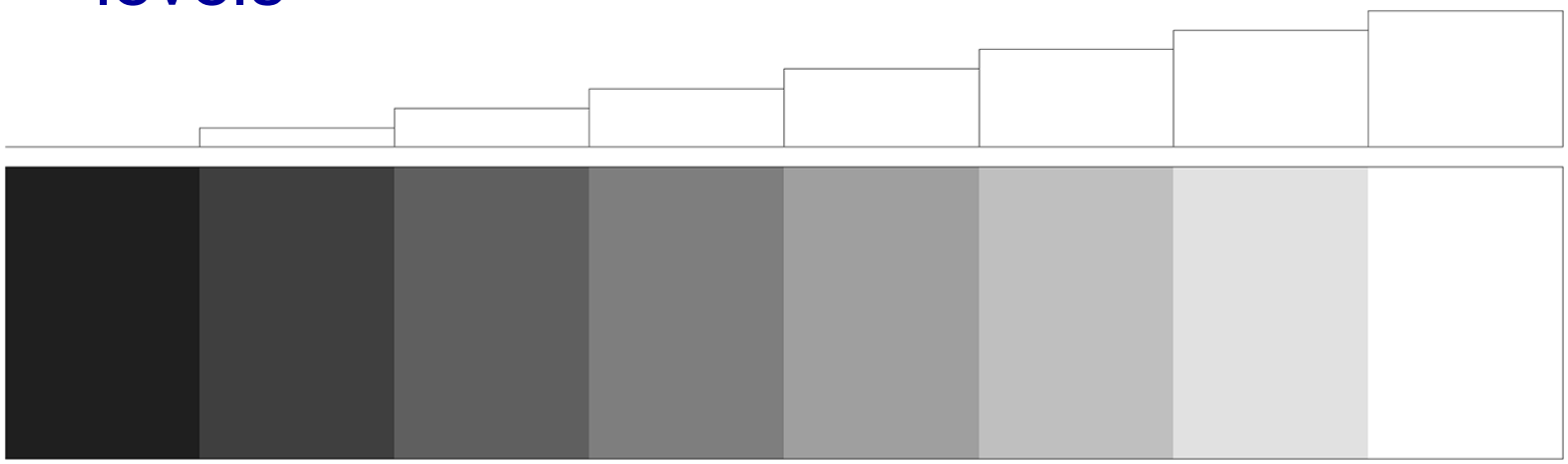
- Contrast
  - HVS operates in relative manner. i.e., difference
  - Additionally, the HVS is sensitive to intensity levels



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- Weber's fraction: $\Delta I / I$
  - HVS sensitivity relative to difference and intensity

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- Spatial Frequency
  - Visual acuity (cyc/deg) of the human optics
  - Expressed by the modulation transfer function (MTF)
  - MTF Formulation (Mannos and Sakrison):

$$F_{MTF}(f_r) = 2.6(0.0192 + 0.144 f_r)e^{-(0.114 f_r)^{1.1}}$$

f_r denotes spatial frequency normalised by viewing angles

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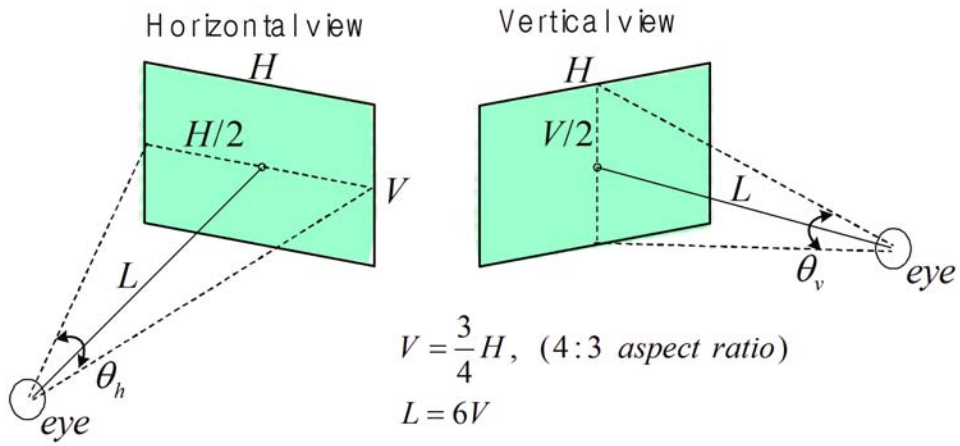
Viewing environment and spatial frequency concept



Horizontal angle

$\theta_h = 2\arctan((H/2)/6V)$

Vertical angle

$\theta_v = 2\arctan((V/2)/6V)$

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- Masking
  - Occurs during the interaction of neural signals
  - Results in the suppression and enhancement of certain details in images

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1.7 Digital Picture Coding Standards and Systems

- JPEG Still Image Coding Standard
  - Block Based DCT
    - 8x8 DCT
  - Scalar quantizer
    - For luminance and chrominance channels
  - Run-length and huffman coding
    - Zigzag scanning order

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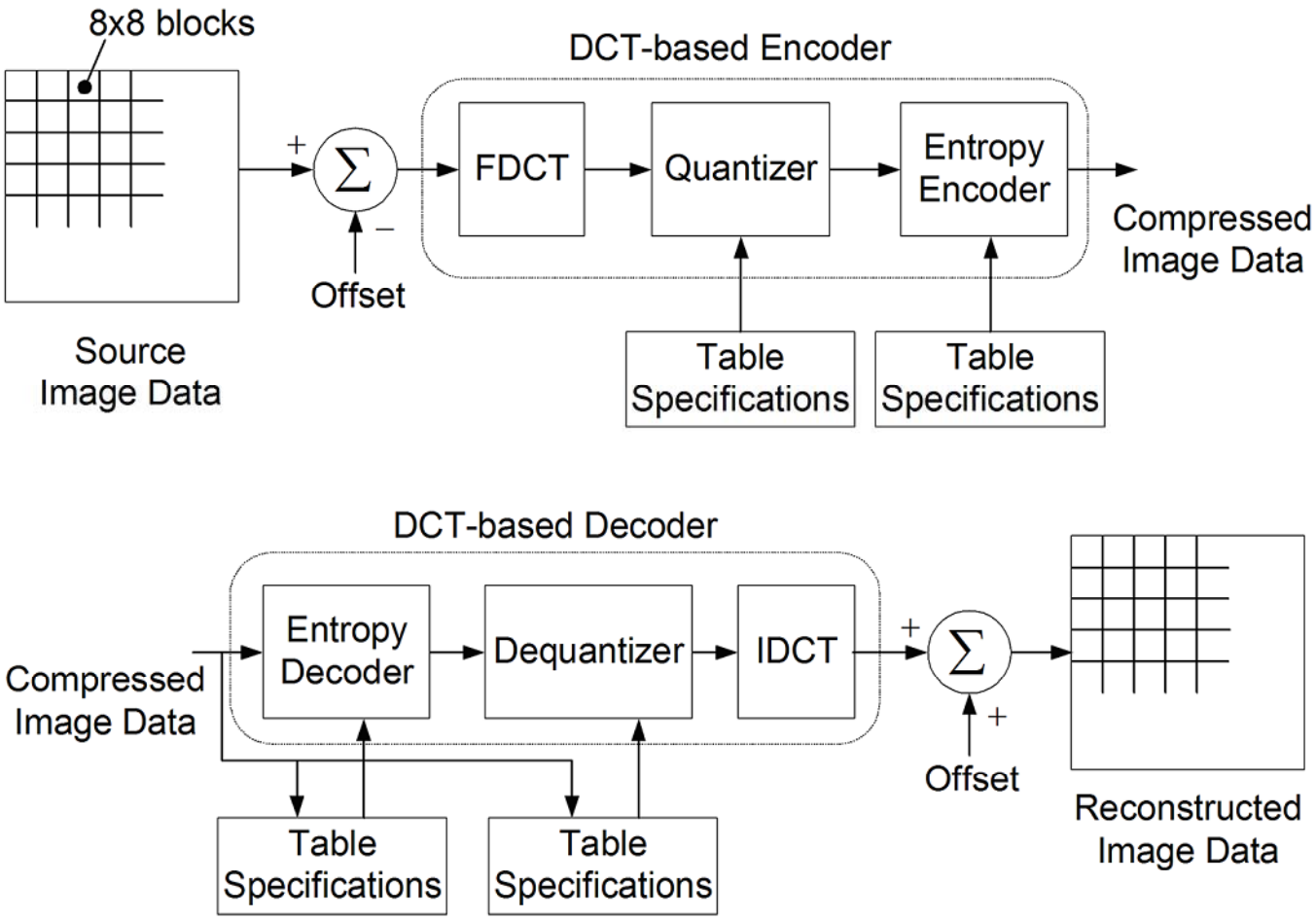
JPEG Coding Structure



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Quantization matrix for luminance (left) and chrominance (right) channels

16	11	10	16	24	40	51	61
12	12	14	19	26	58	60	55
14	13	16	24	40	57	69	56
14	17	22	29	51	87	80	62
18	22	37	56	68	109	103	77
24	35	55	64	81	104	113	92
49	64	78	87	103	121	120	101
72	92	95	98	112	100	103	99

17	18	24	47	99	99	99	99
18	21	26	66	99	99	99	99
24	26	56	99	99	99	99	99
47	66	99	99	99	99	99	99
99	99	99	99	99	99	99	99
99	99	99	99	99	99	99	99
99	99	99	99	99	99	99	99
99	99	99	99	99	99	99	99

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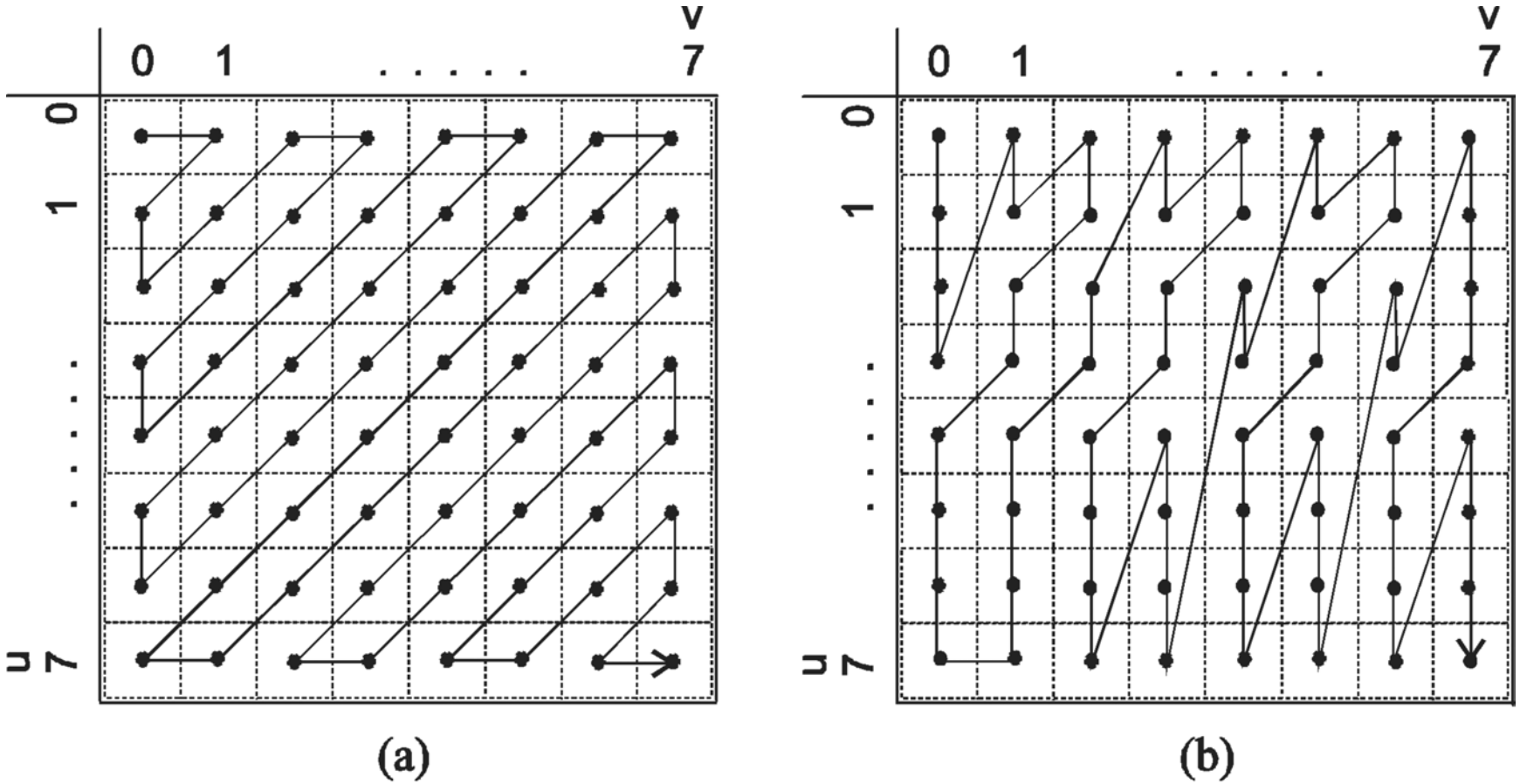
Scanning order for DCT Coefficients



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- JPEG2000 Standard
  - Wavelet transform
    - Multi-resolution
    - Any bi-orthogonal filters
      - Typically 9/7 or 5/3 integer filter set
  - Progressive bitplane quantization
  - Run-length and arithmetic coding
  - Scalable coding
    - Rate
    - Resolution

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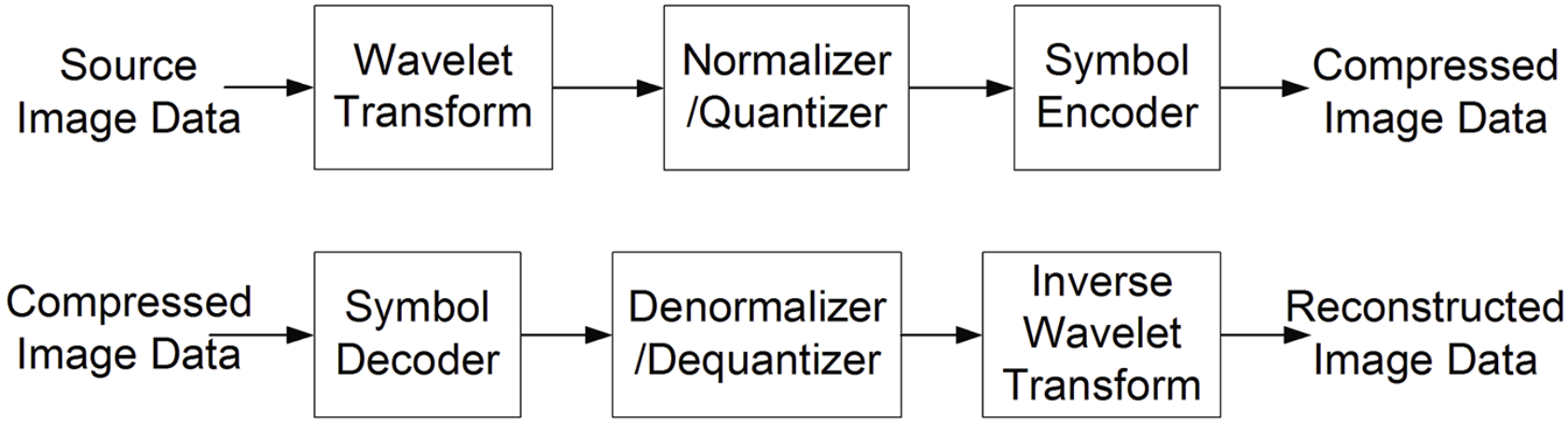
Simplified JPEG2000 coding structure



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Comparative performance of JPEG and JPEG2000 with *Girl* image

	Compression Ratio	Error (rms)	Compression Parameter
JPEG	21.85	7.63	Quality factor = 4
JPEG2000	22.53	6.26	M = 8, e = 8.4

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Left column: JPEG

Right column: JPEG2000

Bottom row: Difference image (between original and coded)

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MPEG-X Standards

- Basic Framework
  - Block based DCT coding
  - MC/DPCM for inter-frame coding
  - Scalar quantisation
    - Different quantisation strategies for inter- and intra-frame coding
    - Different matrix for different colour channel
  - Run-length and huffman coding
    - Zigzag scanning of DCT coefficients

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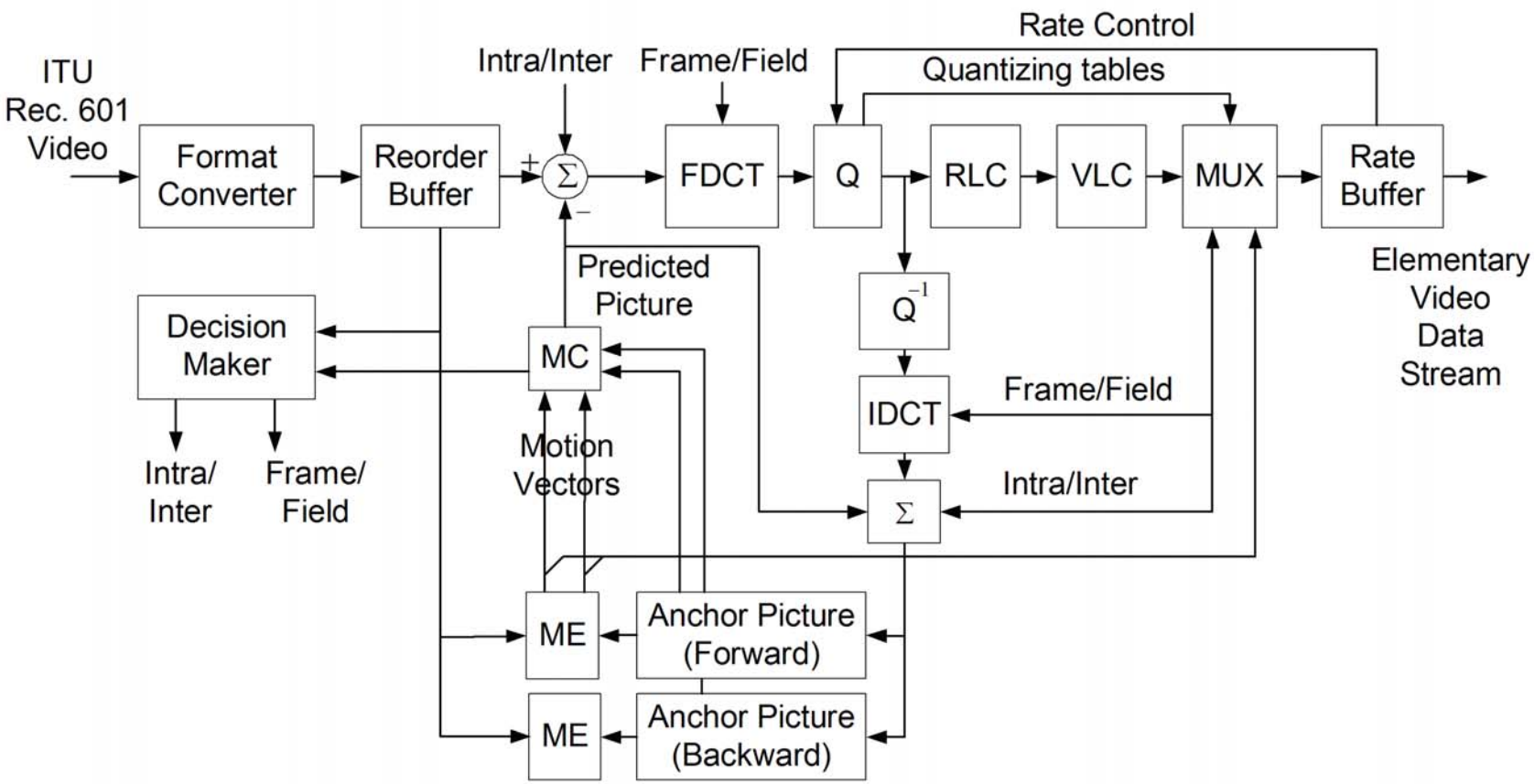
MPEG-1 Coding Structure



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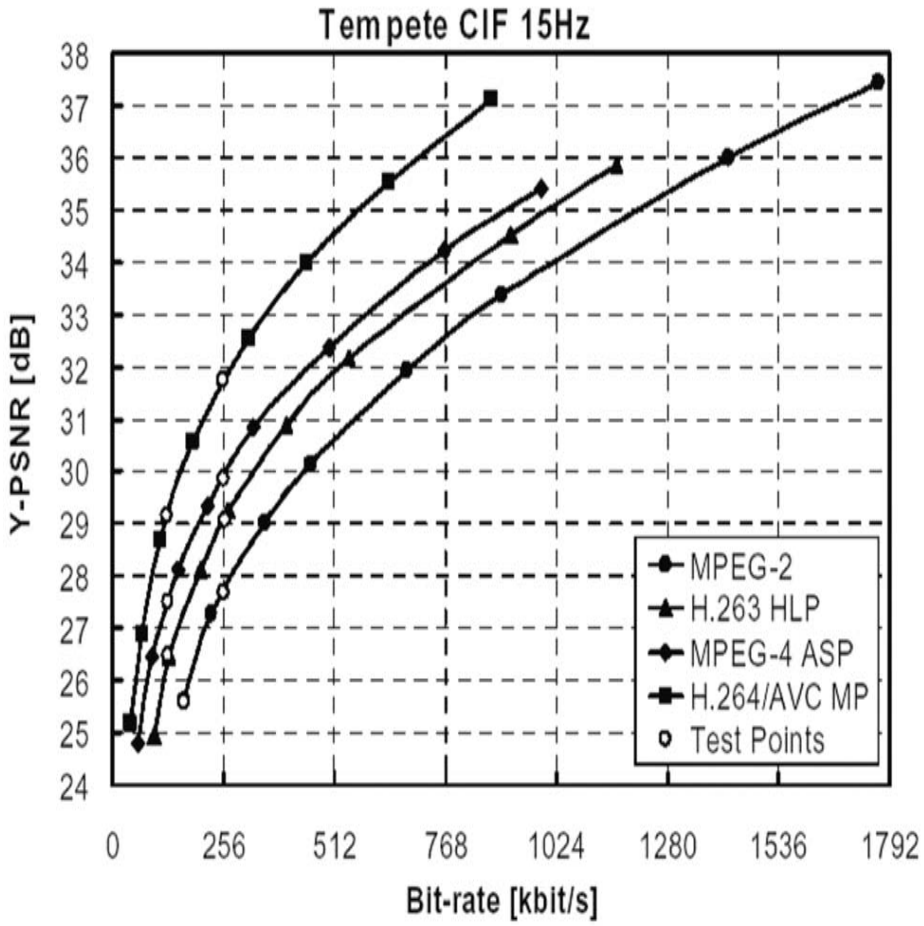
Video coding standards

- Chronology
  - MPEG1/H.261
  - MPEG2 → H.263
  - MPEG4/ASP
  - H.264/AVC

Left: standardized video codecs performances



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Comparison of standards: MPEG1, MPEG2, MPEG-4 and H.264/MPEG-4 Part10

Feature/ Standard	MPEG-1	MPEG-2	MPEG-4	H.264/MPEG-4 Part 10
Macroblock size	16x16	16x16 (frame mode) 16x 8 (field mode)	16x16	16x16
Block size	8x8	8x8	16x16, 8x8, 16x8 8x8, 16x8	8x8, 16x8, 8x16, 16x16, 4x8, 8x4, 4x4
Transform	DCT	DCT	DCT/Wavelet transform	4x4 Integer transform
Transform size	8x8	8x8	8x8	4x4
Quantization step size	Increases with constant increment	Increases with constant increment	Vector Quantization	Step sizes increase at rate of 12.5%
Entropy coding	VLC	VLC(different VLC tables for Intra and Inter modes)	VLC	VLC, CAVLC and CABAC
Motion estimation & compensation	Yes	Yes	Yes	Yes, more flexible up to 16 MVs per MB
Pel accuracy	Integer 1/2-pel	Integer 1/2-pel	Integer 1/2-pel, 1/4-pel	Integer 1/2-pel, 1/4-pel
Profiles	No	5 profiles. Several levels within a profile	8 profiles. Several levels within a profile	3 profiles. Several levels within a profile
Reference frame	Yes, One frame	Yes, One frame	Yes, One frame	Yes, Multiple frames(as many as 5 frames allowed)
Picture types	I, P, B, D	I, P, B	I, P, B	I, P, B, SI, SP
Playback & random access	Yes	Yes	Yes	Yes
Error robustness	Synchronization concealment	Data partitioning, redundancy, FEC for important packet transmission	Synchronization, data partitioning, header extension, reversible VLCs	Deals with packet loss and bit errors in error-prone wireless network
Transmission rate	Up to 1.5Mbps	2-15 Mbps	64Kbps-2Mbps	64Kbps-150Mbps
Encoder complexity	Low	Medium	Medium	High
Compatible with previous standards	Yes	Yes	Yes	No

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Average bitrate savings for video streams [J+02]

	Average bitrate saving relative to		
Coder	MPEG-4 ASP	H.263	MPEG-2
H.264/MPEG-4 Part 10 AVC	39%	49%	64%
MPEG-4 ASP	-	17%	43%
H.263	-	-	31%

- Substantial improvement in H.264

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1.8 Summary

- Basic introduction to digital picture coding
  - Characteristics of picture data
  - Picture coding techniques
  - Quantisation
  - Rate-distortion
  - Human visual system and picture coding
- Brief description of existing image and video coding standards

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Ber71	T. Berger. *Rate-Distortion Theory*. Upper Saddle River, NJ: Prentice Hall, 1971
Bov05	A. Bovik (Ed.). *Handbook of Image and Video Processing*. Orlando, FL: Academic Press, 2nd Ed., 2005
CCI90	CCITT Study Group XV. Recommendations of the H-Series, CCITT Study Group XV – Report R37. Technical report, CCITT, August 1990
Cho95	C.H. Chou. Adaptive transform coding of images based on removing just noticeable distortion. In *Proceedings of SPIE Visual Com. Im. Proc.*, 2501:607-618, Taipei, Taiwan, May, 1995
Cla85	R.J. Clarke. *Transform Coding of Images*. New York: Academic Press, 1985
CSE00	C. Christopoulos, A. Skodras and T. Ebrahimi. The JPEG2000 still image coding system: An overview. *IEEE Trans. Consumer Elect.* 46:1103-1127, November 2000
Ger77	A. Gersho. Quantization. *IEEE Communications Society Magazine*, 15:16-29, September, 1977

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Gah03	M.Ghanbari. *Standard Codecs: Image Compression to Advanced Video Coding*. Londonm UK: IEE, 2003
Gib97	J.D. Gibson (Ed.). *Multimedia Compression: Applications and Standards*. San Francisco, CA: Morgan Kaufmann, 1997.
Gla95	A.S. Glassner. *Principles of Digital Image Synthesis*. San Francisco, CA: Morgan Kaufman, 1995
GW02	R.C. Gonzalez and R.E. Woods. *Digital Image Processing*. Upper Saddle River, NJ: Prentice Hall, 2nd Ed., 2002
Hec24	S. Hecht. The visual discrimination of intensity and the weber-frechner law. *Journalof General Physiology*. 7:241, September 1924
ISO92	ISO/IEC JTC1/S2/WG9. CD11544, Progressive Bi-Level Image Compression, Revision 4.1. Technical report, ISO/IEC, September 1992
ISO93a	ISO/IEC. ISO/IEC 1172 Information Technology: Coding of Moving Pictures and Associated Audio for Digital Storage Media at up to about 1.5 Mbit/s. Technical report. ISO/IEC, 1993

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ISO93b	ISO/IEC JTC1 10918-1. ITU-T Rec. T.81, Information Technology – Digital Compression and Coding of Continuous-Tone Still Images: Requirements and Guidelines. Technical report, ISO/IEC, 1993
ISO93c	ISO/IEC JTC1/SC29/WG11. CD 13818, Generic Coding of Moving Pictures and Associated Audio. Technical report, ISO/IEC, November 1993
ISO00	ISO/IEC FCD 15444-1. JPEG 2000 Image Coding System. Technical report, ISO/IEC, March 2000
ISO01	ISO/IEC. ISO/IEC 14496, Information Technology – Coding of Audio Visual Objects. Technical report, ISO/IEC, 2001
ITU82	ITU-R. ITU-R Recommendation BT.601, Encoding Parameters of Digital Television for Studios. Technical report, ITU-R, 1982
ITU96	ITU-T. ITU-T Recommendation H.263, Video Coding for Low Bit Rate Communication. Technical report, ITU-T, 1996
ITU03	ITU-T. ITU-T Recommendation H.264, Advance Video Coding for Generic Audio Visual Services. Technical report, ITU-T, 2003

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J+02	A. Joch *et al*. Performance comparison of video coding standards using lagrangian coder control. In *Proceedings of International Conference on Image Processing*, 2:501-504, September 2002. Special Session: The emerging JVT/H.26L video coding standard
JN84	N.S. Jayant and P. Noll. *Digital Coding of Waveforms, Principles and Applications to Speech and Video*. Upper Saddle River, NJ: Prentice Hall, 1984
LBG80	Y. Linde, A. Buzo and R.M. Gray. An algorithm for vector quantization desgin. *IEEE Trans. on Commun.*, 28:84-95, January 1980
LOW91	A. Leger, T. Omachi and G.K. Wallace. JPEG still picture compression algorithm. *Optical Engineering*, 30:949-954, July 1991
LR78	J.O. Limb and C.B. Rubenstein. On the design of quantizer for DPCm coders: A functional relationship between visibility, probability and masking. *IEEE Trans. on Commun.*, 26:573-578, May 1978
Max60	J. Max. Quantizing for minimum distortion. IRE Trans. Information Theory, IT-6:16-21, March 1960.

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MPFL97	J.L. Mitchell, W.B. Pennebaker, C.E. Fogg and D.J. LeGall. *MPEG Video Compression Standard*. New York: Chapman Hall, 1997
MS74	J.L. Mannos and D.J. Sakrison. The effects of a fidelity criterion on the encoding of images. *IEEE Trans. Information Theory*. IT-20:525-536, July 1974
NH95	A.N. Netravali and B.G. Haskell. *Digital Pictures-Representation, Compression, and Standards*. New York and London: Plenum Press, 2nd Ed., 1995
O'N76	F.B. O'Neal, Jr. Differential pulse code modulation with entropy coding. *IEEE Trans. Information Theory*, IT-21:169-174, March 1976
PC00	A. Puri and T. Chen (Eds.). *Multimedia Systems, Standards and Networks*. New York: Marcel Dekker, 2000
PE02	F.Pereira and T. Ebrahimi (Eds.). *The MPEG-4 Book*. Upper Saddle River, NJ: IMSC Press, 2002
RH96	K.R. Rao and J.J. Hwang. *Techniques and Standards for Image, Video and Audio Coding*. Upper Saddle River, NJ: Prentice Hall, 1996

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Ric03	I.E.G. Richardson. *H.264 and MPEG-4 Video Compression*. Hoboken, NJ: Wiley, 2003
RY90	K.R. Rao and P. Yip. *Discrete Cosine Transform: Algorithms, Advantages, Applications*. San Diego, CA: Academic Press, 1990
Sal00	D. Saloman. *Data Compression: The Complete Reference*. Berlin: Springer-Verlag, 2000
Say00	K. Sayood. *Introduction to Data Compression*. San Francisco, CA: Morgan Kaufmann, 2000
Sch83	R. Schafer. Design of adaptive and nonadaptive quantizers using subjective criteria. *Signal Processing*. 5:333-345, July 1983
Sch86	W.F. Schreiber. *Fundamentals of Electronic Imaging Systems*. Berlin: Springer-Verlag, 1986
SN77	D.K. Sharma and A.N Netravali. Design of quantizers for DPCm coding of picture signals. *IEEE Trans. on Commun*. 25-1267-1274, November 1977

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SW96	D. Shen and S. Wang. Measurements of JND property of HVS and its applications to image segmentation, coding and requantization. In *Proceedings of SPIE Dig. Comp. Tech. Sys. For Vudeo Com.*, 2952:113-121, October 1996
VH92	M. Vetterli and C. Herley. Wavelets and filter banks: theory and design. *IEEE Trans. On Sig. Proc.*, 40:2207-2232, November 1992

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2. Fundamentals of Human Vision and Vision Modelling

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Chapter 2 Outline

2.1 Introduction
2.2 Brief Introduction of the Visual System
2.3 Colour Vision
2.4 Luminance and the Perception of Light Intensity
2.5 Spatial Vision and Contrast Sensitivity
2.6 Temporal Vision and Motion
2.7 Visual Modelling
2.8 Conclusion

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2.1 Introduction

- Picture display and coding systems are adapting to the human visual system
- The need to understand the HVS
  - Characteristics
  - Limitations
  - Sensitivity to spatial and temporal changes
  - Colour perception

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2.2 Brief Introduction of the Visual System

- Human Optics
  - Lens for focusing
  - Cornea
    - 3 cellular and 2 synaptic layers
    - Fovea - Primary focal point of the visual field
  - Photoreceptors
    - Cones for photopic vision – 7 million
      - Short (S), medium (M) and long (L) wavelengths
    - Rods for scotopic vision – 120 million

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- Optic nerve
  - Integrates receptor signals via ganglion cells
    - 100 rods to 1 ganglion
      - Increase sensitivity of scotopic vision
    - 1 cone to 1+ ganglion
- Light adaptation - localized in the retina
- Opponent colour
  - Due lateral ganglion inter-connection

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- Visual Cortex
  - Neurons are orientation and frequency selective
- Medial Temporal region of the Cortex
  - Sensitive to motion

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2.3 Colour Vision

- Colour sensation
  - of the mind not of worldly objects
- Functionally
  - Colour signals are linearly related to cone signals
  - No standardized method for specifying cone signals

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2.3.1 Colorimetry

- All colours are derived from 3 primaries
  - Red, Blue and Green

$$C_1 = r_1R + g_1G + b_1B$$

- Colour matching – *Tristimulus*
  - Follows linear algebraic rules
    - additive

$$C_2 = r_2R + g_2G + b_2B$$

$$C_3 = C_1 + C_2 = (r_1+r_2)R + (g_1+g_2)G + (b_1+b_2)B$$

    - Proportion/product

$$kC_3 = kC_1 + kC_2$$

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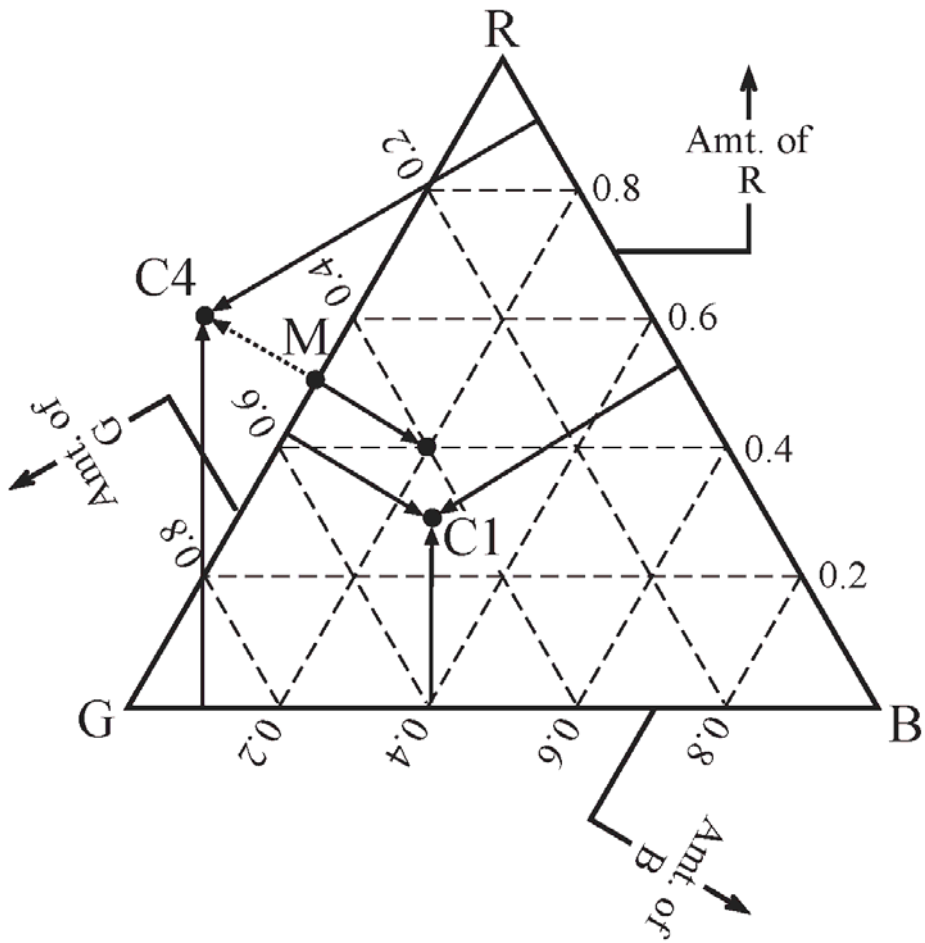
Maxwell diagram for colour matching with 3 primaries. $C_1 = 0.3R + 0.45G + 0.25B$



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- Adding primaries to test light
  - Resulting colour outside gamut

$$C_4 = rR + gG - bB$$

- Colorimetry - matching experiments
  - real R, G and B primaries
  - CIE 1931 standard observer system
    - Imaginary primaries X, Y and Z

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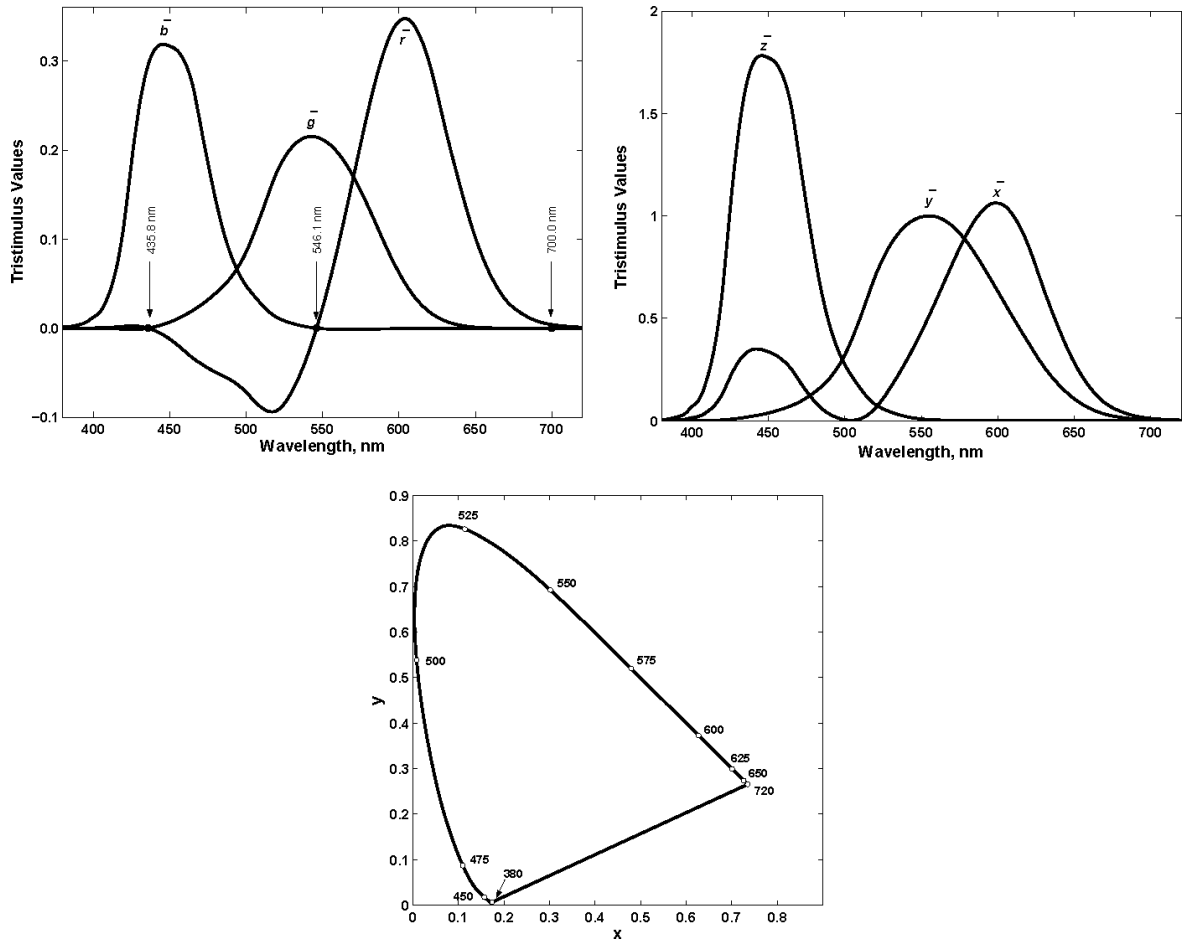
CIE 1931 2°. Top: Colour Matching for RGB (left) and XYZ (right). Bottom: Chromaticity diagram



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2.3.2 Colour Appearance, order system and difference

- Depends on
  - Adaptation, local and global
  - Stimulus in visual field
    - Size, location and configuration (shape)
  - Objects
    - Colour and location
  - Background/surrounding colour
- Same chromaticity and luminance → may have different appearances

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- Colour has 5 attributes
  - Brightness → intensity
  - Lightness → intensity relative to white
  - Colourfulness → chromaticity
  - Chroma → chromaticity relative to white
  - Hue → attribute of a colour
- Brightness and Colourfulness - Absolute
- Lightness and Chroma - Relative

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- Unique Hues
  - No mixture of other hues
  - Red, Blue, Green and Yellow
- Opponent colour (hue) pair
  - Cannot co-exist in the same stimulus
  - Red-Green and Blue-Yellow
- Need for uniform description of colour appearance
  - Colour order system (Munsell book of colour)

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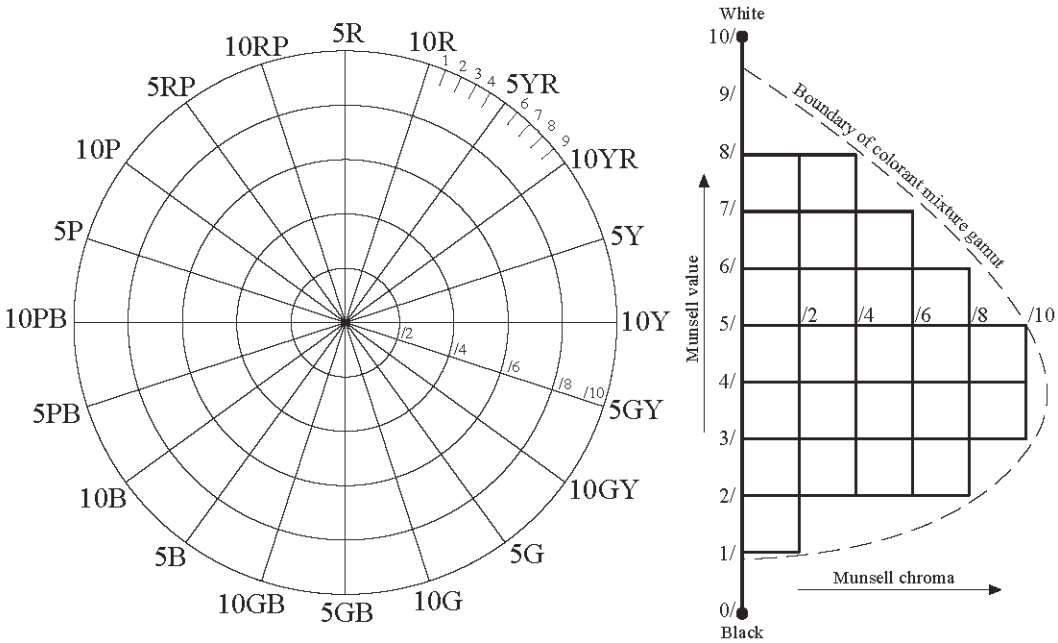
Left: Hue arrangements in constant lightness plane. Right: A Hue leaf with variation in lightness and chroma.



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- Perceived colour difference
  - CIE 1976 *L*, a*, b** (CIELAB) colour space
    - Quantify perceived difference between two colours
- Colour appearance models
  - Dependent on viewing conditions
  - Calculates relative colour attributes
  - Predict brightness and colourfulness
  - may adjust for changes in colourfulness and contrast

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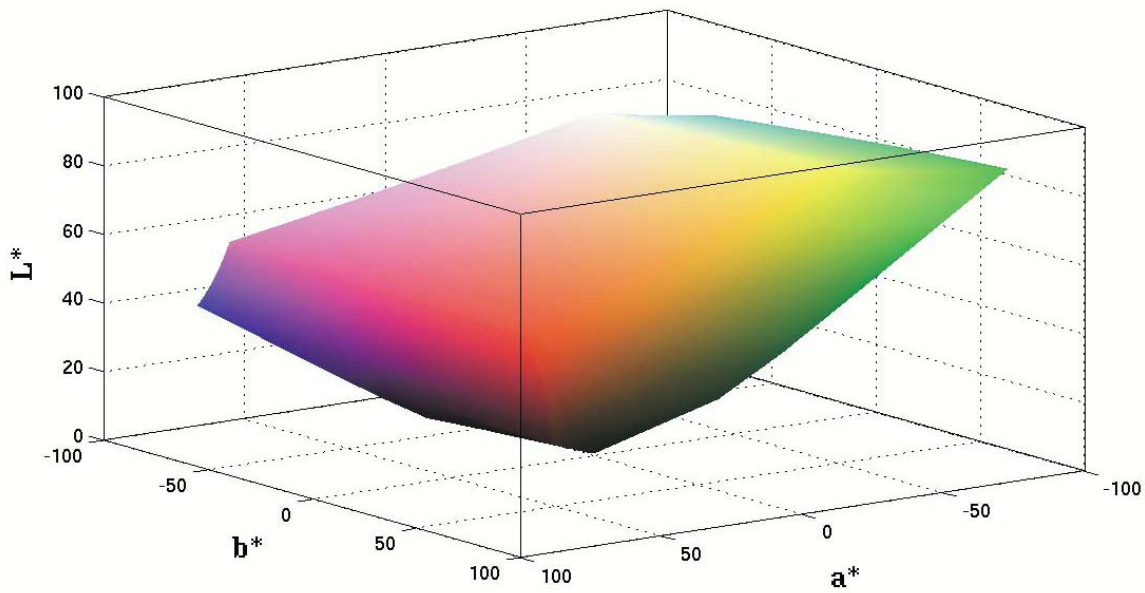
CRT gamut plot in CIELAB space



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2.4 Luminance and the Perception of Light Intensity

- Luminance
  - Different definitions
  - Leads to confusion
  - Described as "**apparent intensity**"
  - Used to label achromatic (luminance) channel in visual processing
- Actual definition
  - Effectiveness of light of different wavelengths in specific photometric matching task

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2.4.1 Luminance

- CIE functional definition of luminance

$$L = k \int_{\lambda} P_{1\lambda} V_{\lambda}(\lambda) d\lambda$$

Where *k* is a constant, *P1λ* and *V(λ)* are the radiance and photopic spectral luminous efficiency function

V(λ) = ratio of radiant flux of wavelengths λ_m and λ

- Luminance measured in candelas (cd/m^2)
- CIE heterochromatic brightness matching
  - Additive (Abney's) law fails
    - Brightness not always additive in coloured stimulus

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- Alternate matching methods
  - Heterochromatic Flicker Photometry (HFP)
    - Luminance intensity adjusted to match test and flickering light
  - Minimally Distinct Border (MDB)
    - Intensity adjusted to minimize the distinctness between the borders of bipartite luminance fields
  - HFP and MDB obeys additivity rule

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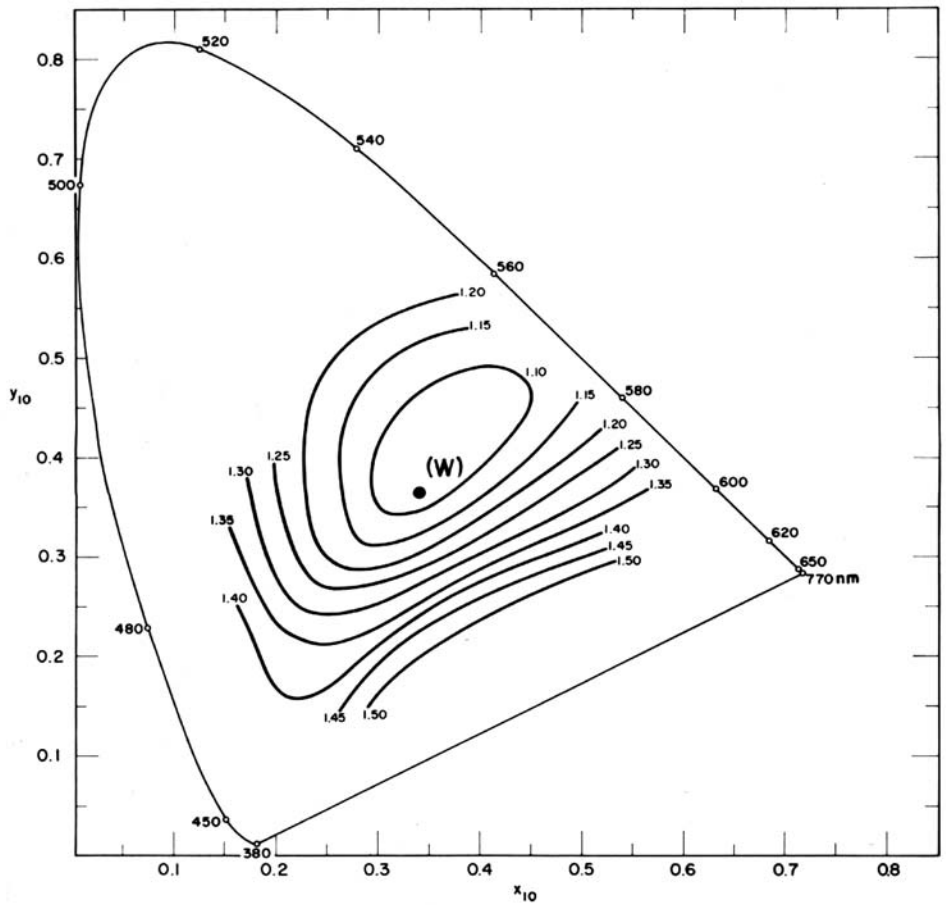
Helmholtz-Kohlrause effect. The apparent isoluminant chromatic colours increases with chroma.



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- Luminance efficiency function
  - Relative to the sensitivity of cone types
  - Dependent on adaptation, esp., chromatic
    - Can only be defined under conditions for which it is measured
  - HFP and MDB
    - Luminosity taken as weighted sum of L and M cones
    - Contribution of S cones is negligible under normal conditions
  - Affected colour blindness (L and M cones)

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2.4.2 Perceived Intensity

- Weber's Law : $\Delta I / I = k$
  - General rule of thumb
  - Measures contrast (relative intensity)
  - States that the ratio of background (*I*) and incremental (*ΔI*) intensities is constant (*k*)
  - As *I* increase, *ΔI* also increase to meet detection threshold – Just Noticeable Difference (JND)
  - Does not hold for full range of intensities
  - Reliable for intensities above 100 cd/m^2

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- Fechner's Law
  - Logarithmic relationship between stimulus intensity and associated sensation, S

$$S = k \log(I)$$

I is the intensity

k is a constant dependent on stimulus condition

  - Does not match data from direct brightness experiments
    - Data exhibit power function profile: $S = k I^a$

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- luminance and lightness relationship
  - Non-linear general profile
  - Specific profile depends on
    - Exact stimulus conditions
    - Data collection methods

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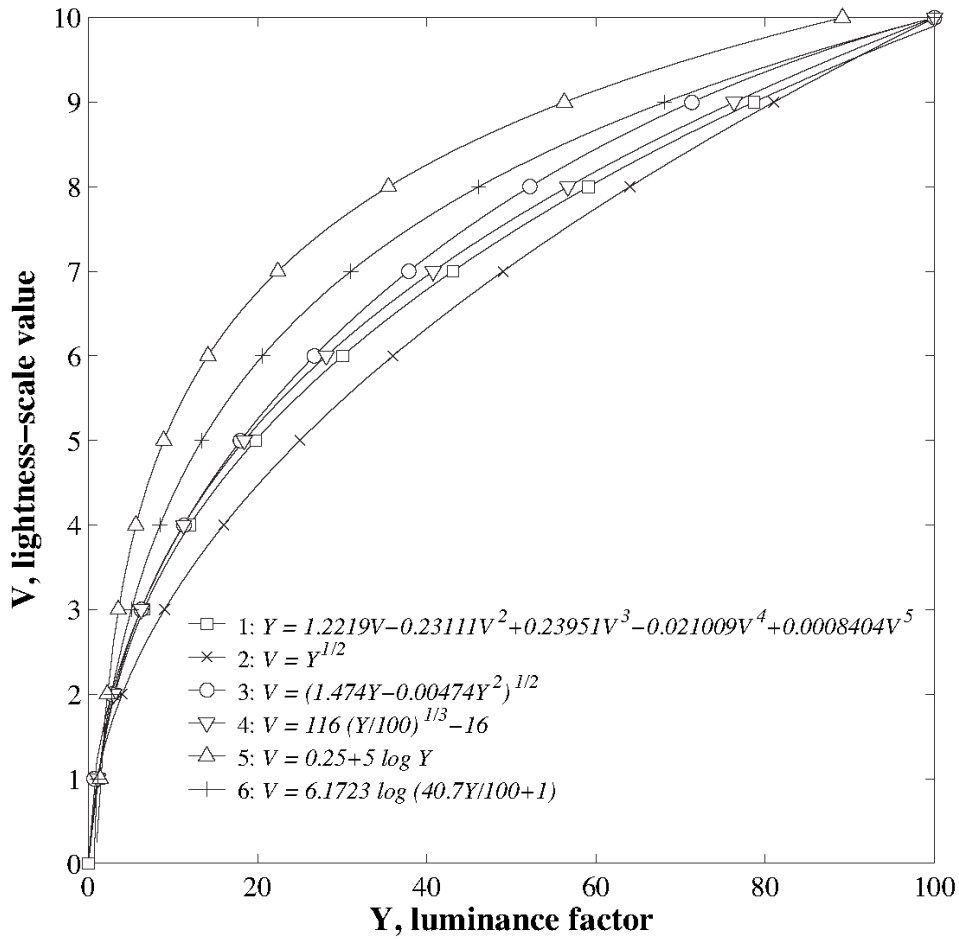
Luminance vs Lightness



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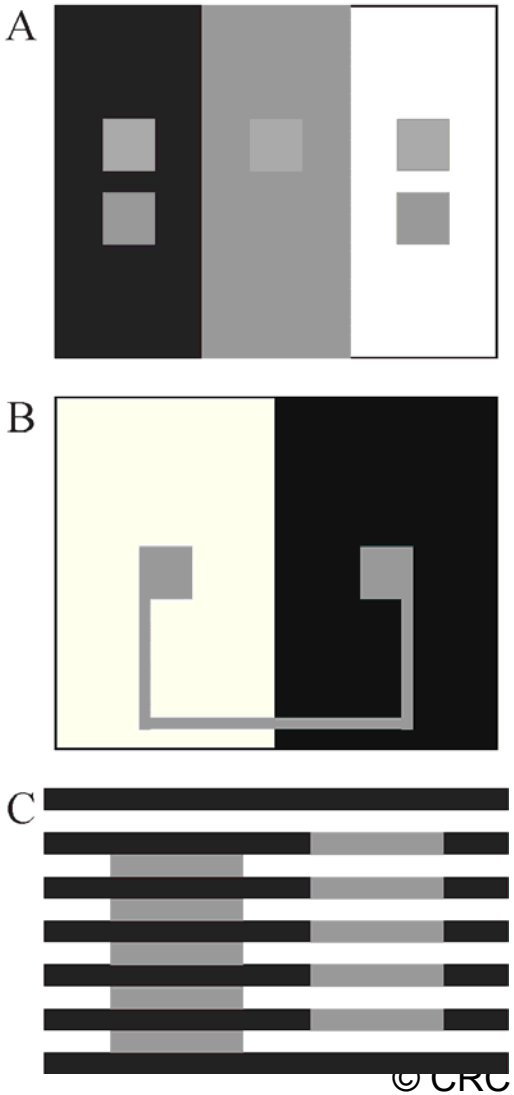
Lightness illusions



A. Simultaneous contrast
B. Crispening
C. White's illusion

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2.5 Spatial Vision and Contrast Sensitivity

- Spatial information processing
  - Visual acuity of the human optics
    - Modelled by
      - Modulation transfer function (MTF)
    - Able to detect spatial variation and spatial alignment (Vernier acuity or hyperacuity)
  - Sampling by photoreceptor array
    - Sampling rate of 120 samples/degree → nyquist frequency of 60 cpd (cycles per degree)
    - Optics degrades images above 60 cpd, no aliasing

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2.5.2 Contrast Sensitivity

- Studied with harmonic stimuli (sine wave)
- Definition
  - Reciprocal of the threshold needed to detect stimuli of different frequencies
- Contrast sensitivity function
  - Measures visual system sensitivity to varying sinusoidal frequencies
- Michelson's Contrast

$$C_m = (L_{max} - L_{min})/(L_{max} + L_{min})$$

L_{max} and L_{min} are peak and trough luminance

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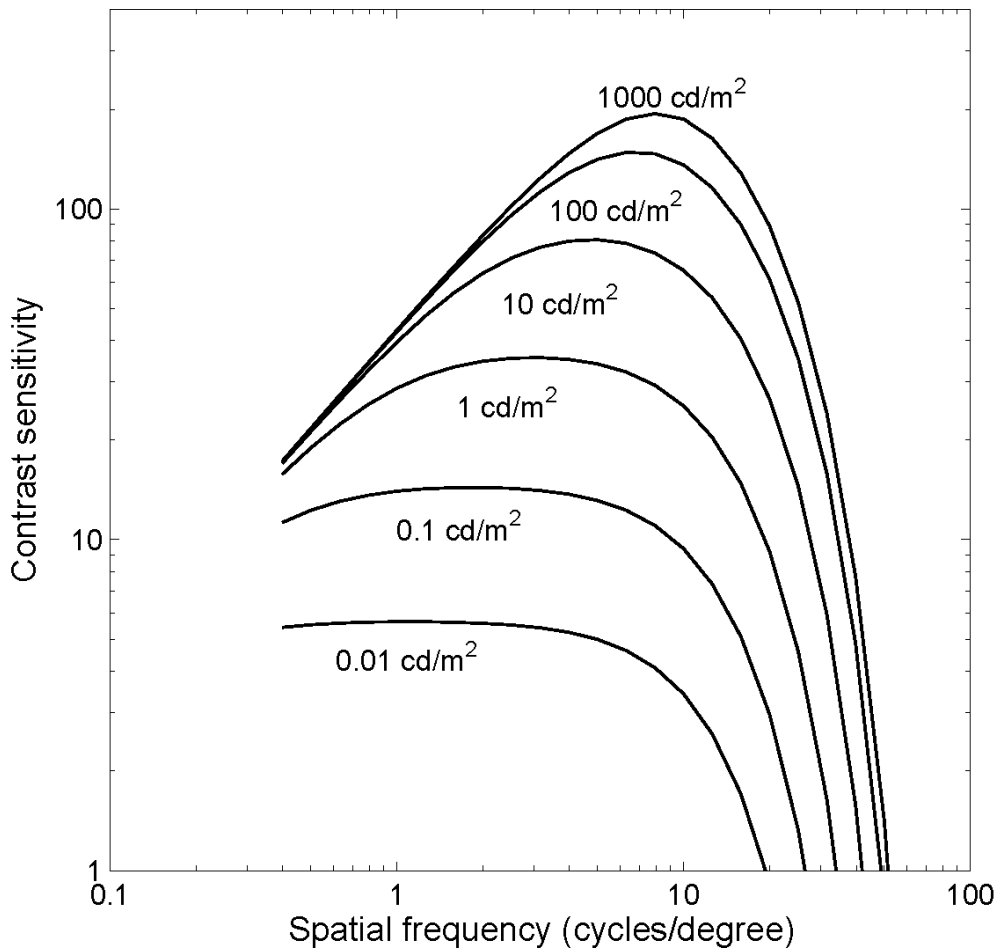
Contrast Sensitivity Function for different mean luminance (Barten's Empirical Model)



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- Contrast Sensitivity depends on
  - Mean luminance
  - Orientation
  - Temporal frequency
  - Spatial position in retina
    - Maximal sensitivity at the fovea
- Oblique effect
  - Reduced contrast sensitivity for obliquely oriented gratings (2-3 times)

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2.5.3 Multiple Spatial Frequency Channels

- CSF represent multiple narrowly tuned spatial frequency channels
  - Supported by physiological, psychophysical and anatomical evidence
- Concept of multi-channel structure for human vision
  - narrow frequency bands
  - narrow orientation bands

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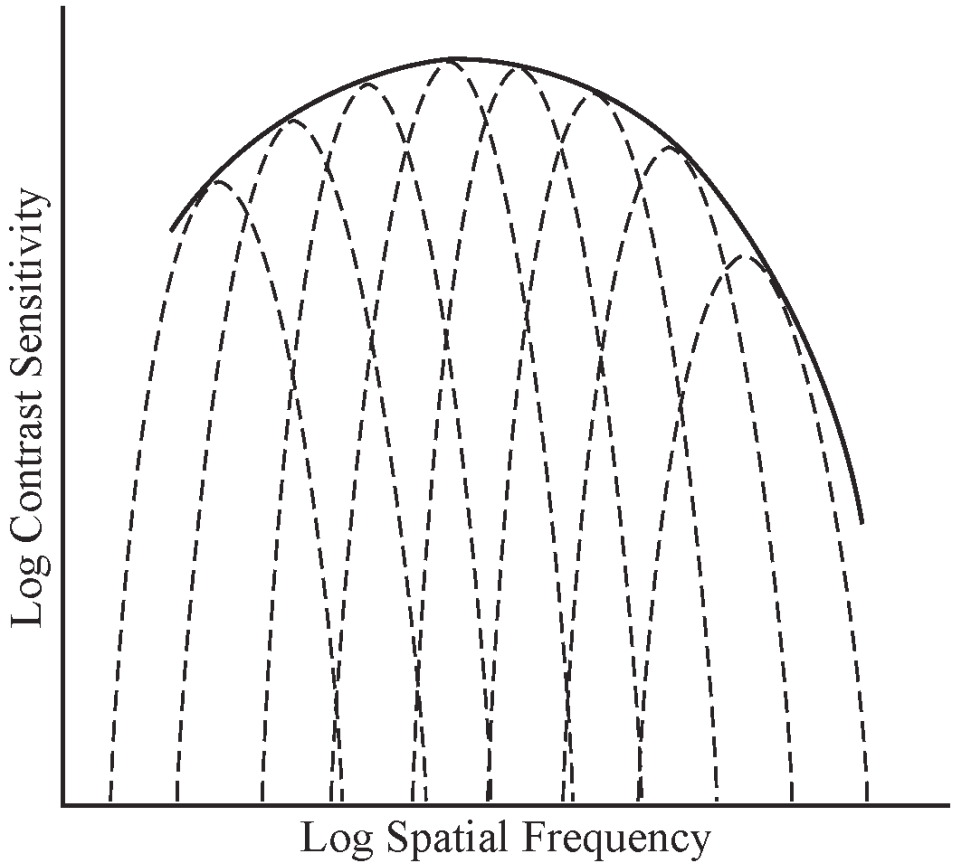
Envelop of multiple CSFs tuned to narrow spatial frequencies channels



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- Cortical receptive fields
  - Are size specific
  - Indicative of multi-resolution structure
- Frequency bandwidths
  - broader at low frequencies
  - Narrower at high frequencies

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- Pattern Adaptation
  - Vision system takes inputs from multiple spatial frequency channels
  - Channels most sensitive to adaptation stimuli responds less vigorously
  - Once adaptation sets in, the distribution of inputs responses is skewed
  - Also affects orientation channels

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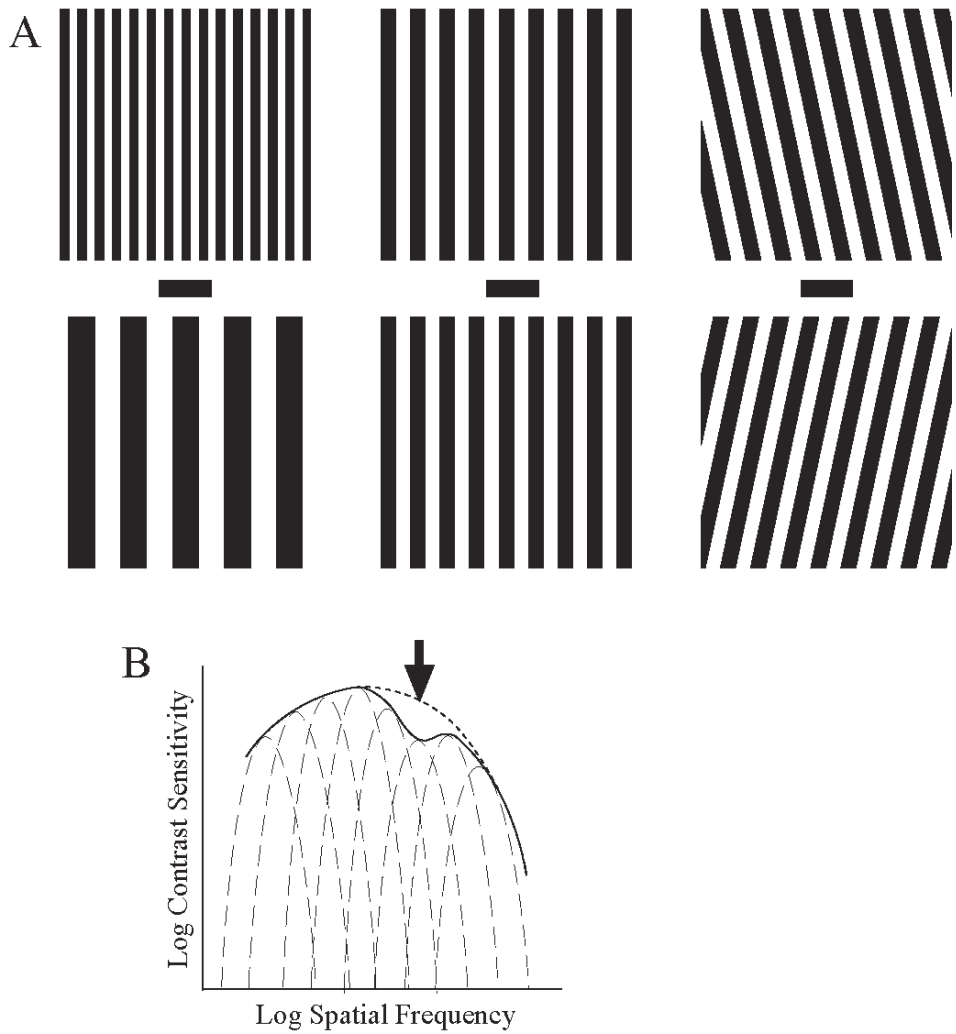
Pattern and orientation adaptation. *A)* adaptation test. *B)* skewed sensitivity due to adaptation



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- Pattern Detection
  - Dependent on contrast of fundamental components, not overall contrast
- Masking and Facilitation
  - Masking hinders detection
  - Facilitation aids detection.
  - Depends spatial frequency, orientation and phase

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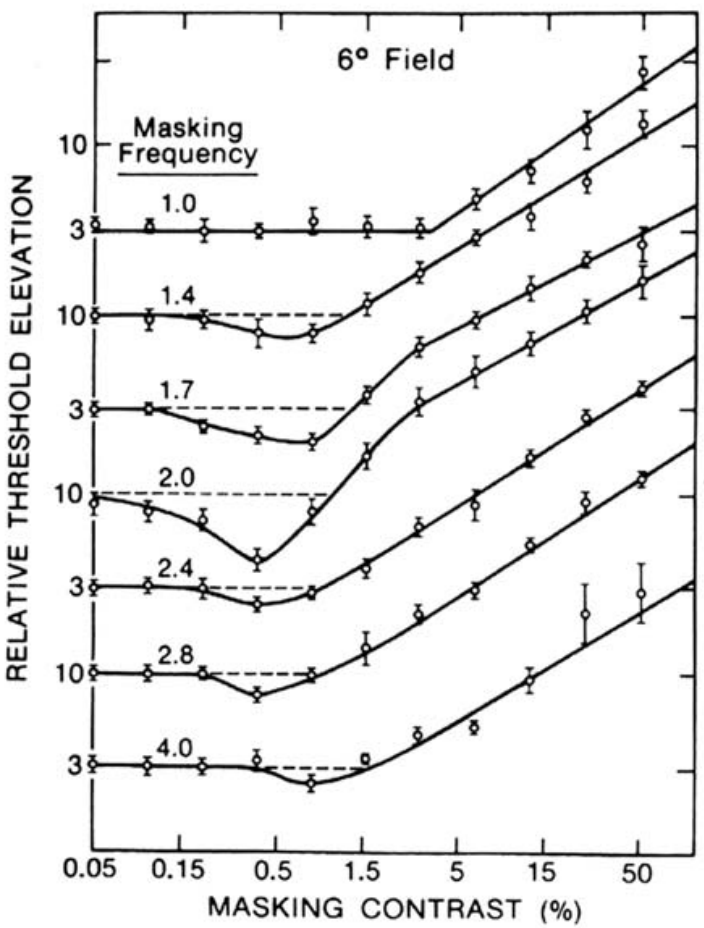
Masking and facilitation



- Target frequency 2.0
- “dips” on curves signifies facilitation
- Facilitation is strongest at low contrast when target and masking frequencies are closest

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- Dependencies in spatial frequencies and orientation
  - Non-linear interactions between separate spatial frequency and orientation bands exist
  - Physiological and psychophysical evidence supports inter-channel dependencies
  - However, Some Vision Models assumes independence between spatial frequency and orientation channels

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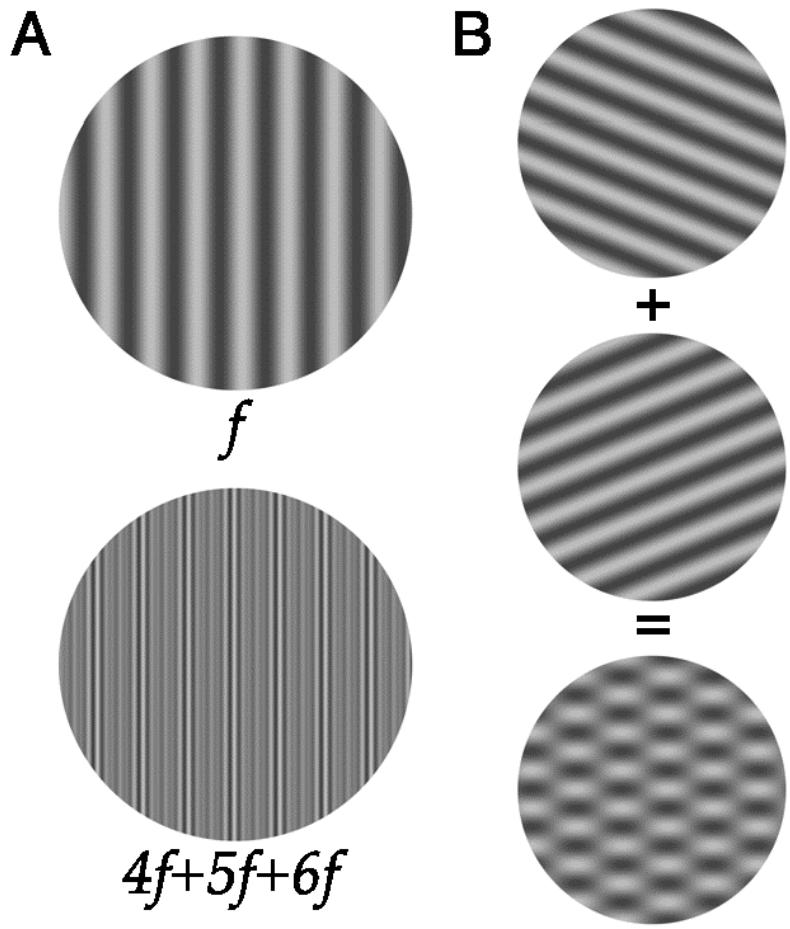
Inter-channel dependencies



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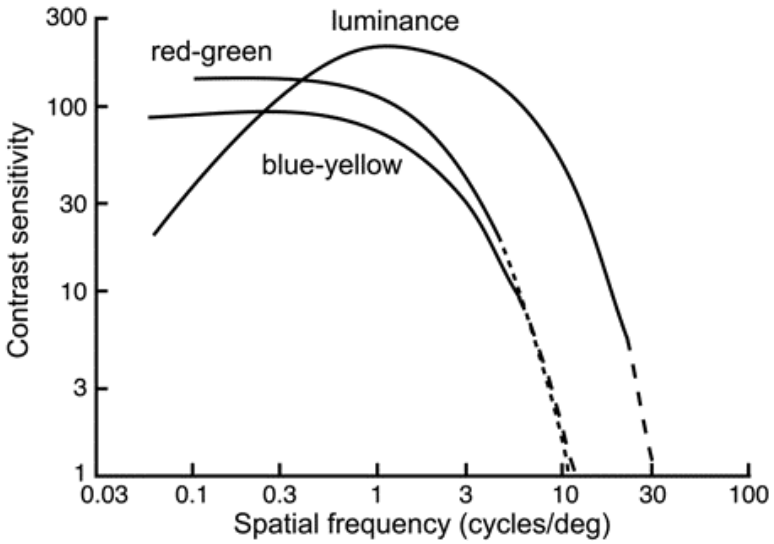
Chromatic contrast sensitivity

- Opponent colour
- Chromatic and achromatic profile differs
- Luminance contrast operates at higher frequencies



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- Supra-threshold contrast sensitivity
  - Effects of threshold and supra-threshold are different
  - Flattening effect or “non-constancy”
    - Occurs as contrast of gratings exceed far beyond that of the threshold levels
- Hypothesis (Georgeson and Sullivan)
  - Spatial frequency channels adjust gains independently to operate at supra-threshold

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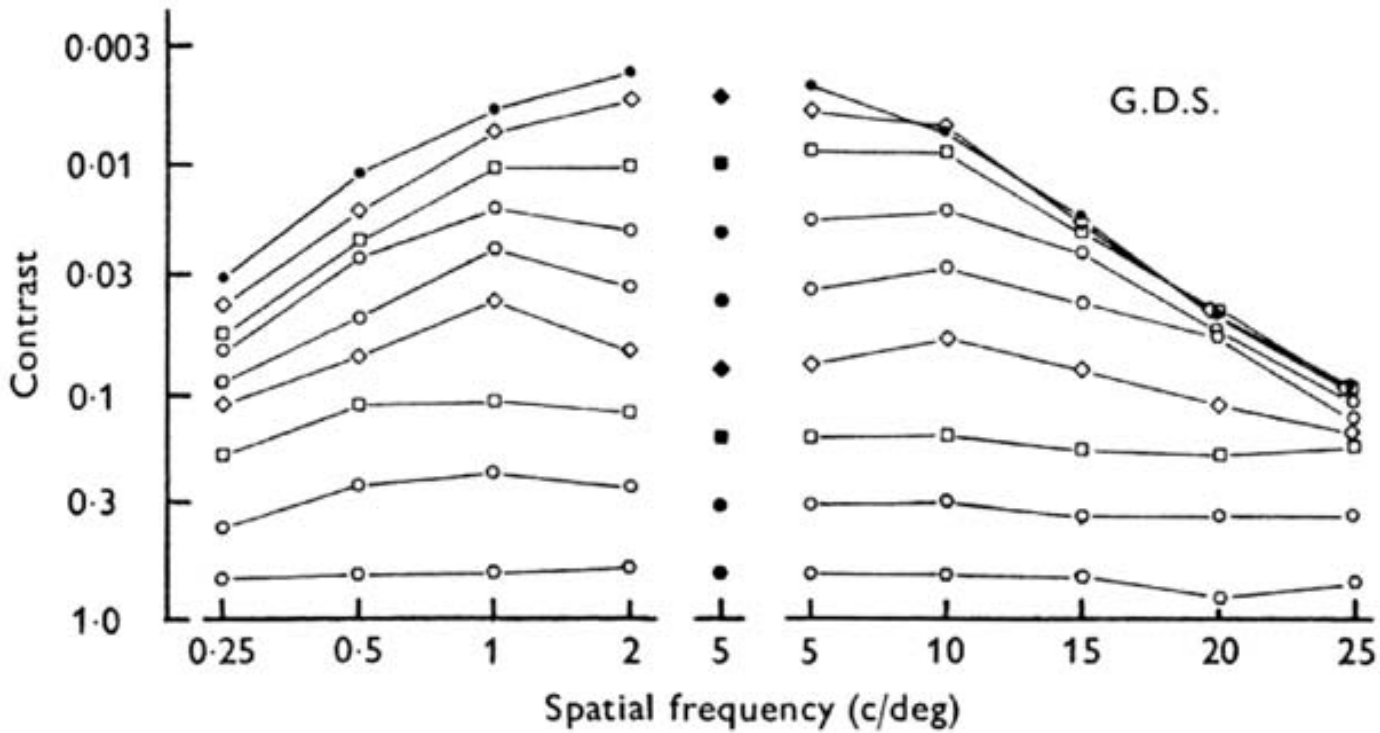
Supra-threshold contrast matched to 5 cpd gratings



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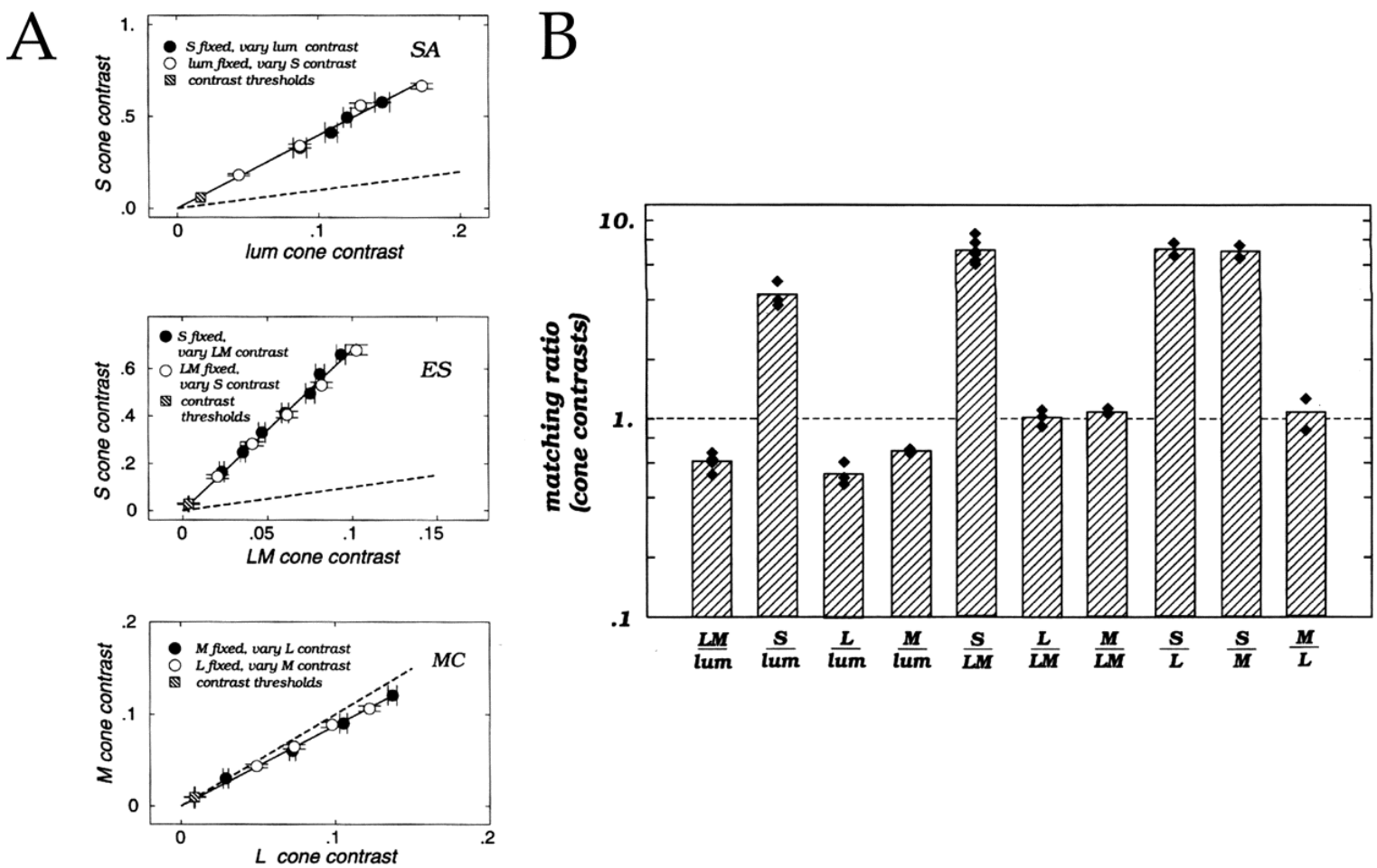
Contrast matching. A) achromatic and chromatic matching. B) Contrast ratio of colour matching.



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- Image Compression and Image Difference
  - Incomplete understanding of human vision
  - Have some operational knowledge of visual system
    - Improve image processing/compression system
      - Perceptually lossless coding
      - Perceptual coding (JPEG2000)
      - S-CIELAB computes visible colour difference

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2.6 Temporal Vision and Motion

- Temporal CSF
  - Critical Flicker Frequency (CFF)
  - Ferry-Porter Law
    - T-CSF increase linearly with average background intensity (in log scale)
  - Talbot-Plateau Law
    - Perceived intensity of a fused periodic stimulus is equivalent to a steady stimulus of the same time-average intensity

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- Counter phase grating for experiments
  - Contrast reverses over time
- Temporal contrast threshold for detection, a function of
  - temporal frequency of the modulation
  - spatial frequency of the pattern

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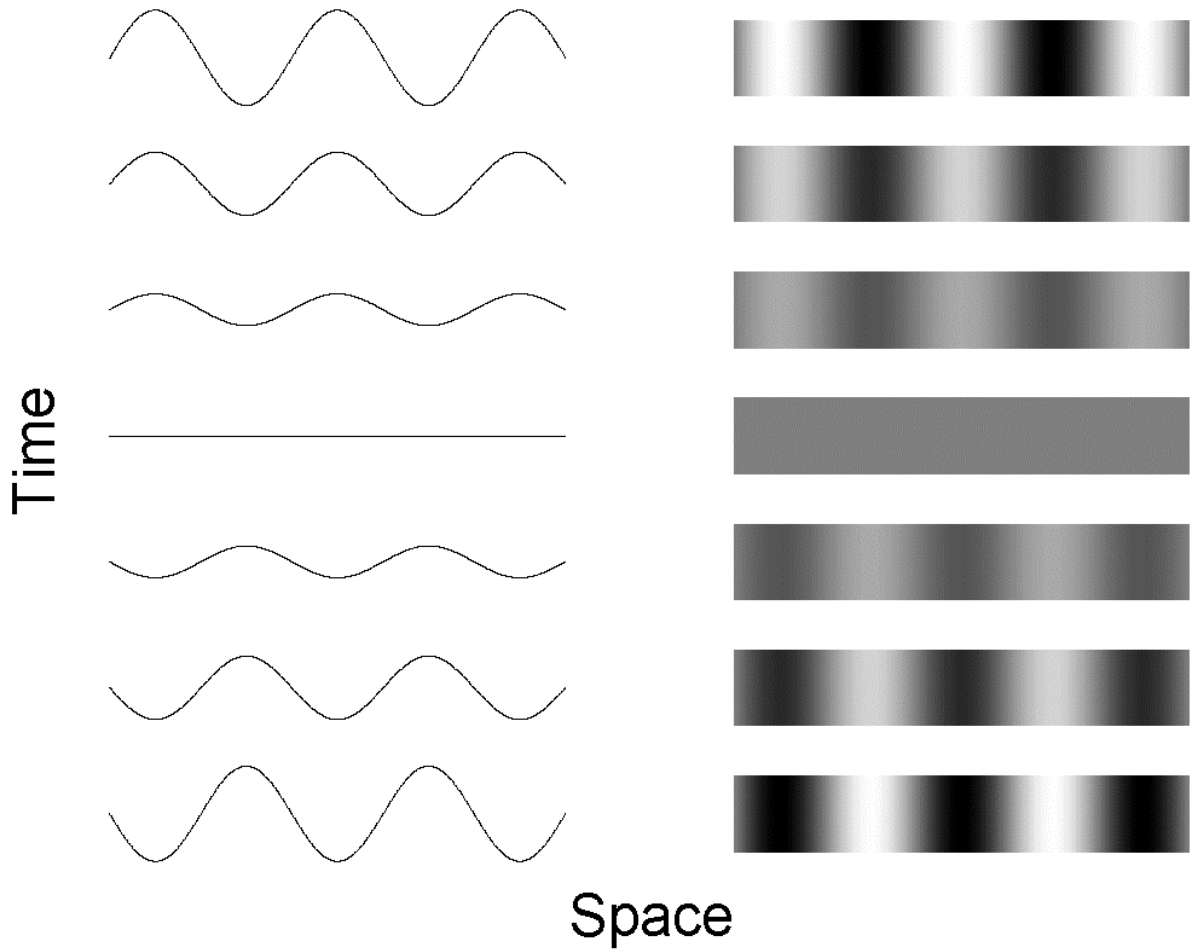
Temporally counter phased grating



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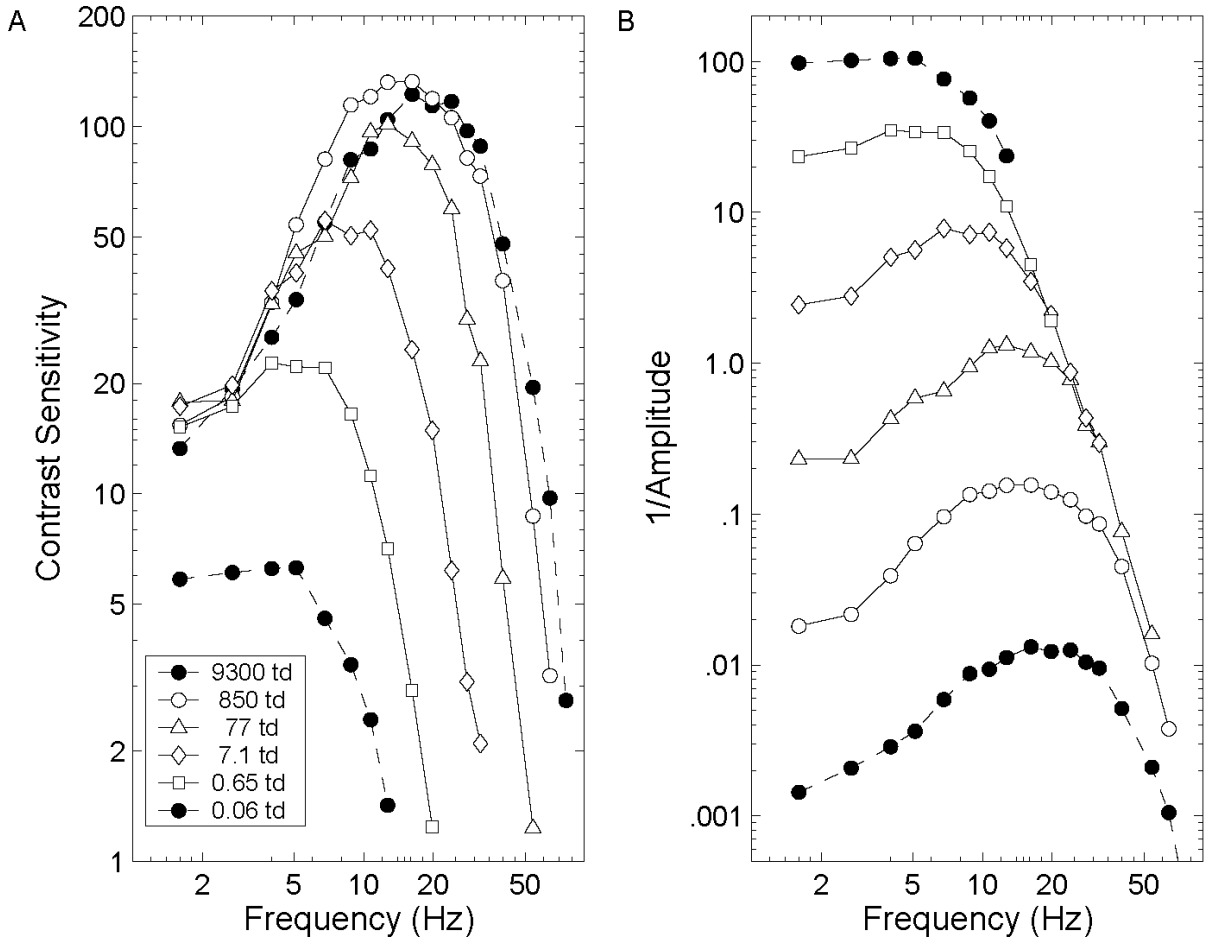
Temporal CSF with mean luminance measured in trolands



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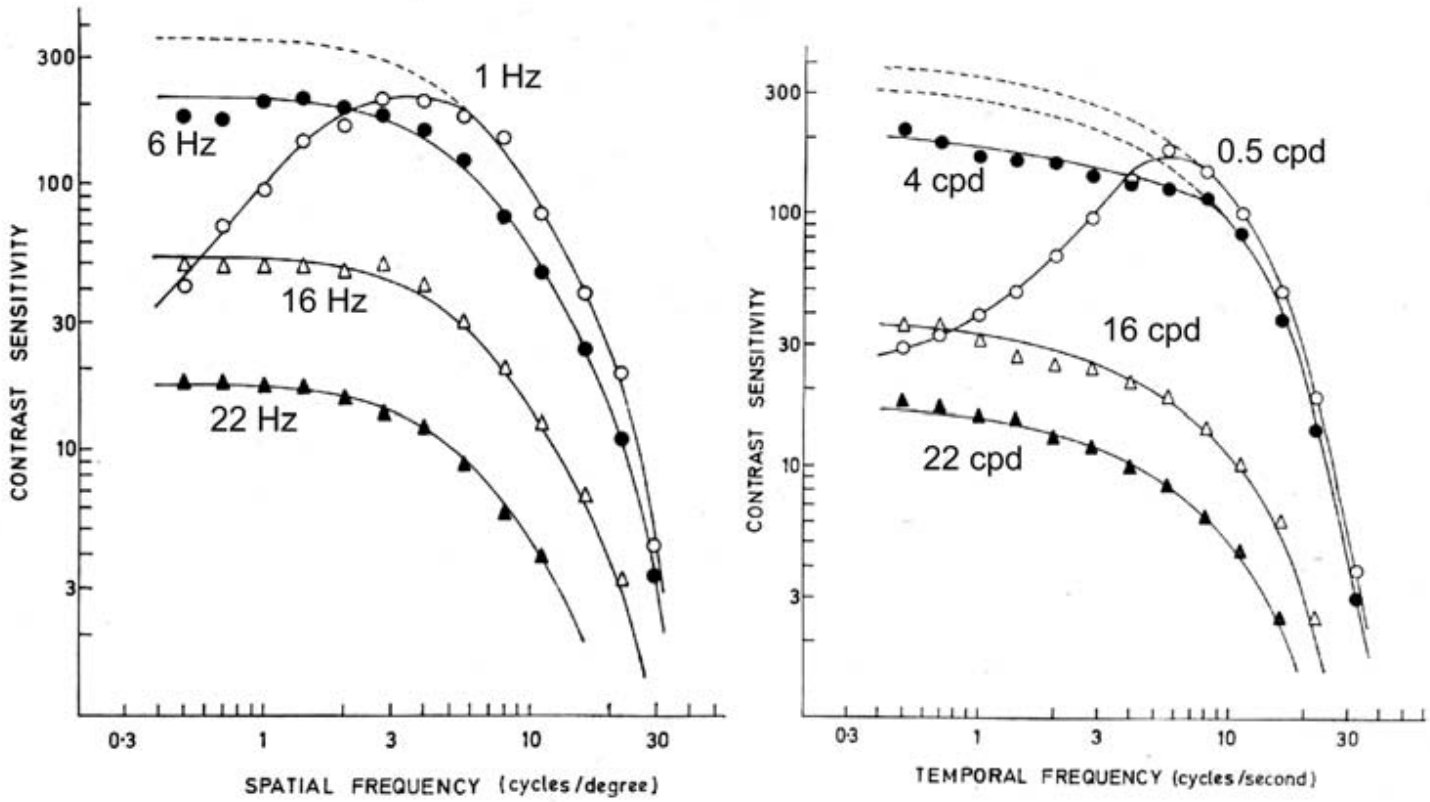
Spatial contrast sensitivity at various temporal frequencies (left) and vice versa (right)



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- Apparent Motion
  - motion after-effect due to adaptation
    - e.g. the moon can appear to move behind clouds
- Inter-Stimulus Interval (ISI)
  - Interval between stimulus
  - Short ISI (< 30 msec), no motion observable
  - Perceived motion between 30 – 60 msec (ISI)
  - Continuous motion with > 100 msec (ISI)

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- Korte's Law
  - Motion Detection
    - higher contrast for larger positional change
    - Higher contrast for shorter ISI
    - Larger positional separations for long ISI

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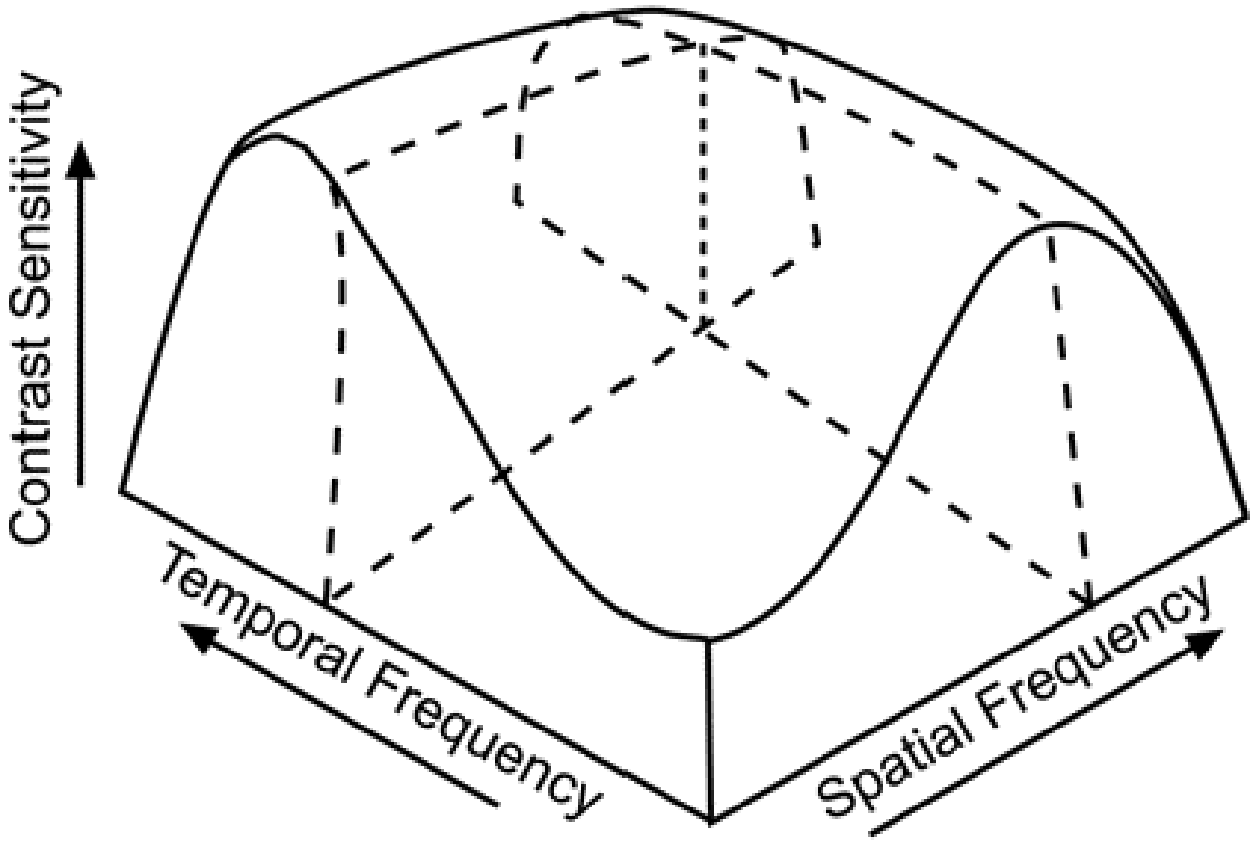
Spatio-temporal contrast sensitivity



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2.7 Visual Modelling

- Discoveries made in small steps
- Purpose of vision modelling
  - Automate tasks
  - Improve reproduction of real world images
- Applications
  - Image/video processing
    - Quality/fidelity measures
  - Image/video compression
    - Improve quality and/or compression performance

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2.8 Conclusion

- Overview of the visual system
- Colour vision
  - Colorimetry, colour appearance
- Luminance and intensity
- Spatial vision
  - Contrast sensitivity
- Temporal vision

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3. Coding Artifacts and Visual Distortions

M. Yuen

ESS Technologies Inc., China

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Chapter 3 Outline

3.1 Introduction

3.2 Blocking Effect

3.3 Basis Image Effect

3.4 Blurring

3.5 Colour Bleeding

3.6 Staircase Effect

3.7 Ringing

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Chapter 3 Outline

3.8 Mosaic Patterns

3.9 False Contouring

3.10 False Edges

3.11 MC Mismatch

3.12 Mosquito Effect

3.13 Stationary Area Fluctuation

3.14 Chrominance Mismatch

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Chapter 3 Outline

3.15 Video Scaling and Field Rate Conversion

3.16 De-interlacing

3.17 Summary

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3.1 Introduction

- Hybrid MC/DPCM/DCT coding
  - Classification and evaluation coding artifacts
  - Leads to improvement of coding systems
    - Constant quality video
- Artifacts identification
  - Attributes
    - Visual manifestation
    - Causes
    - Relationships

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- Classification limited to MPEG-1 artifacts
  - Derived through various coding rates
- Artifacts are difficult to isolate
  - unable specify coding rate which leads to the manifestation of any particular artifact
  - Multiple artifacts may co-exist together

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3.2 Blocking Effect

- Inherent in block based (DCT) coding
- Visual Characteristic
  - Discontinuity at block boundary
- Cause
  - Quantization of DCT coefficients
- Intra-frame mode
  - Prominent smoothly textured regions
  - DC coefficients has highest impact
  - Coarse quantization of AC coefficients

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Example of Blocking Effect

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- Inter-frame mode
  - External blocking
    - Boundary of 16x16 macro-block
    - Occurs around moving objects
      - Resulting from poor MC, block mismatch
  - Internal blocking
    - Boundaries of 8x8 DCT blocks within macro-block
    - Generally appears in mildly textured area with sufficiently high prediction error – errors not quantized to zero

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3.3 Basis Image Effect

- Block bearing distinct DCT basis image
  - AC basis with horizontal and vertical patterns
- Cause
  - Coarse quantization of low magnitude DCT coefficients
- Relationship
  - May lead to other artifacts
    - Blocking and mosaics

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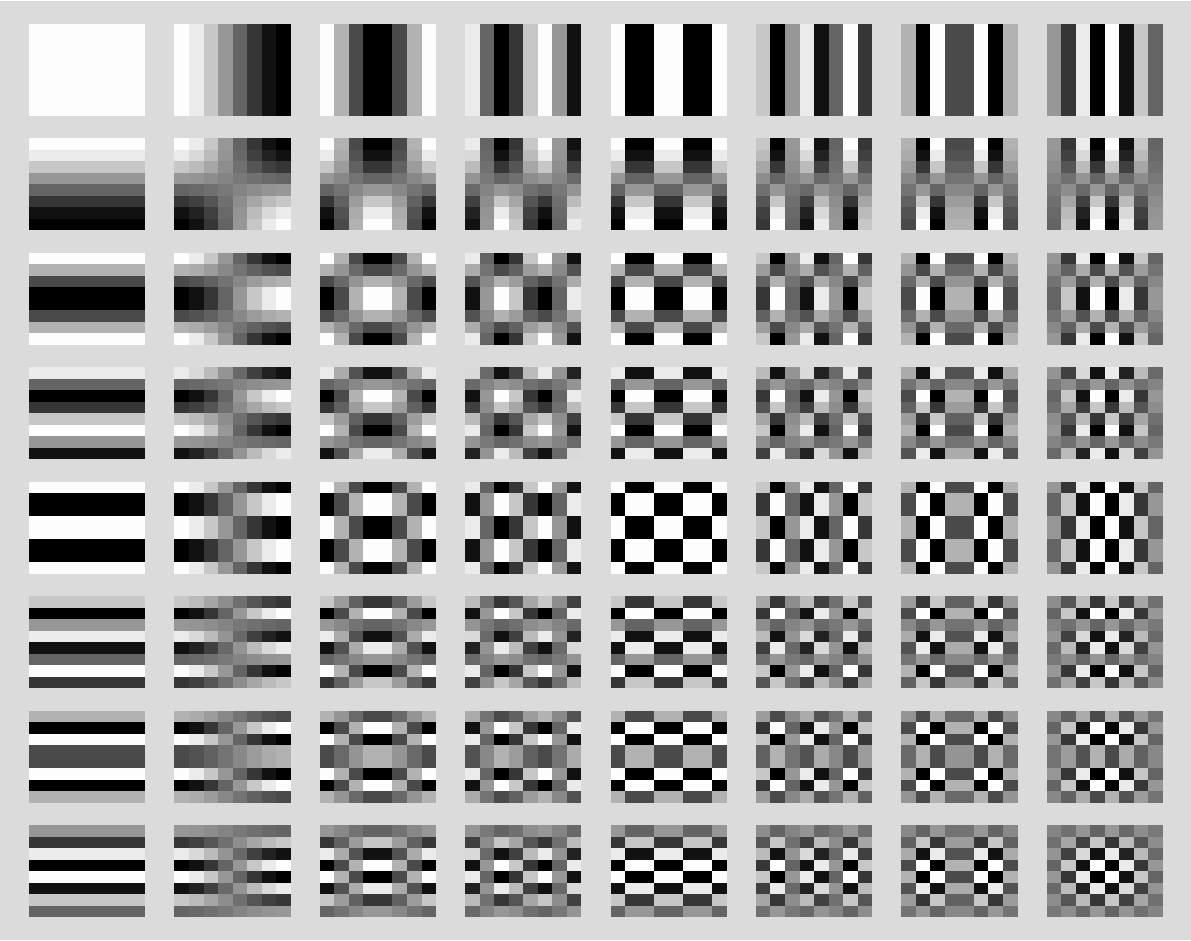
DCT Basis Function



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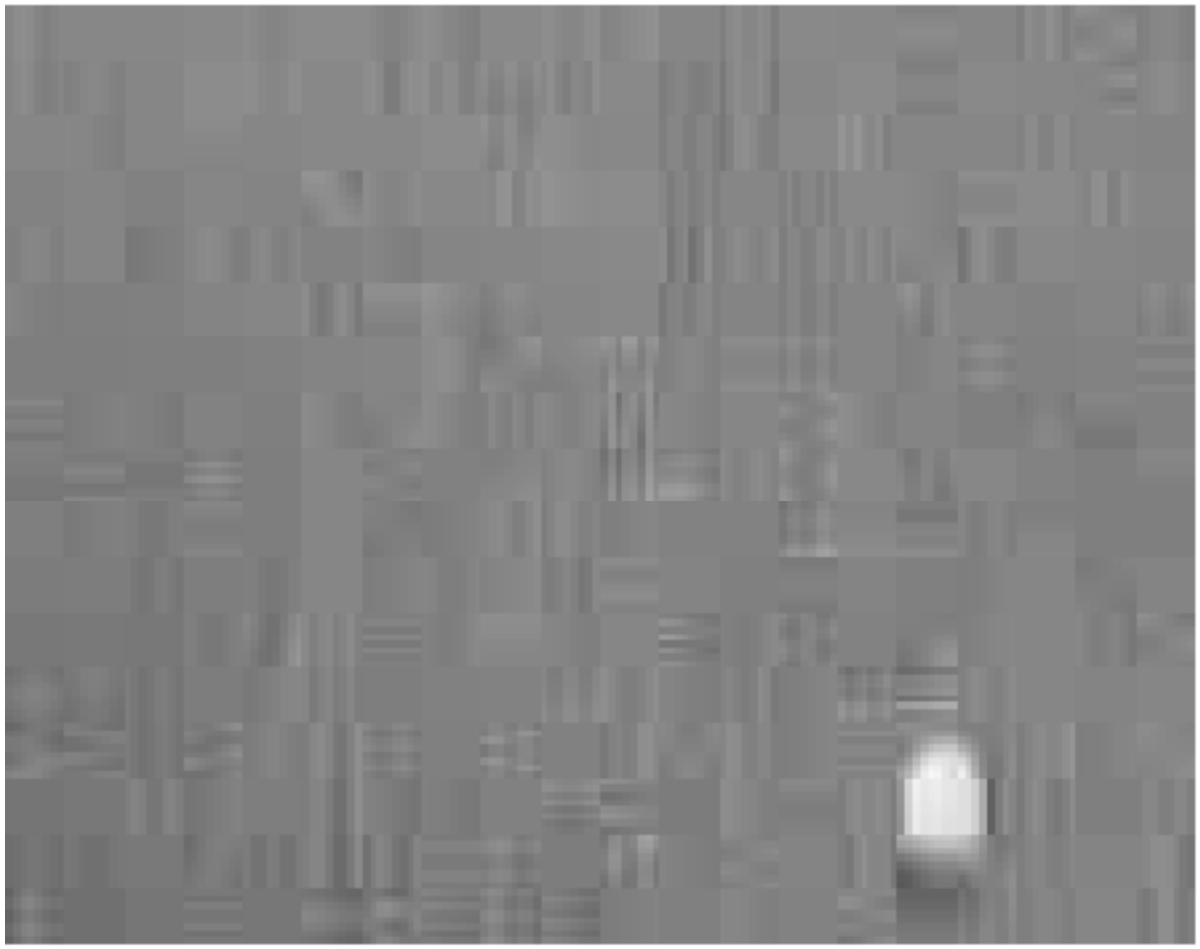
DCT Basis Image Effect



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- Visual significance of basis function
  - Different basis has different significance
  - Proportional to AC energy concentration in each coefficient
- Inter-frame coding
  - Appears in high spatial activity areas due to coarse quantization

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3.4 Blurring

- Loss of spatial detail
- Cause in DCT coding
  - Coarse quantization of mid to high frequency AC coefficients
- Associated artifacts
  - Blocking and mosaic effects if sufficient spatial information has been blurred
- Inter-frame coding
  - Prediction from macro-blocks with spatially degraded details

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3.5 Colour Bleeding

- Effectively colour blurring
  - Smearing of colour over areas of strong contrasting chrominance
- Cause
  - Coarse quantization of AC components
- Manifestation extends to macro-block boundaries
  - Due to sub-sampling of chroma channels (4:2:2 or 4:2:0)

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Colour bleeding in coded (0.6Mbps) chroma channels

Top left: C_b channel
Bottom left: C_r channel
Right: Decoded frame

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3.6 Staircase Effect

- Primary reason - no diagonal DCT basis function
- Cause by coarse quantization of AC components associated with diagonal edges
- Related to blocking and mosaic
- Appears around block boundaries

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Staircase Effects

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3.7 Ringing

- Occurs along high contrast edges in areas of generally smooth texture
- Appears as ripples moving outwards from the edge
- Chrominance Ringing
  - Related to colour bleeding/mismatch
  - Spans whole macro-block

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Ringing Artifact: along the edge of the table and the arm

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Low Ringing: *Claire* sequence @ 1Mbps. PSNR: approximately 45 dB

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3.8 Mosaic Patterns

- Mismatch between all or parts of adjacent blocks
  - Analogy from mismatch of mosaic tiles
- Cause
  - Coarse quantization of AC components
  - Subsequent contour and/or texture difference between adjacent blocks

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Mosaic Effect post de-blocking filter

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- Intra-frame mode
  - Generally occurs in areas of high spatial activity
  - Related to basis image effect
  - Mosaic effect more pronounced if mismatched patterns have different orientations

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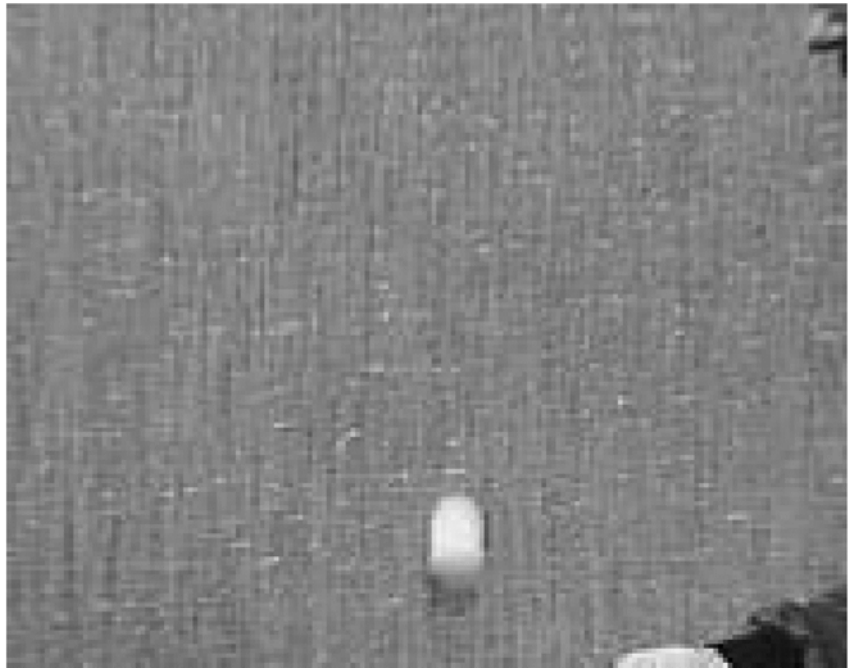
Mosaic effect and basis image effect. *left:* original frame. *Right:* coded frame



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- Inter-frame mode
  - MC mismatch
  - Occurs in high spatial activity areas
  - Successive prediction affects the degree of the mosaic effect
    - Successive prediction improves/refine spatial information

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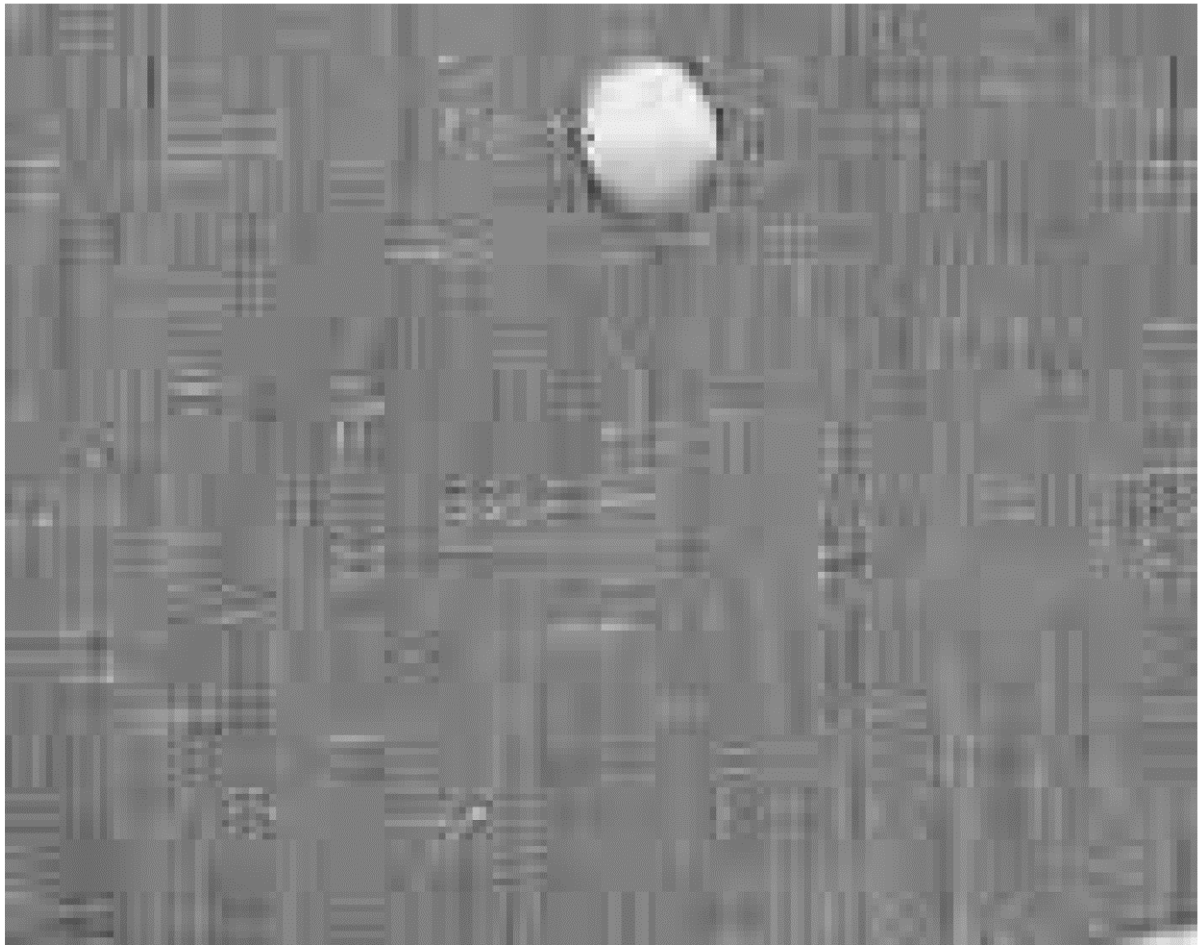
Mosaic effect in I-frame



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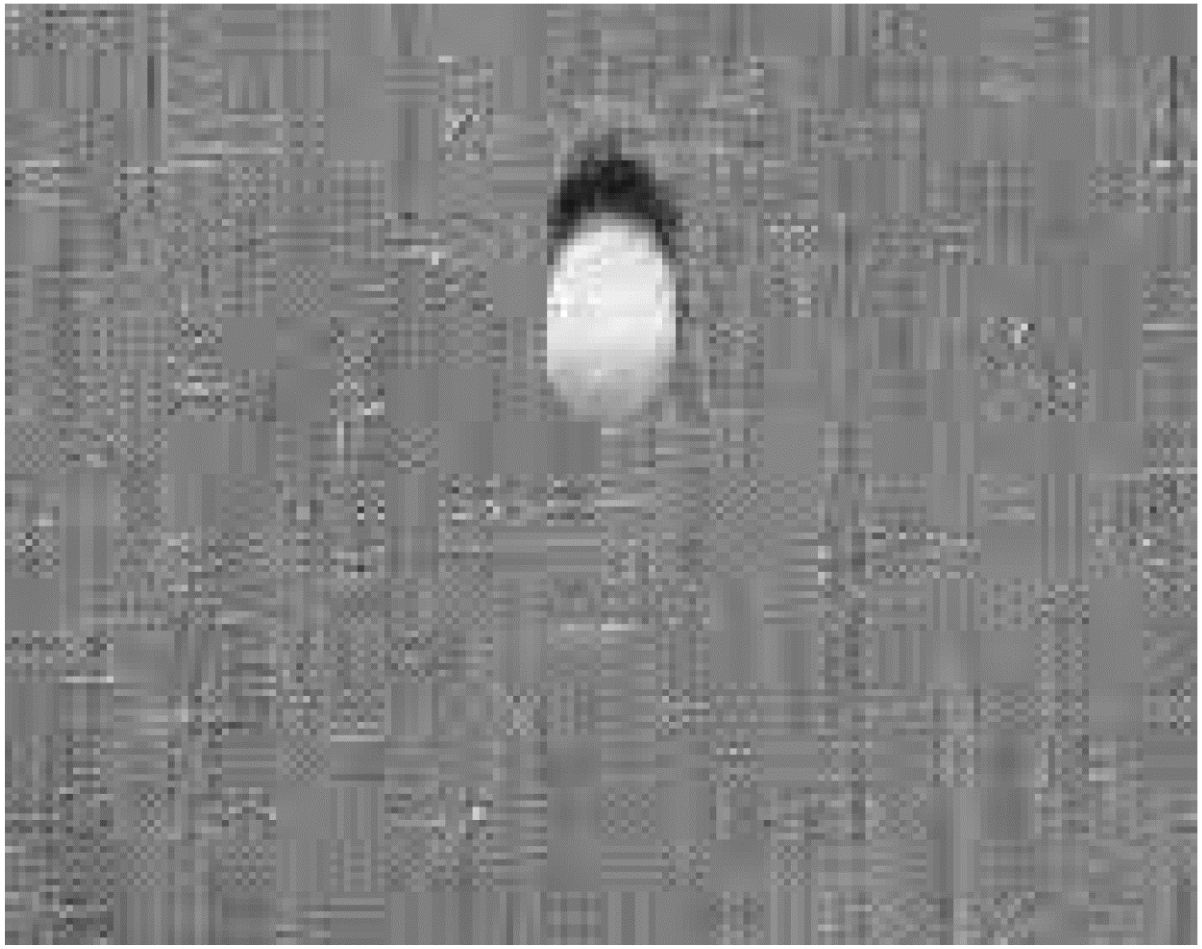
Mosaic effect in P-frame predicted from I-frame



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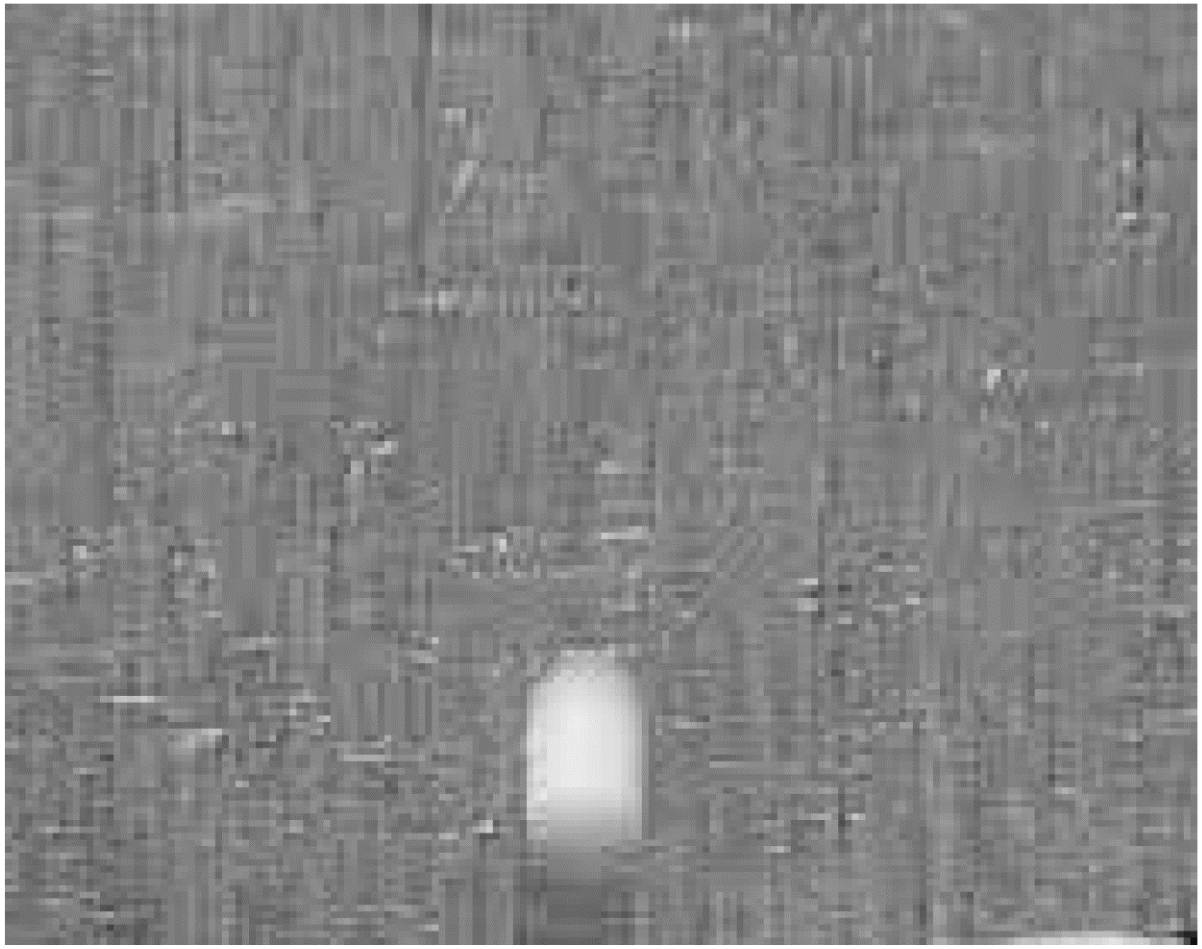
Deterioration on Mosaic effect in P-frame predicted from P-frame



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3.9 False Contouring

- Occurs in smoothly textured area with gradual transition in pixel intensity/value
- Appears as step-like gradation in affected areas
- Cause
  - Inadequate number of quantization levels
  - Irregular distribution of AC energy due to quantization

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False Contouring

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3.10 False Edges

- Occurs within inter-frame mode
- Propagated through blocking effect
  - Block-edge discontinuity used as reference of motion estimation
- Most prominent in smooth areas
- Usually localized to neighbouring frames

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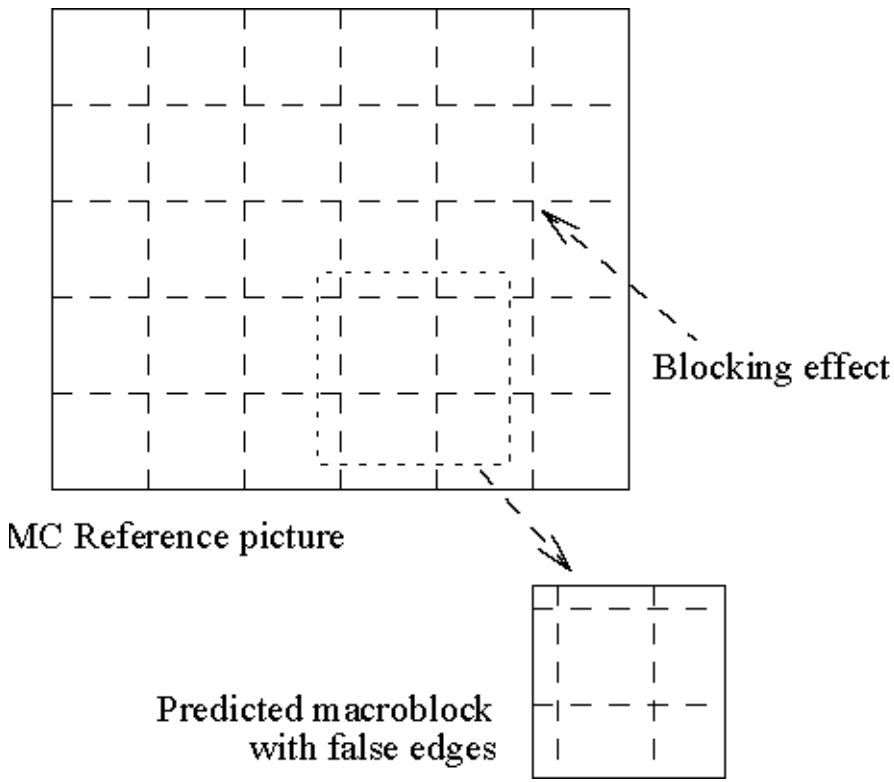
Propagation of blocking effect to false edges



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3.11 MC Mismatch

- Occurs when objects overlap in macro-blocks
- Subsequent MC will be unable to find a satisfactory match for overlapping objects
- Resulting in high prediction errors
- Errors ineffectively coded due to quantization
- Mismatch becomes visible

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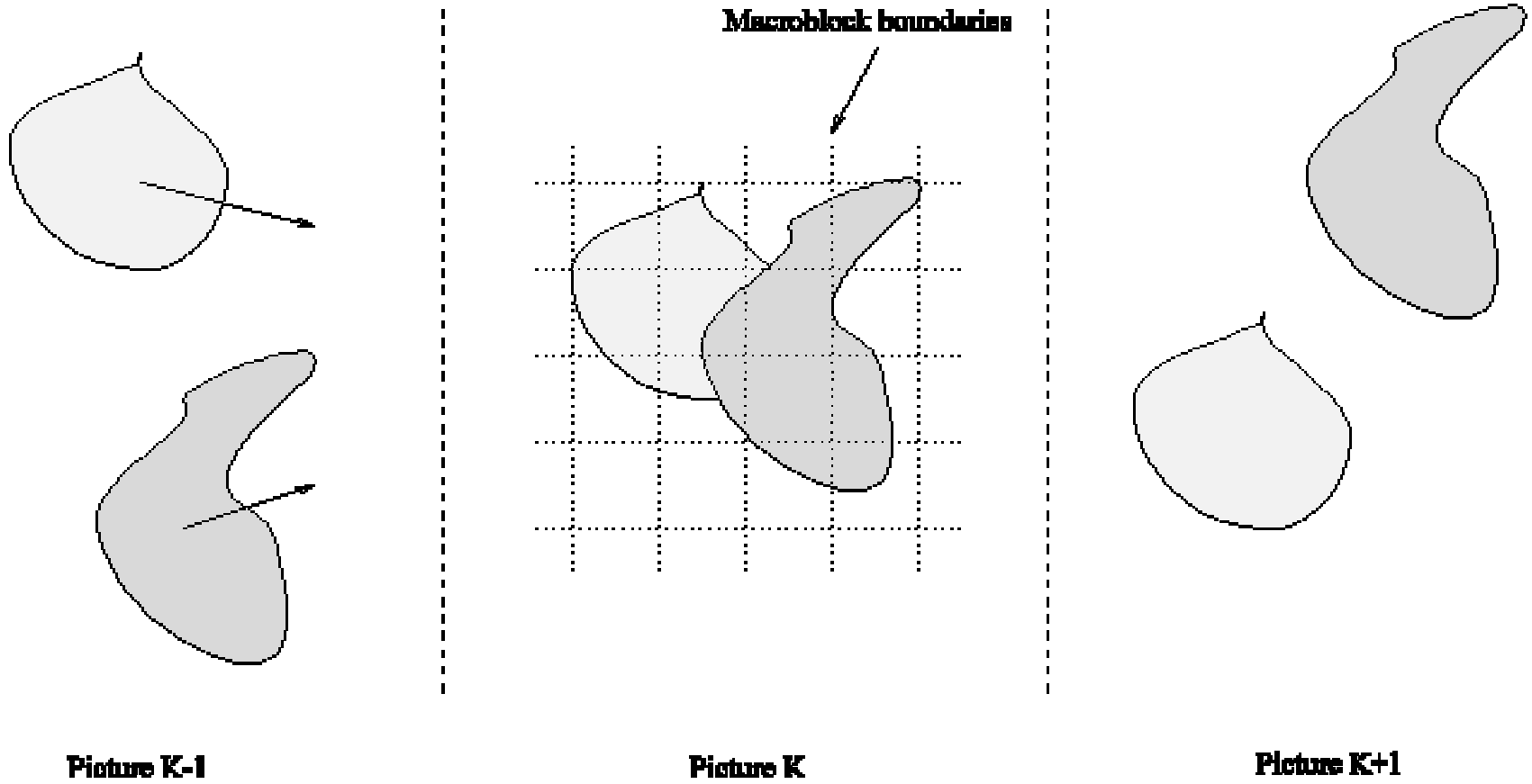
Macro-blocks encompassing the region of two objects with diverging motion



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High frequency noise induced by motion mismatch

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3.12 Mosquito Effect

- Due to temporal fluctuations
- Related to
  - Block mismatch
  - Ringing effect
- Ringing related mosquito effect
  - Occurs when coarse quantization is applied to high prediction errors in adjacent frames
  - Equivalent to fluctuating ringing

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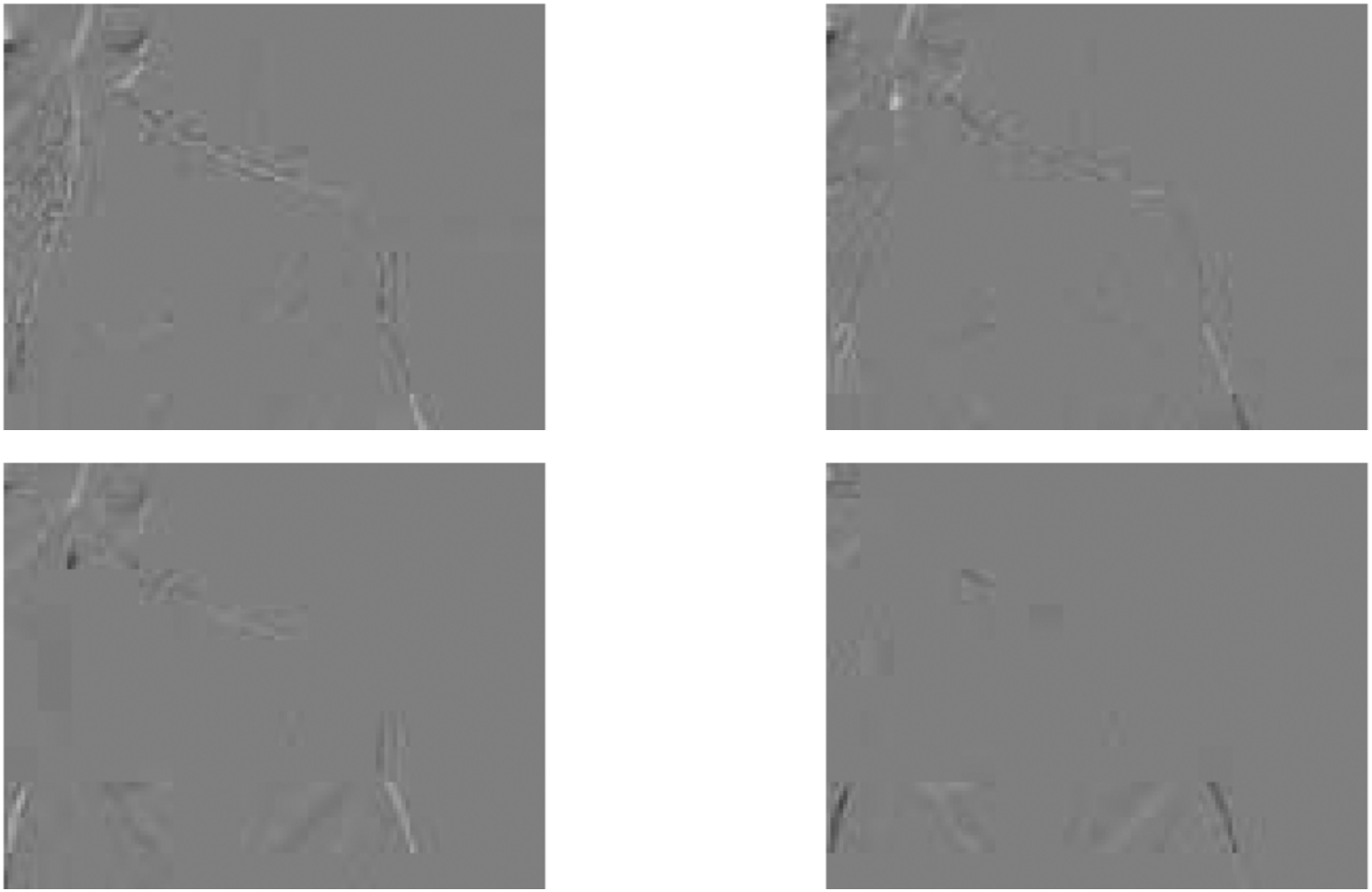
Difference sub-images of 5 successive *Claire* sequence. Order of coded frame: clockwise from top left.



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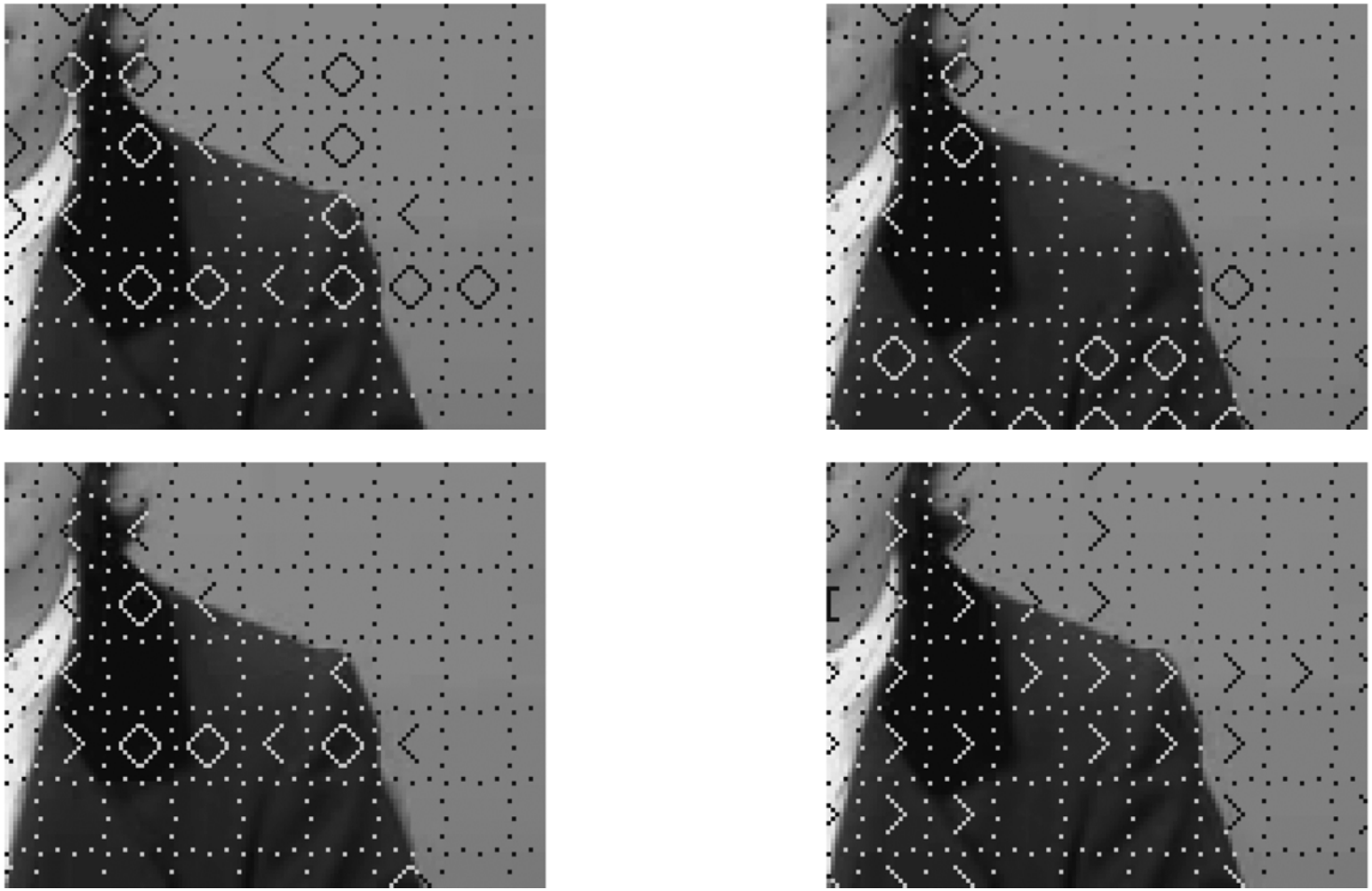
MC prediction type for 4 successive frames. Forward (>), backward (<) and bi-directional (<>) predictions.



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- Mismatched related mosquito effect
  - Enhanced mosquito effect due to MC mismatch of macro-blocks
  - Equivalent to fluctuating MC mismatch

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3.13 Stationary Area Fluctuation

- Occurs around high contrast edges in the temporal domain
- Visible even around areas with high details (e.g. highly textured areas)
- Primary cause
  - Quantization of high frequency prediction errors (DPCM)
    - Resulting in fluctuation of high spatial frequency

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Sons and Daughters Sequence (frame 40 and 41). Static background with some foreground motion

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Difference Image of frame 40 and 41 of *Sons and Daughters* sequence.

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3.14 Chrominance Mismatch

- Misplacement of a macro-block
  - relative to it's own general colour and surrounding colour
- Cause
  - Use of luminance channel motion vectors (MV) for chrominance
    - Optimum luminance and chrominance MVs for a given macro-block may not be the same

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Chrominance mismatch at the top of the tree trunk

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3.15 Video Scaling and Field Rate Conversion

- Scaling
  - Decimation → aliasing
  - Interpolation → blurring
- Field Rate Conversion
  - 60 Hz (NTSC) → 50 Hz (PAL) and vice versa
  - Jerky motion from downsampling
    - Temporal interpolation remove jerky motion, but produces ghosting artifacts

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3.16 De-interlacing

- Interlaced (dual) fields → frame
- Some de-interlacing methods
  - Line repetition and averaging
    - Aliasing at high vertical frequencies and some blurring problems
  - Field repetition
    - Serration artifacts around edges of moving objects
  - Motion adaptivity - hybrid methods
    - Luminance difference, median filters, motion compensation, etc

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3.17 Summary

- Classification of distortions in hybrid MC/DPCM/DCT coders
  - Based on consistent characteristics
- Quantization errors
  - Primary source of distortions
  - Spatial distortions
    - Within blocks and between blocks
  - Temporal distortions
    - Due to MC mismatch and quantized predicted errors

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- Distortions manifestation
  - Multiple types of distortions may co-exists
  - Some distortions are related
    - e.g. blocking and ringing
  - Distortions are difficult to isolate
  - Dependent on
    - Source content – distortion levels varies with picture content
    - Coding parameters – MC, DCT, quantization, etc

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AH94	A.J. Ahumada and R. Horng. De-blocking DCT compressed images. In *Proc. SPIE Human Vision, Visual Processing and Digital Display*, 2179:109-116, May 1994
Ahu92	A.J. Ahumada. Luminance-model-based DCT quantization for color image compression. In *Proc. SPIE Human Vision, Visual Processing and Digital Display*, 1666:365-374, 1992
Cla95	R.J. Clarke. *Digital Compression of Still Images and Video*. London: Academic Press, 1995
DM95	F. Dufaux and F. Moscheni. Motion estimation techniques for digital TV: A review and a new contribution. *Proc. IEEE*, 83(6):858-876, June 1995
Gir89	B. Girod. The information theoretical significance of spatial and temporal masking in video signals. In *Proc. SPIE Human Vision, Visual Processing and Digital Display*, 1077:178187, October 1989
GW92	R.C. Gonzales and R.E. Woods. *Digital Image Processing*, Reading, MA: Addison-Wesley, 1992

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HB98	G.D. Haan and E.B. Bellers. Deinterlacing – an overview. *Proc. IEEE*, 86(9) September 1998
HLS93	H. Hwang, M.H. Lee and D.I. Song. Interlaced to progressive scan conversion with double smoothing. *IEEE Trans. Consumer Electronics*, 39:241-246. August 1993
ITU90	ITU. *ITU-T Recommendation H.261: Video Codec for Audiovisual Services at p x 64 kbits/s*, 1990
ITU95	ITU. *Draft ITU-T Recommendation H.263: Video Coding for Low Bitrate Communication*, 1995
Jay92	N. Jayant. Signal compression: Technology targets and research directions. *IEEE J. Sel. Areas Commun.*, 10(5):796-818, June 1992
KHK87	M. Kaneko, Y. Hatori and A. Koike. Improvements of transform coding algorithm for motion-compensated inferframe prediction errors – DCT/SQ coding. *IEEE J. Sel./ Areas Commun.*, SAC-5(7):1068-1078, August 1987

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KK95	S.A. Karunsekera and N.G. Kingsbury. A distortion measure for blocking artifacts in images based on human visual sensitivity. *IEEE Trans. Image Processing*, 4(6):713724, June 1995
KSC92	S.A. Klein, A.D. Silverstein and T. Carney. Relevance of human vision to JPEG DCT compression. In *Proc. SPIE Human Vision, Visual Processing and Digital Display*, 1666:200-215, 1992
Le91	D. Le Gall. MPEG: A video compression standard for multimedia applications. *Communications of the ACM*, 34(4):47-57, April 1991
NH89	A.N. Netravali and B.G. Haskell. *Digital Pictures: Representation and Compression*, New York: Plenum Press, 1989
PAW93	H.A. Peterson, A.J. Ahumada and A.B. Watson. Improved detection model for DCT coefficient quantization. In *Proc. SPIE Human Vision, Visual Processing and Digital Display*, 1913:191-201, September 1993
Plo89	R. Plompen. Motion video coding for visual telephony, 1989

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RG86	B. Ramamurthi and A. Gersho. Nonlinear space-variant postprocessing of block coded images. *IEEE Trans. Acoust., Speech and Signal Processing*, ASSP-34(5):1257-1268, October 1986
RL83	H.C. Reeve and J.S. Lim. Reduction of blocking effects in image coding. In *Proc. IEEE ICASSP*, 1212-1215, Boston, MA, April 1983
RY90	K.R. Rao and P. Yip. *Discrete Cosine Transform: Algorithms, Advantages, Applications*. San Diego, CA: Academic Press, 1990
Sec91	Secretariat ISO/IEC JTC1/SC29. *ISO CD11172-2: Coding of moving pictures and associated audio for digital storage media at up to about 1.5 Mbits/s*. ISO, November 1991
Sec92	Secretariat ISO/IEC JTC1/SC29/WG11. *Test Model 1*. ISO , May 1992. Description of MPEG-2 test model
Tzo88	K.H. Tzou. Post-filtering of transform-coded images. In *Proc. SPIE Human Vision Visual Processing and Digital Display*, 2178:99-108, May 1994

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YGK95	Y. Yang. N.P. Galatsanos and A.K. Katsaggelos. Projection-based spatially adaptive reconstruction of block-transform compressed images. *IEEE Trans. Image Processing*, 4(7):896-908, July 1995
YWR95	M. Yuen, H.R. Wu and K.R. Rao. Performance evaluation of POCS loop filtering in generic MC/DPCM/DCT video coding. In *Proc. SPIE Visual Communication and Image Processing*, 2501:65-75, Taipei, Taiwan, May 1995

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II. Picture Quality Assessment and Metric

4. Video Quality Testing

Philip Corriveau

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Chapter 4 Outline

4.1 Introduction
4.2 Subjective Assessment Methodologies
4.3 Selection of Test Materials
4.4 Selection of Participants - Subjects
4.5 Experimental Design
4.6 International Testing Methods
4.7 Objective Assessment Methods
4.8 Summary

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4.1 Introduction

- Proliferation of audio/visual media
- Audio/visual services
  - Important to maintain quality of services
  - How to measure picture quality?
  - Difference between analogue and digital media
- Two approach to Quality measure
  - Subjective assessment
  - Objective assessment

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4.2 Subjective Assessment Methodologies

- Utilize human subjects for assessment
- Most reliable way for quantify picture quality
- Different assessment methodology for different conditions

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4.3 Selection of Test Materials

- Variations in picture quality
  - is subjected to compression, transmission and manipulation operations
- Picture content also affects picture quality
  - video sequences with minimal motion can maintain sufficiently high picture quality at low bitrates (*Susie*)
  - At similar bitrates, other types (content) of video sequences exhibit noticeable distortions. e.g. *Mobile & Calendar*

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Susie Sequence

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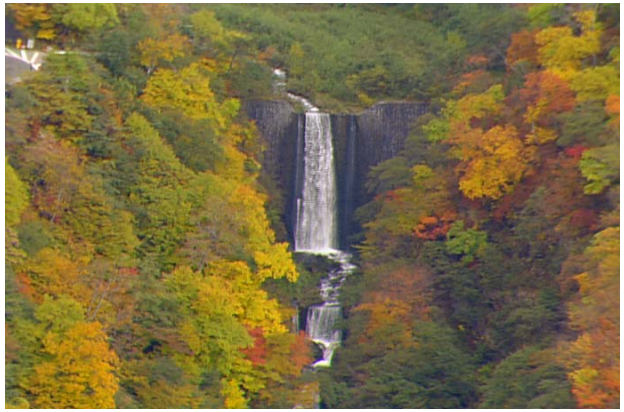
Common test sequences: clockwise from top left: *Waterfall, Tree, Mobile & Calendar and Tempete*



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- Robust picture quality test for motion video equipment and system should
  - Have multiple sources
  - 8 to 16 different source material types
- Source materials provided through standards and co-operative bodies:
  - IEEE
  - SMPTE
  - VQEG (Video Quality Experts Group)

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4.4 Selection of Participants - Subjects

- Either experts or non-experts
- Screening
  - Visual acuity
  - Colour blindness
  - Other visual impairments
- Subject numbers
  - 16 to 24 subjects to maintain statistic relevance

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- Experts
  - Advantages
    - Experience
    - More precise evaluation – good for evaluating technical performance
  - Disadvantages
    - Bias evaluation
    - Critical evaluation – does not reflect the generalized view of the average consumer

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- Non-experts
  - General public, average user
  - May see artifacts that experts missed
    - Since they generally have a non-structured approach to evaluating picture quality/impairment
  - Generally reliable if tests are structured properly
  - Factors influencing non-expert
    - Age, gender, etc

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- Screening
  - For visual defects
  - Standardized tests
    - Snellen Eye Chart ©
      - Screens for 20/20 normal or corrected vision
    - Ishihara ©
      - Screens for colour blindness

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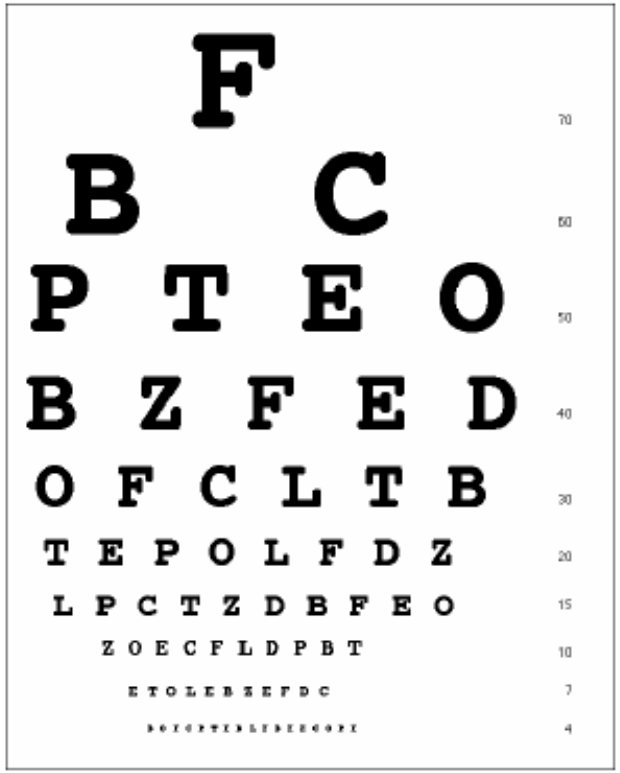
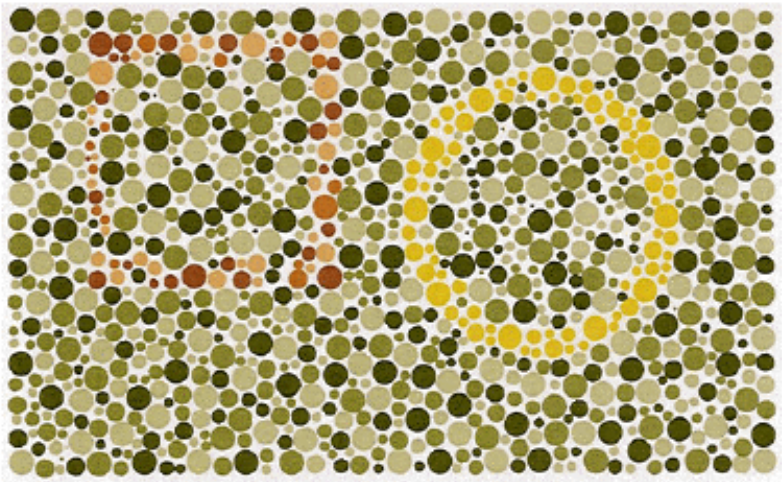
Snellen eye chart (left) and Ishihara test plate (right)





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4.5 Experimental Design

- Factors to consider for tests
  - Time
    - Excessive test duration leads to fatigue
    - Commonly 30 mins session with warm-up trials
  - Double/Single presentation
    - Affects test duration and limit number of test conditions covered
  - Repeat tests
    - For stabilizing results.
    - Past experience has shown little gain in data stability with repeats

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- Factors affecting testing environment
  - Lighting
  - Ambient noise
  - Quality and calibration of display device
- Environmental specifications
  - ITU-T BT.500 standard
  - Exemplar testing environment
    - Communications Research Centre (CRC), Canada

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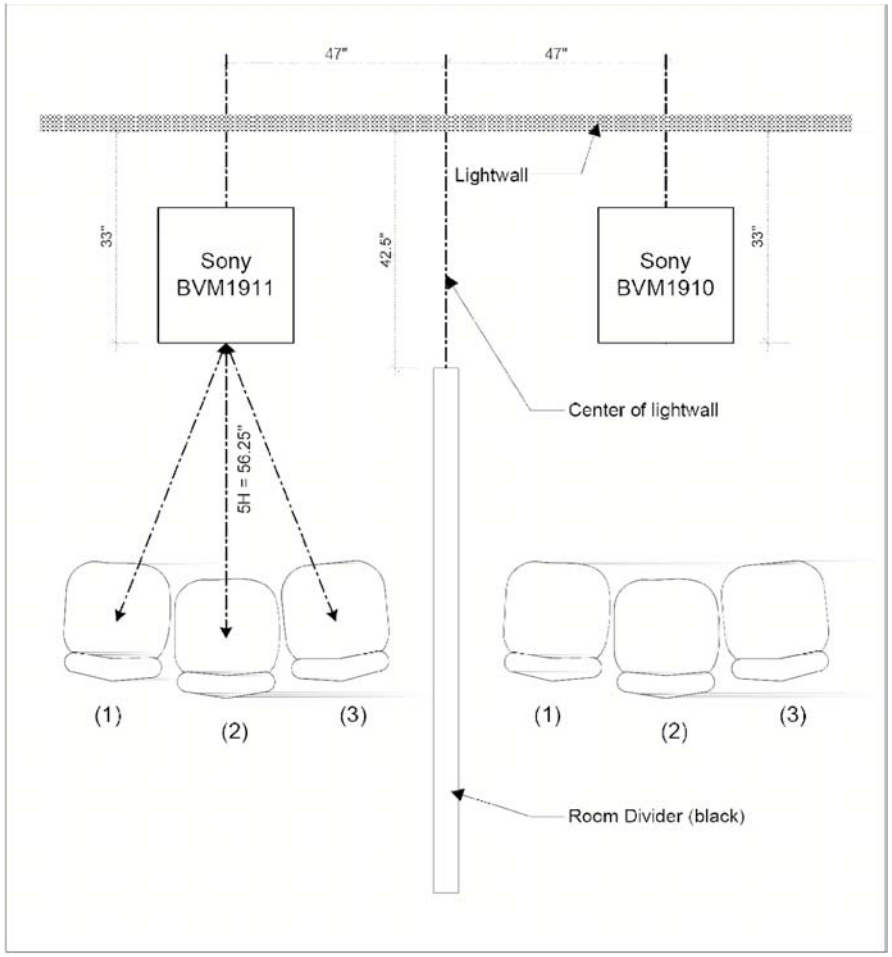
Testing room layout at CRC



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- Common experimental mistakes
  - Limited set of test material
  - Inadequate coverage of the range of conditions to be tested
    - Make sure that which is to be tested is tested thoroughly
  - Excessively long test durations → fatigue
  - Neglecting warm-up and re-set trials
    - Allows adjustment to testing procedures

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4.6 International Testing Methods

- Double Stimulus Impairment Scale (DSIS)
- Double Stimulus Quality Scale (DSQS) Method
- Comparative Test
- Single Stimulus Continuous Quality Evaluation (SSCQE)
- Clear instructions on “how to do the test” must be given to subjects prior to test

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4.6.1 Double Stimulus Impairment Scale (DSIS)

- Impairment measurement
- A 5-point discrete scale is commonly used
  - *Imperceptible* – perfect quality
  - *Perceptible, but not annoying*
  - *Slightly annoying*
  - *Annoying*
  - *Very Annoying* – unwatchable

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DSIS 5-point rating scale

Imperceptible	☐
Perceptible, But Not Annoying	☐
Slightly Annoying	☐
Annoying	☐
Very Annoying	☐

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DSIS test instructions

INSTRUCTIONS FOR IMPAIRMENT TESTS

In this test, we ask you to judge the visibility and severity of impairments in the television picture resulting from imperfections or interference in broadcasting.

Each trial will be announced verbally by number. The first presentation of a trial will be announced as "Reference", and the second presentation will be announced as "Test".

The test consists of a series of judgement trials, each consisting of two presentations of the same piece of video material. The first presentation shows the video material from a Reference signal (a broadcast not subjected to interference). The second presentation shows the same material from a Test signal (a broadcast subjected to a measured amount of interference).

We will now show you four demonstration trials. Across the four demonstrations, the test material will exhibit different levels of visible impairment to illustrate the kinds of impairments you will see during the test session.

DEMONSTRATION TRIALS

You are asked to examine the Reference presentation and note any deficiencies present, and then to assess the visibility and severity of any additional impairment in the Test material.

In judging the visibility and severity of transmission impairments, we ask you to use judgement scales like the sample shown below.

IMPERCEPTIBLE	☐
PERCEPTIBLE, BUT NOT ANNOYING	☐
SLIGHTLY ANNOYING	☐
ANNOYING	☐
VERY ANNOYING	☐

SAMPLE JUDGEMENT SCALE

The judgement scale offers five response options. These options are: "imperceptible", "perceptible, but not annoying", "slightly annoying", "annoying", and "very annoying". You are asked to place a single "X" in the box that best corresponds to your judgement (as shown in the example).

IMPERCEPTIBLE	☐
PERCEPTIBLE, BUT NOT ANNOYING	☒
SLIGHTLY ANNOYING	☐
ANNOYING	☐
VERY ANNOYING	☐

SAMPLE JUDGEMENT SCALE

We ask you to use the judgement scales to express your judgement of the visibility and severity of the incremental impairment in the Test material. Please note, in some trials, the Reference material itself may have visible impairments. These are not of interest in this test.

Please refrain from recording your judgement until the final grey period of the trial.

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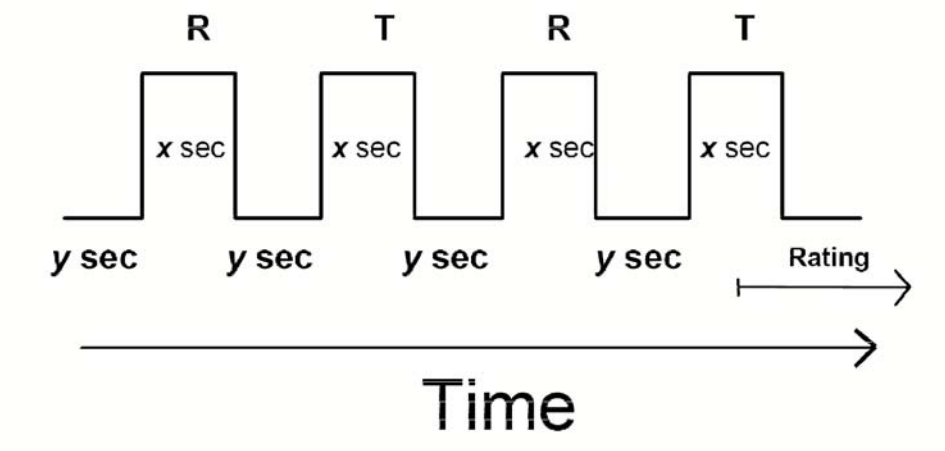
- DSIS measures failure characteristics
  - e.g. minimum coding rate relative to quality

Below: DSIS trial structure with reference (*R*) and test (*T*) material. Impairment is recorded during the rating period



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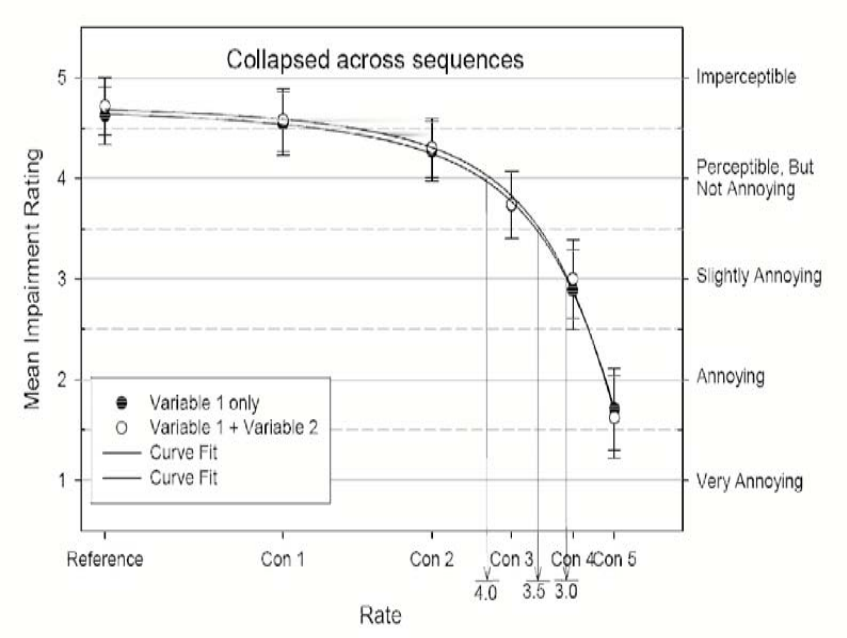
Typical outcome of the overall impairment results



- Overall analysis
  - Testing various conditions (con1, con2, etc)
    - Graph signifies behaviour
  - Test methods with 1 and 2 variables
    - Simultaneous assessment of two systems under multiple conditions

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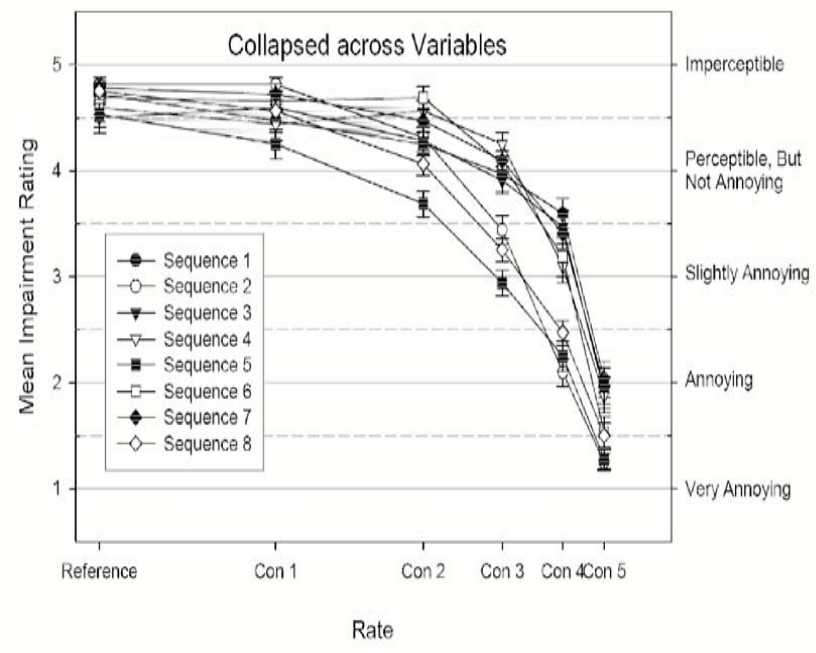
Individual sequence results for a typical DSIS test

- Specific Analysis
  - Evaluate the response of individual sequence
    - Identify extremities, thus operational boundaries of systems
  - Identify system behaviour relative to specific source type
    - Poor with what type?
    - Good with what type?



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4.6.2 Double Stimulus Quality Scale (DSQS) Method

- Quality measurement
- Double scale for grading quality
  - Measurement taken as difference between two scores
- Continuous scale (0-100)
  - Minimizes quantization errors
  - 5 categories: Excellent (80-100); Good (60-79); Fair (40-59); Poor (20-49) and bad (0-19)

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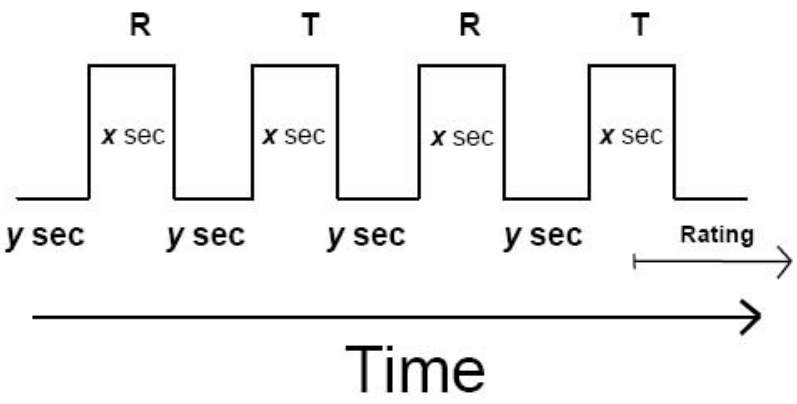
- Subjects rate both the first (*R*) and the second (*T*) sequence.
- Double blind test
  - *R* and *T* may be in reverse order
  - Sequence order is unknown to both subject and tester



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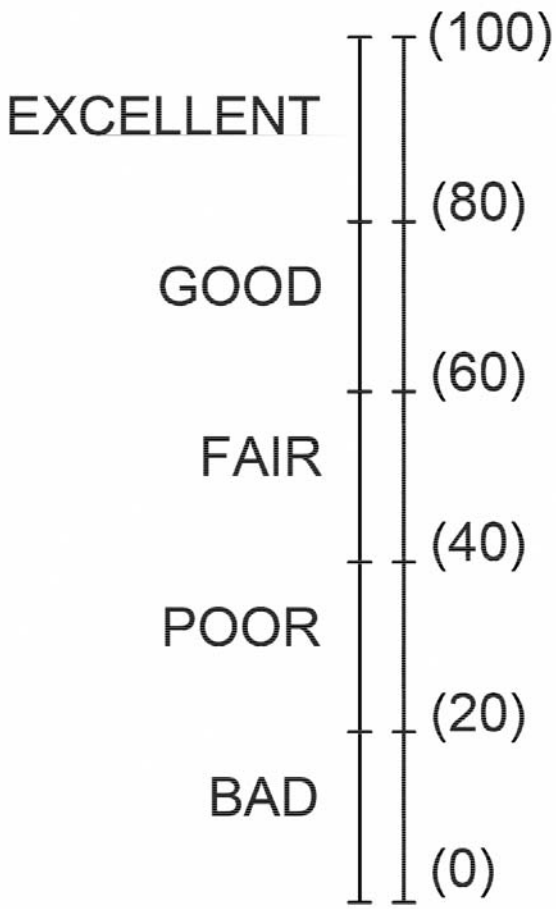
DSQS scale



- Properly design tests
  - Score difference between 1st and 2nd sequence rarely exceed 40 units
  - Often under 25
- Reference may be rated lower than test sequence

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DSQS test instructions

INSTRUCTIONS FOR QUALITY TESTS

In this test, we ask you to evaluate the overall quality of the video material you see. By overall quality, we mean the quality of the appearance of the video, not the desirability of the material itself.

Possible problems in quality include:

- poor, or inconsistent, reproduction of detail;
- poor reproduction of colours, brightness, or depth;
- poor reproduction of motion;
- imperfections, such as false patterns, or "snow".

The test consists of a series of judgement trials, each consisting of four presentations of the same piece of video material.

Each trial will be announced verbally by number. The first presentation of a trial will be announced as "A", and the second as "B". This pair of presentations will then be repeated, thereby completing a single trial. Please note that one of the presentations, A *or* B, will be a reference picture that shows the video material in a high quality format, with the other being a test picture that shows the same video material in the format being tested.

We will now show you four demonstration trials.

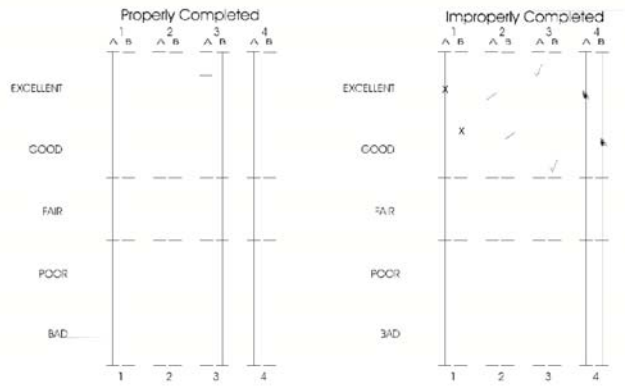
DEMONSTRATION TRIALS

In judging the overall quality of the presentations, we ask you to use judgement scales like the samples shown below.

SAMPLE QUALITY SCALE

As you can see, there are two scales for each trial, one for the "A" presentation and one for the "B" presentation, since both the "A" and "B" presentations are to be judged.

The judgement scales are continuous vertical lines that are divided into five segments. As a guide, the adjectives "excellent", "good", "fair", "poor", and "bad" have been aligned with the five segments of the scales. You are asked to place a single horizontal line at the point on the scale that best corresponds to your judgement of the overall quality of the presentation (as shown in the example).



You may make your mark at any point on the scale which most precisely represents your judgement.

In making your judgements, we ask you to use the first pair of presentations in the trial to form an impression of the quality of each presentation, but to refrain from recording your judgements. You may then use the second pair of presentations to confirm your first impressions and to record your judgements in your Response Booklet.

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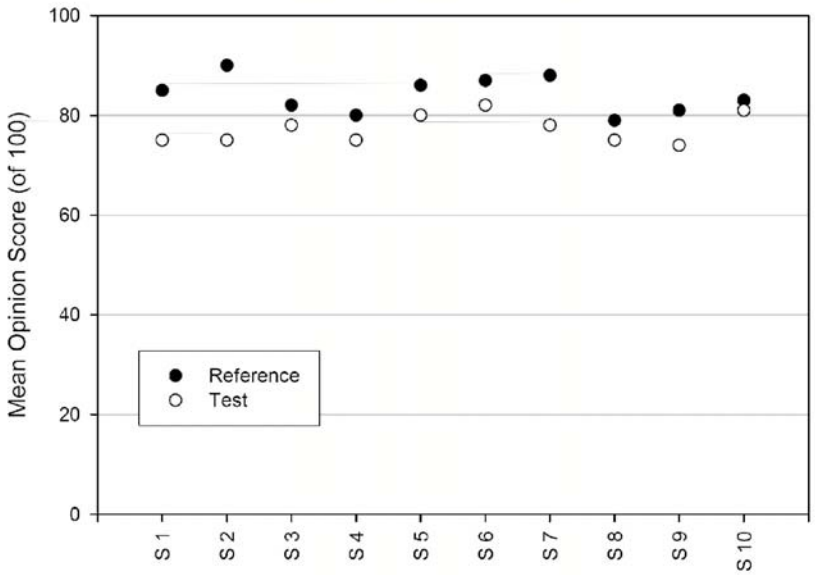
Typical DSQS raw results

- Mean Opinion Score (MOS)
  - Purposes
    - Check stability of reference score
    - Rough indication of differences between reference and test sequences



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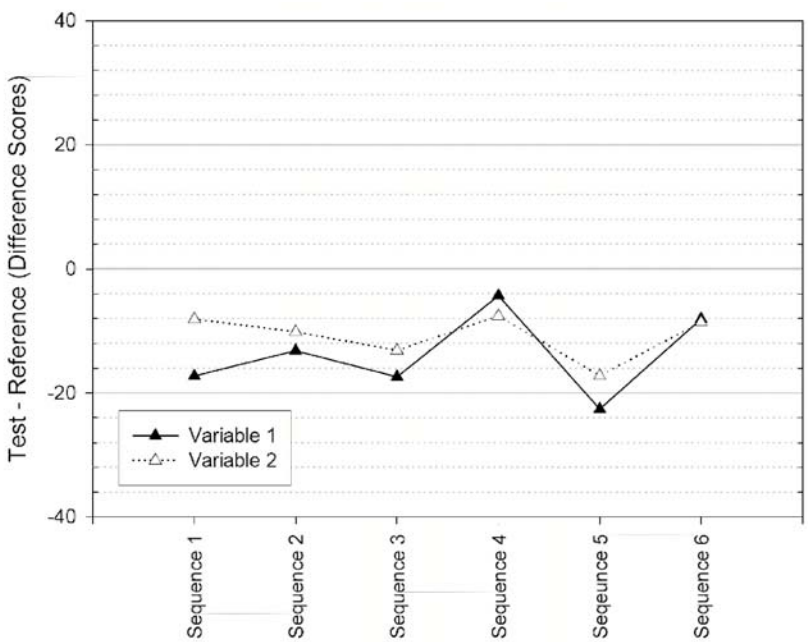
Typical DSQS difference results



- Minus test
  - Check if test sequence has been rated higher than reference
- Analysis
  - Test methods
    - Ascertain the difference between 1 and 2 variables
  - Is quality dependent on sequences?

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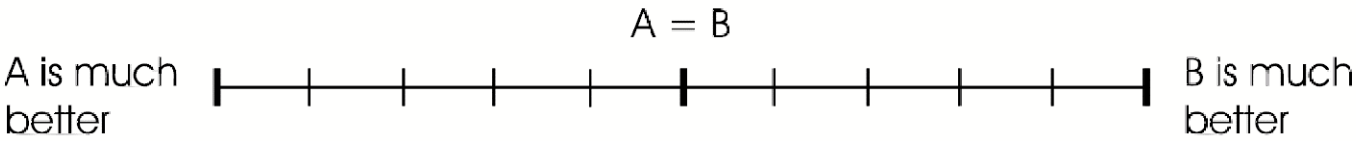
4.6.3 Comparison Scale Method

- For comparing systems with equal capability
- Comparative Scale (below)
  - 100 units: -50(A) → 0 (A=B) → 50(B)



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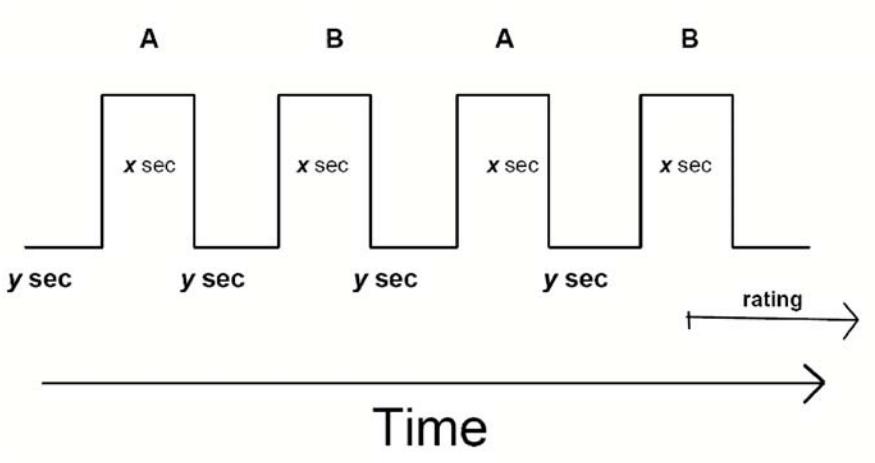
Comparative test trial structure



- Double blind test
- Single or double stimulus

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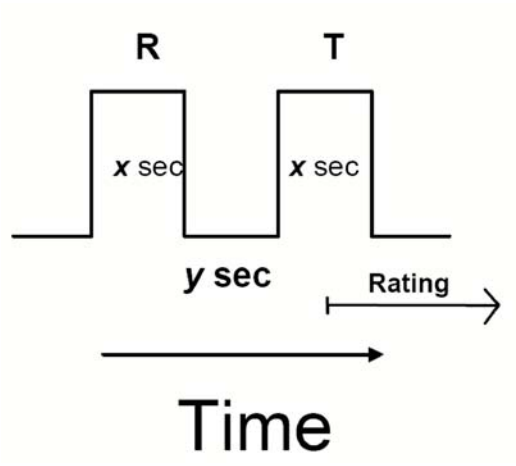
4.6.4 Single Stimulus Method

- One stimulus per set of sequence
  - One opportunity to evaluate, no repeat
- Shorter testing time
- Applicable to DSQS, DSIS, CS, etc



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4.6.5 Continuous Quality Evaluations

- Single Stimulus Continuous Quality Evaluation (SSCQE) method
- No reference sequences
- Continuous rating
  - Sequences under evaluation are rated for the duration of the sequence
    - Record variation in picture quality within sequences in addition to between sequences
  - Continuous recording with slider (i.e. mouse or cursors) in computer

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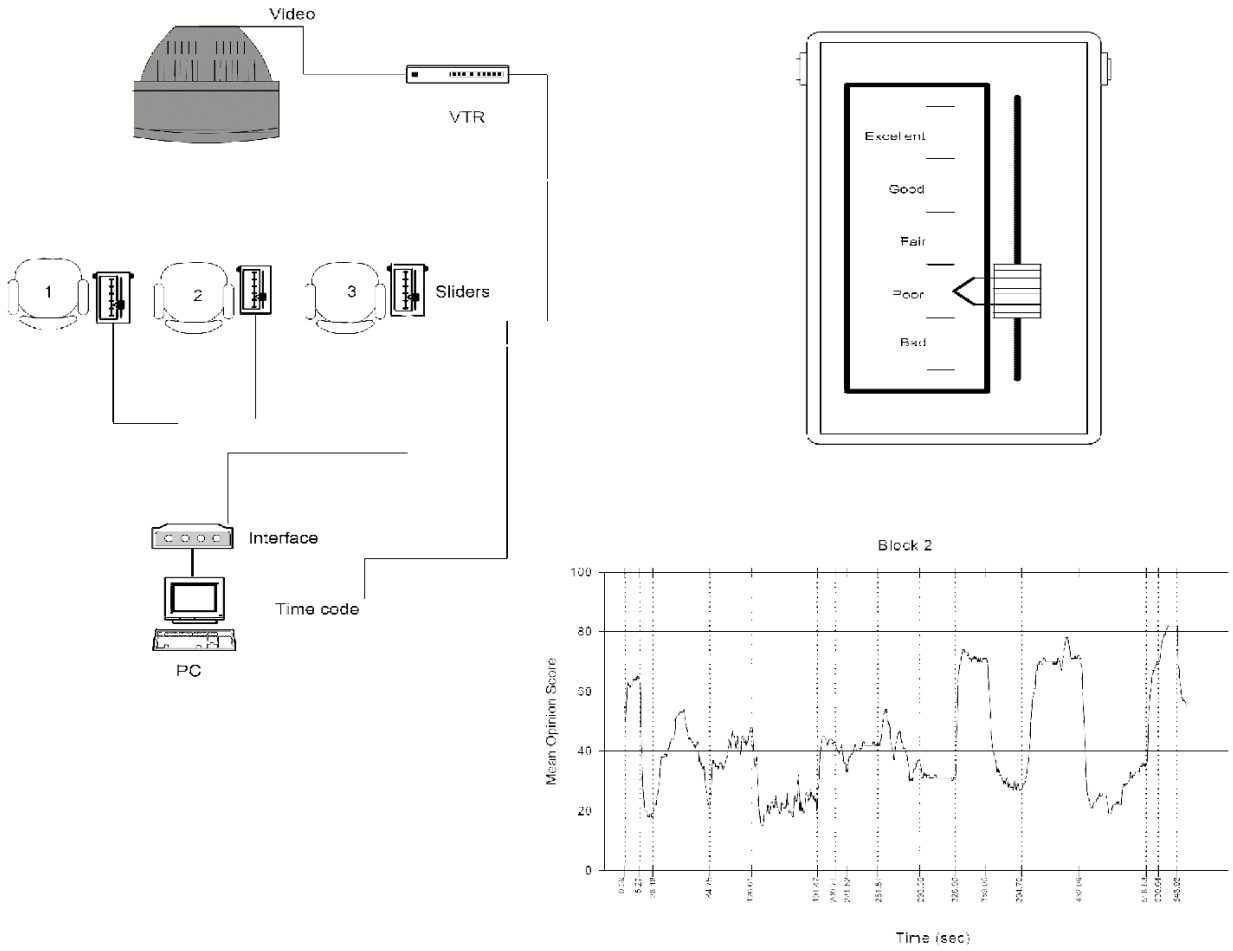
SSCQE evaluation layout (left), slider (right) and typical continuous score (bottom)



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4.6.6 Discussion of SSCQE and DSCQS

- Primary difference
  - SSCQE
    - Continuous opinion scoring
    - Computer recorded with slider
  - DSCQS
    - Single opinion score per set of test sequences
    - Recorded on score sheet
- Slider vs Score Sheet
  - Marking errors on score sheets
    - Leads to discarding of data

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- Continuous score vs single score
  - Pinpoint error segments in sequences
    - SSCQE can, DSCQS cannot
  - Real-time application
    - Evaluation of pictures during broadcast
  - Reflects subjective opinion with better precision
- SSCQE more applicable than DSCQS for quality assessment of video

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- Comparatively, SSCQE and DSCQS results are statistically indistinguishable
  - Within the limits of what could be compared
- Comparative study of SSCQE and DSCQS [PW03]
  - M.H. Pinson and S. Wolf, “Comparing subjective video quality testing methodologies”, In *SPIE Video Comms. And Image Processing Conference,* pp. 146-157, 2003
- DSCQS improvement
  - apply continuous (slider) score

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- Primacy and Recency Effect
  1. Strong impression of distortion (Primacy)
  2. Impression lingers and subsequently weights heavily in picture quality for a certain duration of time (Recency)
  - SSCQE prone to this problem
  - Uni-opinion score DSCQS has no problem
- Uneven changes with continuous score
  - Sharp degradation with poor quality frames
  - Slow recovery with good quality frames

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4.6.7 Pitfalls of different methods

- Contextual effect –
  - Manifests according to operational context
  - Dependency between sequences
    - Perceived quality is at times influenced by previous sequences
  - Ceiling or floor (range) effect
    - Perceived quality does not properly match the range of quality score.
      - e.g., “excellent” is matched to “good” due to inadequate quality range for test materials
      - Partially remedied with anchors

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- Joint investigation into contextual effect
  - Labs involved
    - CRC (communications Research Centre), Canada
    - CCRTT (France Telecom)
    - IRT (Institut für Rundfunktecknik), Germany
    - SPTT (Swiss Telecom)
  - Assessment method studies
    - DSCQS
    - DSIS
    - Comparative

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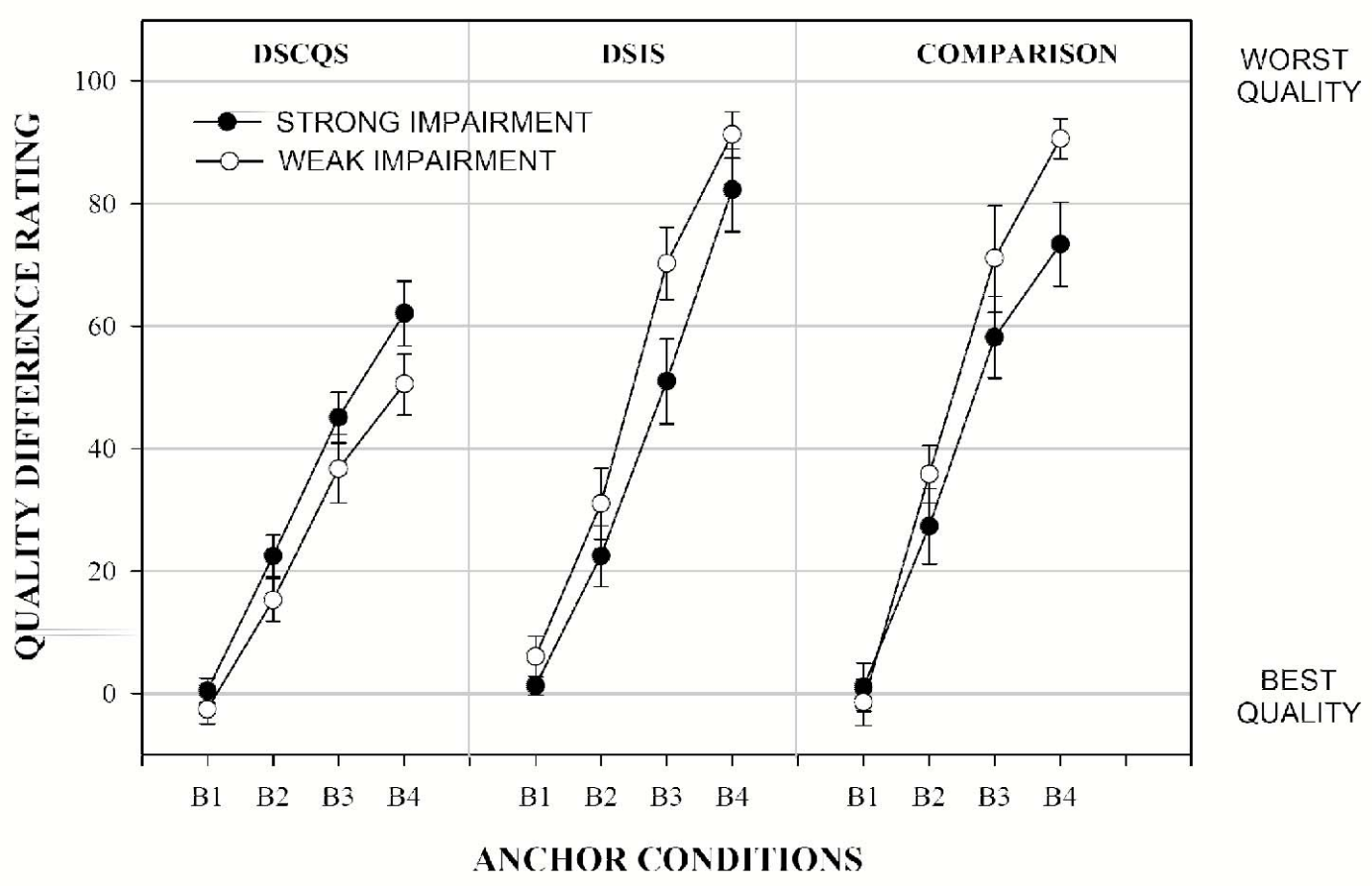
CRC results for various anchor conditions in DSCQS, DSIS and Comparison methods



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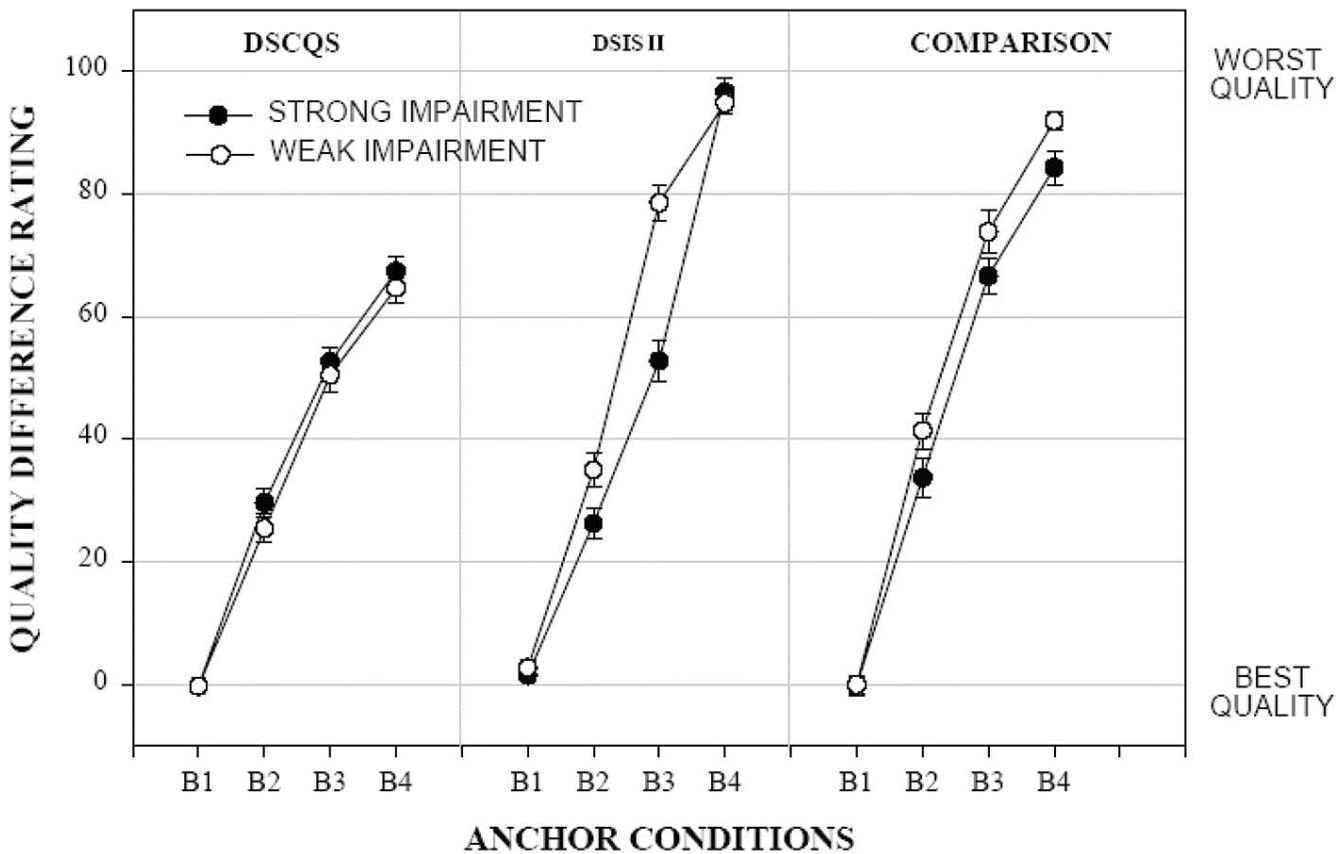
Collapse (combined) results from CRC, CCETT, IRT and SPTT [ITU97] for various anchor conditions



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- CRC results
  - Moderate contextual effect for all methods studied at most conditions except **B1**
- Combined results
  - Slight contextual effect overall except DSIS under condition **B3**
- Noticeable difference between CRC and combined results
  - Variations unavoidable, but acceptable if within limits

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4.7 Objective Assessment Methods

- Automated assessment
  - Without direct human input
- Classical analogue objective measures
  - Peak Signal-to-Noise Ratio (PSNR)
  - Mean Square Error (MSE)
- Analogue measures inadequate for digital pictures
  - Different characteristics between digital and analogue pictures

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- For digital pictures
  - Quality is source dependent
  - Distortions are structured
    - According to coding techniques
- Different objective measures required for digital pictures
  - Should account for the HVS
  - Able to handle a variety of picture types
    - Natural, animated, synthetic, etc

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- Industrial requirements
  - Full reference
    - Assessment based on an original reference
  - Reduced reference
    - Assessment based on a partial/reduced original reference
  - No reference
    - No point of original reference for quality/distortion assessment

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4.8 Summary

- Subjective Assessment
  - Design test to answer question one is seeking
    - Assessment method depends on
      - Quality or Impairment measure
      - Comparison or discrimination
      - Double or single stimulus
    - Selection of test material
    - Selection of subjects
      - Experts or non-experts

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All80	J.W. Allnatt. Subjective assessment method for television digital codecs. *Electronics Letters*, 16(12):450-451, June 1980
Cea99	P. Corriveau *et al*. All subjective scales are not created equal: The effect of context on different scales. *Signal Processing*, 77:1-9, 1999
CW99	P. Corriveau and A. Webster. VQEG evaluation of objective methods of video quality assessment. *SMPTE Journal*, 108:645-648, 1999
IL93	A.F. Inglis and A.C. Luther. *Video Engineering*. New York: McGraw-Hill, 1993
ITU97	ITU-R. *Investigation of Contextual Effects*. ITU-R, March 1997. ITU-R Document 11E/34-E, 24
ITU98	ITU. ITU-R BT. 500-9, methodology for the subjective assessment of the quality of television pictures. *ITU-R BT*, 1998
MD82	I.F. MacDiarmid and P.J. Darby. Double-stimulus assessment of television picture quality. *EBU Technical Review*, E78-A(192):70-78, April 1982
Nar94a	N. Narita. Consideration of subjective evaluation method for quality of image coding. *Electronics and Communications in Japan, Part 3*, 77(7):84-103, 1994

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Nar94b	N. Narita. Proposal of a modified ebu method for reliable evaluation of picture quality. *NHK Laboratories Note*, E78-A(431):1-10, December 1994
Nar97	N. Narita. Effect of impairment ranges on reliability of the modified ebu method. *IEICE Tans. Fundamentals*, E78-A(11):1553-1555, Nov. 1997
NS97	N. Narita and Y. Sugiura. On an absolute evaluation method of the quality of television sequences. *IEEE Transaction on Broadcasting*, 43(1):26-35, 1997
PW03	M.H. Pinson and S. Wolf. Comparing subjective video quality testing methodologies. In *SPIE Video Communications and Image Processing Conference*, 146-157, Lugano, Switzerland, July 2003
Ris86	D.R. Riskey. Use and abuse of category scales in sensory measurement. *Journal of Sensory Studies I*, 217-236, 1986
Sar67	V. Sarris. Adaptation-level theory: Two critical experiments on Helson's weighted average model. *America Journal of Psychology*, 80:331-334, 1967
VQE03	VQEG. *Final Report from the Video Quality Experts Group on the Validation of Objective Models of Video Quality Assessment, Phase II*. VQEG, August 2003

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WA80	T. White and J. Allnatt. Double Stimulus quality rating method for television digital codecs. *Electronics Letters*, 16(18):714-716, 1980
ZC96	E. Zou and P. Corriveau. Methods for evaluation of digital television picture quality. In *SMPTE 138th Technical Conference and World Media Expo*, 146-457, October 1996

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5. Perceptual Video Quality Matrix – A Review

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Chapter 5 Outline

5.1 Introduction
5.2 Quality Factors
5.3 Metric Classification
5.4 Pixel-Based Metrics
5.5 The Psychophysical Approach
5.6 The Engineering Approach
5.7 Metric Comparison
5.8 Conclusion and Perspective

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5.1 Introduction

- Evaluation and Optimization of Picture Coding/Processing Systems
  - Reliant on the Human Visual System (HVS)
    - Determines visual distortion → perceived quality
- Subjective Assessment
  - Most reliable for quantifying perceived quality
  - Complicated and time consuming to implement
  - Impractical for real-time applications

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- Objective Assessment
  - Mathematical metrics
    - MSE, PSNR, etc
    - Simple and fast
    - Unreliable predictors of perceived quality/distortion
  - HVS based metrics
    - Give a more consistent account of perceived quality and distortion
- Still image and video metrics
  - Discussions limited to video

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5.2 Quality Factors

- What influences quality?
  - Interest and expectation
    - of services (DVD, VHS, mobile broadcasts)
    - of programs (movie, sports, etc)
  - Display type and properties
    - CRT, LCD, Plasma, etc – affects contrast
  - Viewing Condition
    - Distance, size, resolution, etc
    - Luminance from ambient lighting

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- What else influences quality?
  - Fidelity of reproduction
    - Visible distortions (e.g. blurring)
    - Enhancement (e.g. sharpness, clarity)
  - Accompanying soundtrack
    - Synchronization with video
    - Clarity of audio
- “Interests” (of viewers) are the most difficult factor to account for

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5.3 Metric Classification

- Psychophysical – HVS modelling
  - Quantify picture quality relative to HVS
    - Simple models with contrast, colour modelling
    - More complicated with neurological modelling
  - Suitable for a wide range of video applications
- Engineering – signal analysis
  - Quantify quality relative to structural features and/or distortions
  - May consider HVS characteristics

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- Metric referencing types
  - Full reference (FR)
    - Frame by frame comparison between reference and test video
  - Reduced reference (RR)
    - Only some references are available
  - No reference (NR)
    - Only has test video for measurement
      - Problem with distinguishing distortions from content
  - FR, RR and NR are driven by applications

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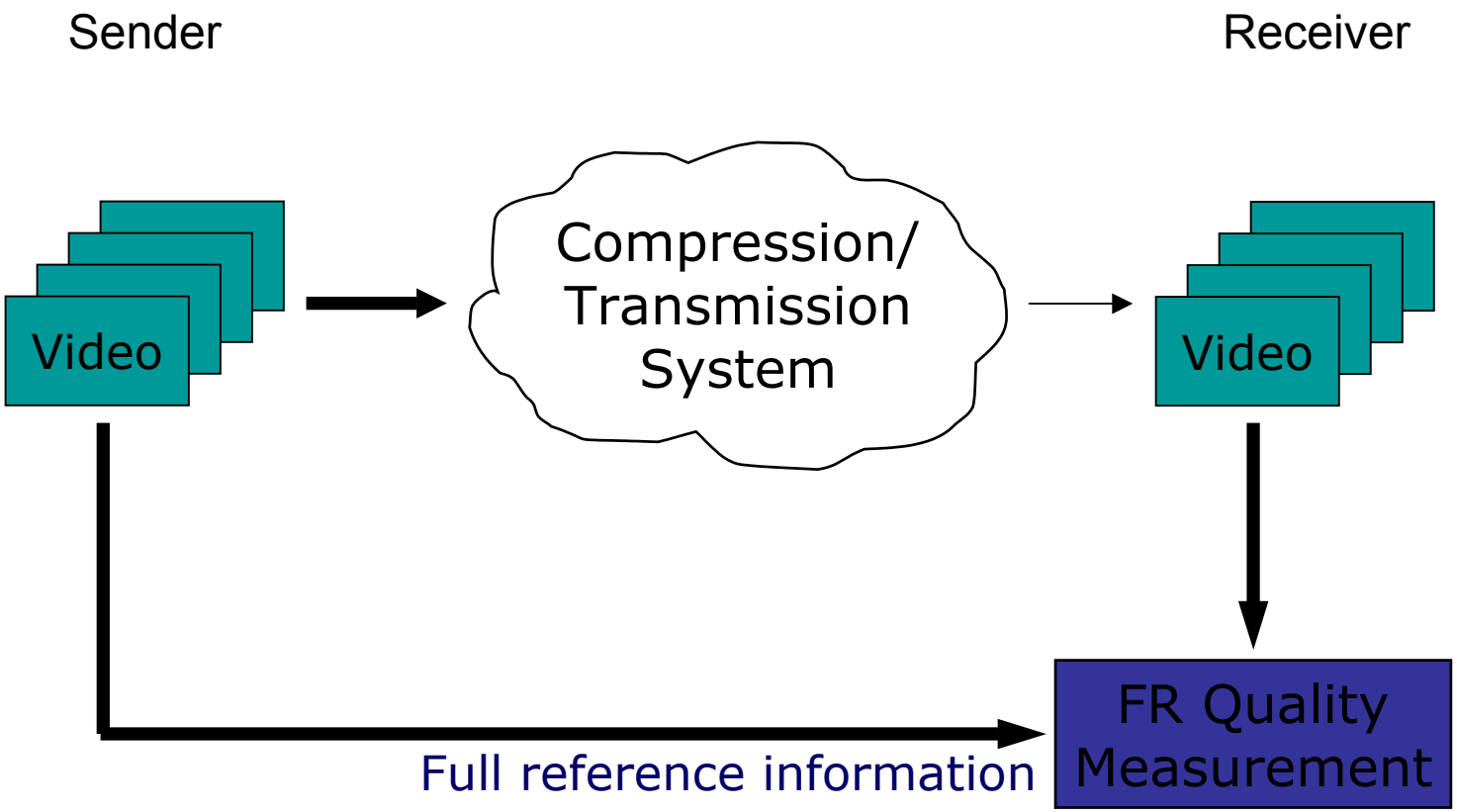
Full-Reference Metrics



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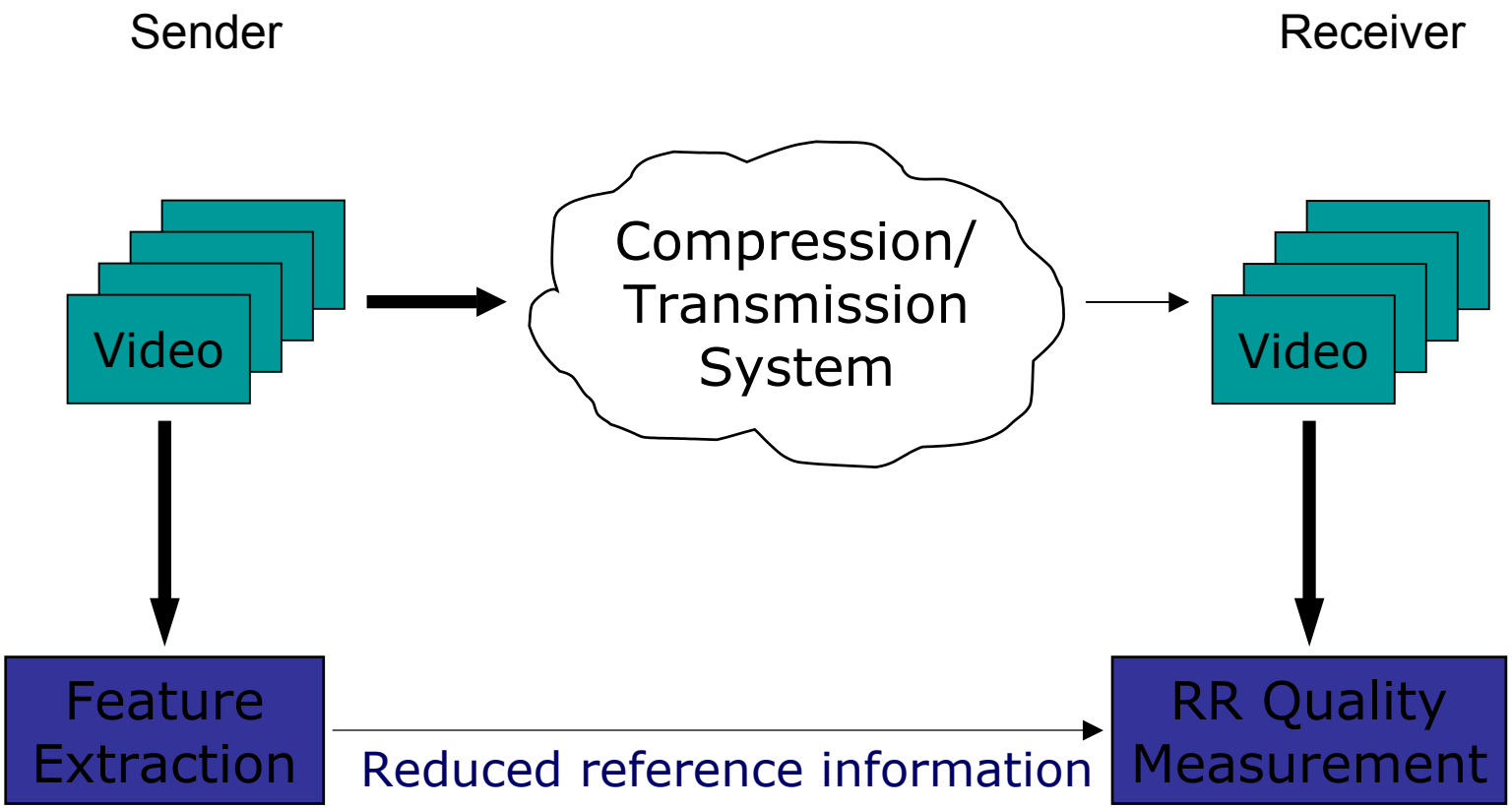
Reduced-Reference Metrics



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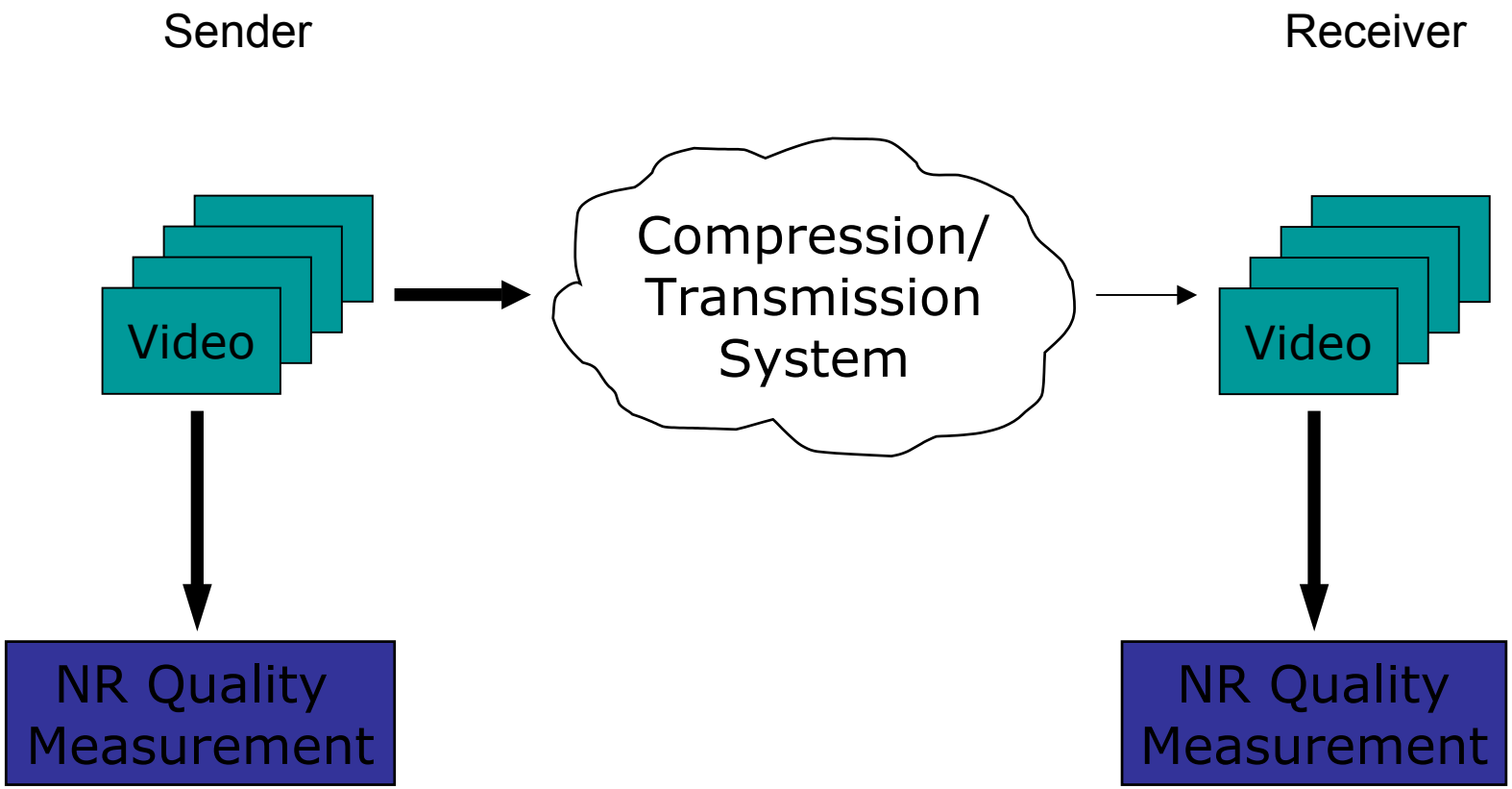
Non-Reference Metrics



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5.4 Pixel-Based Metrics

- The Classics
  - Mean Square Error (MSE)

$$MSE = \frac{1}{TMN} \sum_t \sum_m \sum_n [x_o(m,n,t) - x_r(m,n,t)]^2$$

  - Peak Signal-to-Noise Ratio (PSNR)

$$PSNR = 10 \log_{10} \frac{I^2}{MSE}$$

Temporal (t) and spatial (m,n) axis with maximum luminance/chrominance magnitude (I)

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- MSE measures picture difference
- PSNR measures picture fidelity
- Fast but limited approximation of perceived distortion/quality
  - similar MSE/PSNR does not always equate to similar perceived distortion/quality
- Effectiveness of Pixel-based metric
  - Tailored to specific type of distortion
    - MSE good for additive noise, poor for coding artifacts

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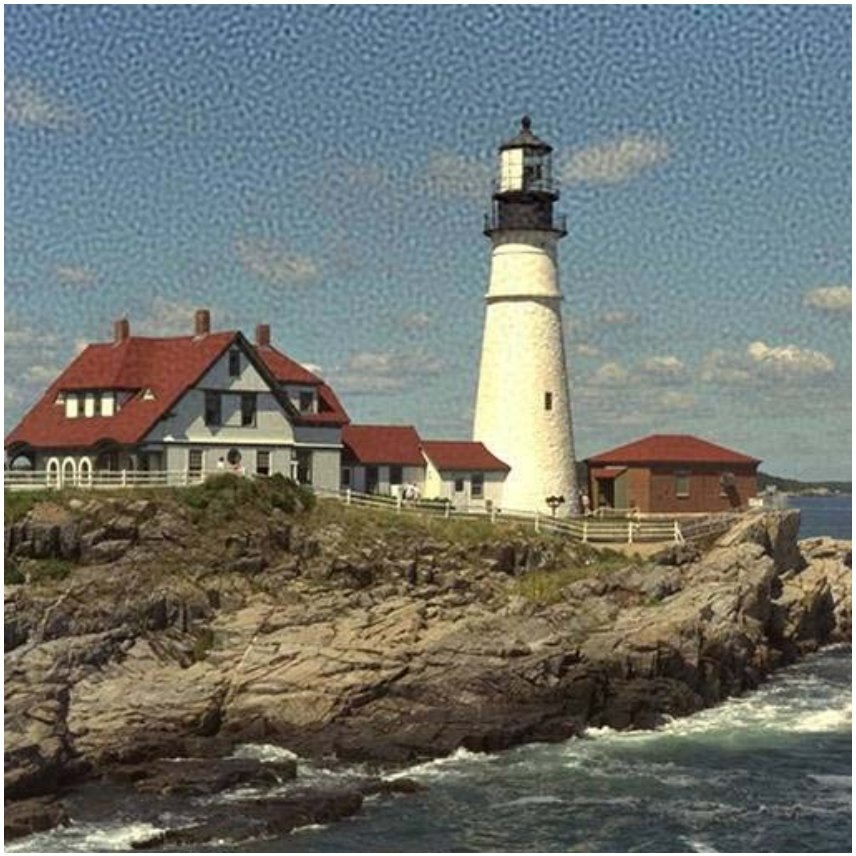
Images polluted with high frequency noise (left) and band-pass filtered noise (right) having identical PSNR.



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5.5 The Psychophysical Approach

- Basic components of vision models
  - Colour processing
    - Colour space conversion
  - Multi-channel decomposition
    - Spatial and temporal frequencies
  - Contrast sensitivity and adaptation
    - HVS operates in contrast (difference) levels
    - Affected by adaptation to luminance level
  - Masking (facilitation)
    - Suppression and enhancement of visual stimuli

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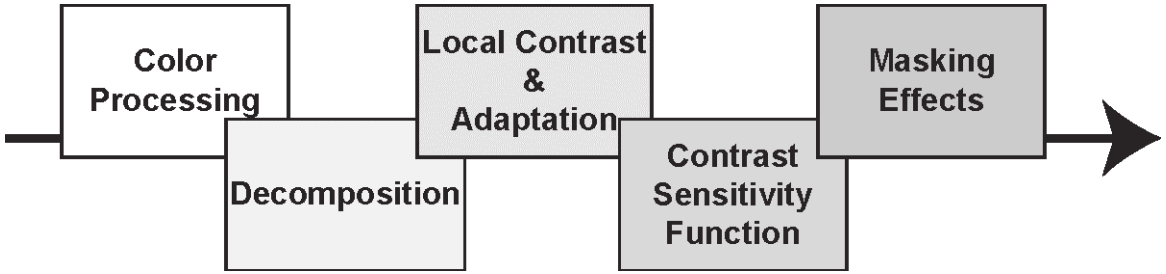
– Pooling

- Integration of (all) visual stimuli
  - Spanning spatial, temporal and colour channels

Below: Block diagram of a typical HVS model



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5.5.2 Single Channel Model

- Single channel spatial filter
- Simple to implement
- Computationally efficient
- Modelling
  - Contrast Sensitivity Function (CSF)
  - Distortion detection depends on some threshold criterion

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- Examples of CSF
  - For Image
    - Mannos and Sakrison's Modulation Transfer Function (MTF)
      - Contrast sensitivity relative to spatial frequencies
  - For Video
    - Lukis and Budrikis's spatio-temporal CSF model
      - Incorporates masking through spatial-temporal activity weighting function

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5.5.3 Multi-Channel Model

Multiple channels

- Each channel deals with one frequency band
- Overall CSF is equivalent to the envelop of sensitivities of all channels
- Detection is independent in each channel when threshold is reached

- Relative to single channel models
  - More complex in implementation
  - Better prediction performance

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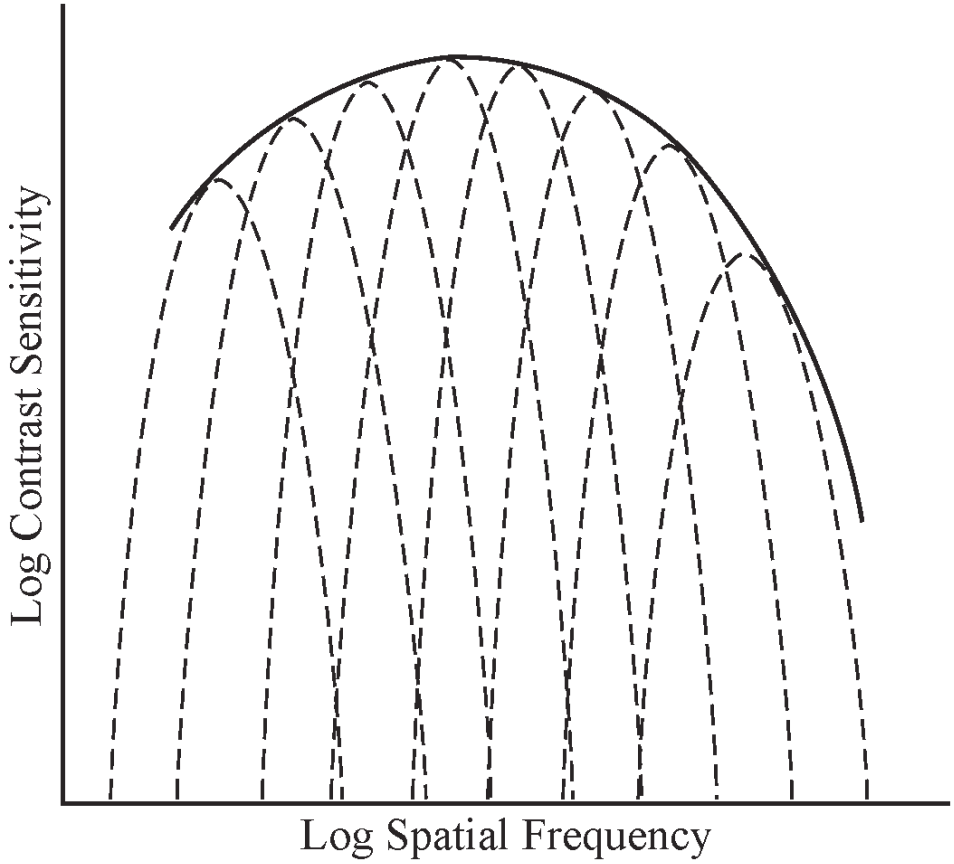
Envelop of multiple CSFs



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- Some Multi-channel models
  - Still images
    - Visible Difference Predictor (VDP)
    - Visual Discrimination Model (VDM)
  - Video
    - Just Noticeable Difference (JND) metric
    - Moving Picture Quality Metric (MPQM)
    - Normalization Video Fidelity Metric (NVFM)
    - Continuous Video Quality Evaluation (CVQE)
      - Designed for low bitrate video

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5.6 The Engineering Approach

- Specialized metrics
  - Ad hoc techniques
  - Operates well within a predefined scope
  - Good computational efficiency
- Some Full Reference (FR) metrics
  - DCTune – for still images
  - Perceptual Video Quality Measure (PVQM)
  - Structural Similarity Index Metric (SSIM)

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- A Reduced Reference (RR) metric
  - Video Quality Metric (VQM)
    - Partial reference derived from extracted features
- No Reference (NR)
  - More specialized in application
  - Used for measuring specific artifacts
    - Blurring, jerkiness, ringing, clipping, blocking
      - Blocking Impairment Metric (BIM)
    - May operate in time or spectral domains

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5.7 Metric Comparison

- Evaluation criterions
  - Prediction accuracy
  - Monotonicity
    - ordering of pictures according to quality
  - Consistency
    - Number of outliers
- Quantified with regression analysis
  - Correlation most commonly used

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5.7.2 Video Quality Experts Group

- VQEG evaluations
  - Source materials
    - Production and distribution videos
    - 20 scenes with 16 test conditions
  - DSCQS Subjective Assessment
  - 2 test phases
- Phase I
  - Evaluated 10 metrics including PSNR
  - Conclusion: no clear winner

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- Phase II
  - Focused on digitally encoded video
  - Covers wider range of distortions
  - New sources and conditions
    - 128 sequences produced
  - Evaluated 6 metrics including PSNR
  - Each metric calibrated to reference videos
  - Mean Opinion Score (MOS) correlation
    - 70% MOS for PSNR
    - 94% MOS for the best metric

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- Current VQEG activity
  - RR and NR metrics evaluations
    - for television and other multi-media services
    - At low bitrates and small frame sizes

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5.7.3 Limitation of prediction performance

- Statistically factor
  - Subjective scores rest on statistical relevance
    - Large sample size needed
- Performance of metrics
  - Phase I below expectation
    - Correlation of MOS across all labs is 90-95%
      - Indicative of the performance limit of metrics
    - Best metric has correlation of 80-85%
  - Phase II
    - Best metric not statistically equivalent to MOS

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5.8 Conclusion and Perspective

- Quality metrics
  - Applicable in many fields
    - e.g. broadcasting services
  - Many issues and problems to be resolved
    - Comprehensive evaluation of quality metrics
    - Better modelling of human vision
      - attention area (region of interest)
    - Perceived quality in addition to picture fidelity
      - Colour, sharpness, brightness, etc, affect quality
    - What is the Impact of audio in video quality?

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ABE98	A.J. Ahumada, Jr., B.L. Beard and R. Eriksson. Spatio-temporal discrimination model predicts temporal masking function. In *Proc. SPIE*, 3299:120-127, San Jose, CA, Jan. 26-29, 1998
Ahu93	A.J. Ahumada, Jr.. Computational image quality metrics: A review. In *SID Symposium Digest*, 24:305-308, 1993
AN93	A.J. Ahumada, Jr. and C.H. Null. Image quality: A multidimensional problem. In A.B. Watson, Ed., *Digital Images and Human Vision*, 141-148. Cambridge, MA: The MIT Press, 1993
ASS02	İ. Avcıbaş, B. Sankur and K. Sayood. Statistical evaluation of image quality measures. *J. Electronic Imaging*, 11(2):206-223, April 2002
Bar99	P.G.J. Barten. *Contrast Sensitivity of the Human Eye and Its Effects in Image Quality*. Bellingham, WA: SPIE, 1999
BP99	V. Baroncini and A. Pierotti. Single-ended objective quality assessment of DTV. In *Proc. SPIE*, 3845:244-253, Boston, MA, Sep. 19-22, 1999
C+00	T. Carney *et al*. Modelfest: Year one results and plans for future years. In *Proc. SPIE*, 3959:140-151, San Jose, CA, Jan. 23-28, 2000

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C+02	T. Carney *et al*. Extending the Modelfest image/threshold database into the spatio-temporal domain. In *Proc. SPIE*, 4462:138-148, San Jose, Jan. 20-25, 2002
CGDC01	F.X. Coudoux, M.G. Gazalet, C. Derviaux and P. Corlay. Picture quality measurement based on block visibility in discrete cosine transform coded video sequences. *J. Electronic Imaging*, 10(2):498-510, April 2001
CO03	J. Cavuedes and F. Oberti. No-reference quality metric for degraded and enhanced video. In *Proc. SPIE*, 5150:621-632, Lugano, Switzerland, July 8-11, 2003
CS04	A. Cacallaro and S. Winkler. Segmentation-driven perceptual quality metrics. In *Proc. ICIP*, 3543-3546, Singapore, Oct. 24-27, 2004
CWT+98	G.W. Cermak, S. Wolf, E.P. Tweedy, M.H. Pinson and A.A. Webster. Validating objective measures of MPEG video quality. *SMPTE J.*, 107(4):226-235, April 1998
Dal93	S. Daly. The visible difference predictor: An algorithm for the assessment of image fidelity. In A.B. Watson, Ed., *Digital Images and Human Vision*, 179-206. Cambridge, MA: The MIT Press, 1993

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Dal98	S. Daly. Engineering observations from spatiovelocity and spatiotemporal visual models. In *Proc. SPIE*, 3299:108-191, San Jose, CA, Jan 26-29 1998
Dau80	J.G. Daugman. Two-dimensional spectral analysis of cortex receptive field profiles. *Vision Research*, 20(10):847-856, 1980
dRBF95	H. de Ridder, F.J.J. Blommaert and E.A. Fedorovskaya. Natyralness and image quality: Chroma and hue variation in color images of natural scenes. In *Proc SPIE*, 2411:51-61, San Jose, CA, Feb. 6-8, 1995
DS98	I. Daubechies and W. Sweldens. Factoring wavelet transforms into lifting steps. *J. Fourier Anal. Appl.*, 4(3):245-267, 1998
EAV98	R. Eriksson, B. Andrén and K Brunnström. Modelling the perception of digital images: A performance study. In *Proc. SPIE*, 3299:88-97, San Jose, CA, Jan. 26-29, 1998
EF95	A.M. Eskicioglu and P.S. Fisher. Image quality measures and their performance. *IEEE Trans. Comm.*, 43(12):2959-2965, Dec. 1995

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Fau79	O./D. Faugeras. Digital color image processing within the framework of a human visual model. *IEEE Trans. Acoust. Speech Signal Process.*, 27(4):380-393, Aug. 1979
FBC95	D.R. Fuhrmann, J.A. Baro and J.R. Cox, Jr. Experimental evaluation of psychophysical distortion metrics for JPEG-coded images. *J. Electronic Imaging*, 4(4):397-406, Oct. 1995
FH98	R.E. Fredericksen and R.F. Hess. Estimating multiple temporal mechanisms in human vision. *Vision Research*, 38(7):1023-1040, 1998
Gh73	E.M. Granger and J.C. Heurtley. Visual chromaticity-modulation transfer function. *J. Opt. Soc. Am.*, 63(9):1173-1174, Sep. 1973
GZR02	P. Gastaldo, R. Zunino and S. Rovetta. Objective assessment of MPEG-2 video quality. *J. Electronic Imaging*, 11(3):365-374, July 2002
$H^{+}02$	A.P. Hekstra *et al*. PVQM – a perceptual video quality measure. *Signal Processing: Image Communication*, 17(10):781-798, Nov. 2002
Han04	D.S. Hands. A basic multimedia quality model. *IEEE Trans. Multimedia*, 6(6):806-816, Dec. 2004

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HMG+03	Y. Horita, T. Miyata, I.P. Gunawan, T. Murai and M. Ghanbari. Evaluation model considering static-temporal quality degradation and human memory for SSCQE video quality. In *Proc. SPIE*, 5150:1604-1611, Lugano, Switzerland, July 8-11, 2003
HMM99	T. Hamada, S. Muyaji and S. Matsumoto. Picture quality assessment system by three-layered bottom-up noise weighting considering human visual perception *SMPTE J.*, 108(1):20-26, Jan. 1999
HS92	R.F. Hess and R.J. Snowden. Temporal properties of human visual filters: Number, shapes and spatial covariation. *Vision Research*, 32(1):47-59, 1992
ITU02	ITU-R Recommendation BT.500-11. Methodology for the subjective assessment of the quality of television pictures. International Telecommunication Union, Geneva, Switzerland, 2002
Jac95	R.E. Jacobson. An evaluation of image quality metrics. *J. Photographic Sci.*, 43(1):7-16, 1995
KCBST97	S.A. Klein, T. Carney, L. Barghout-Stein and C.W. Tyler. Seven models of masking. In *Proc. SPIE*, 3016:13-24, San Jose, CA, Feb. 8-14, 1997

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Kel83	D.H. Kelly. Spatiotemporal variation of chromatic and achromatic contrast thresholds. *J. Opt. Soc. Am.*, 73(6):745-750, June 1983
Kle93	S.A. klein. Image quality and image compression: A psychophysicist's viewpoint. In A.B. Watson, Ed., *Digital Images and Human Vision*, 73-88, Cambridge, MA: The MIT Press, 1993
LB82	F.X.J. Lukas and Z.L. Budrikis. Picture quality prediction based on a visual model. *IEEE Trans. Comm.*, 30(7):1679-1692, July 1982
LF97	J. Lubin and D. Dibush. Sarnoff JND vision model. T1A1.5 Working Group Document #97-612. ANSI T1 Standards Committee, 1997
LLO+03	Z. Lu, W. Lin, E. Ong, X. Yang and S. Yao. PQSM-based RR and NR video quality metrics. In *Proc. SPIE*, 5150:633-640, Lugano, Switzerland, July 8-11, 2003
LMK98	B. Li, G.W. Meyer and R.V. Klassen. A comparison of two image quality models. In *Proc. SPIE*, 3299:98-109, San Jose, CA, Jan. 26-29, 1998
LPB02	S. Lee, M.S. Pattichis and A.C. Bovik. Foveated video quality assessment. *IEEE Trans. Multimedia*, 4(1):129-132, March 2002

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6. Philosophy of Picture Quality Scale

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Chapter 6 Outline

6.1 Objective Picture Quality Scale for Image Coding

6.2 Application of PQS to a Variety of Electronic Images

6.3 Various Categories of Image Systems

6.4 Study at ITU

6.5 Conclusion

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6.1 Objective Picture Quality Scale for Image Coding

- Objective measures
  - Useful for systematic design of coders
    - Allows for rapid evaluation of coding performance
  - Traditional scales (PSNR and MSE)
    - Effective for qualifying random errors
    - Ineffective for structured coding errors
  - need to incorporate human visual system characteristics to objective measures

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- Picture Quality Scale (PQS)
  - Defined as a measurement of difference between coded and original images
  - Two representations of measurement
    - 5 grade quality scale
    - 7 grade deterioration or improvement scale

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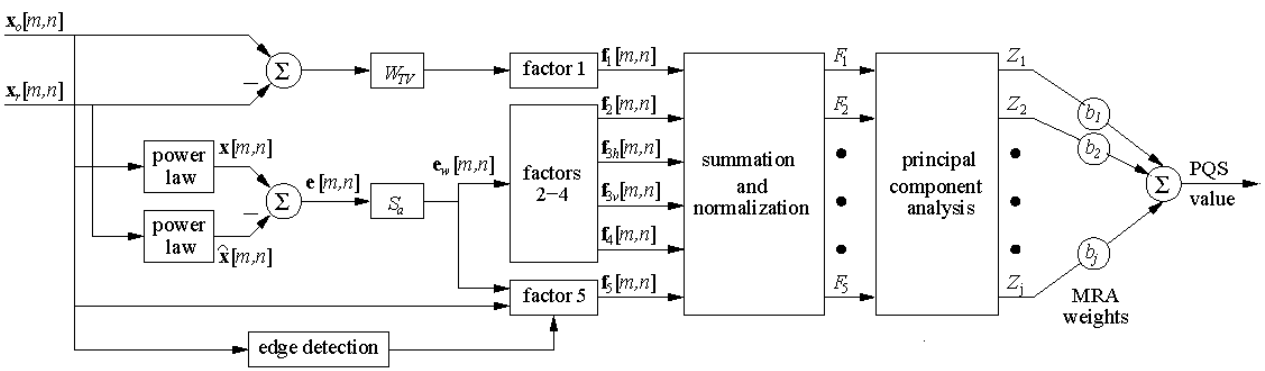
6.1.3 Construction of a Picture Quality Scale

- PQS methodology
  - Compute local distortion map $\mathrm{f}_i[m,n]$
    - from distortion factor F_i
  - Quality derived from combined distortions
    - Via regression methods



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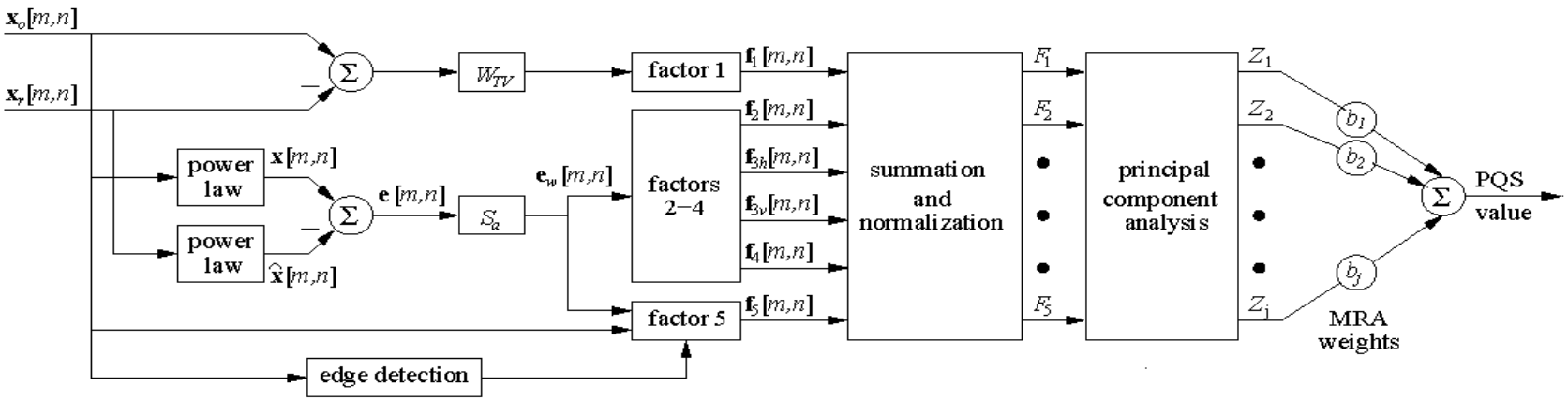
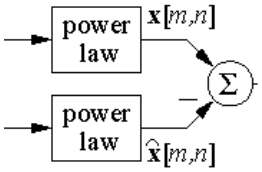
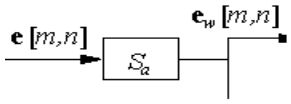
PQS components

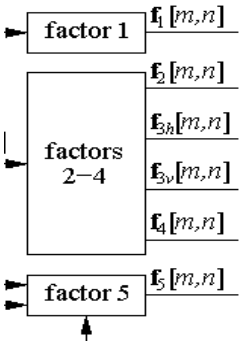




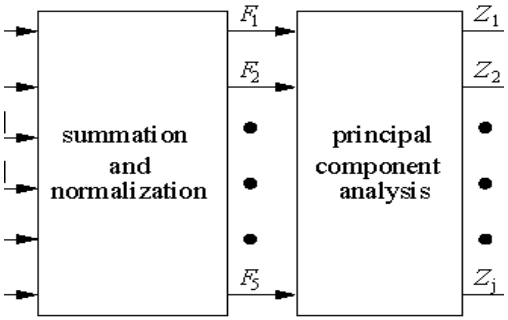
Luminance coding error



Spatial frequency weighting error



Distortion factors F_1 to F_5



Principal Component Analysis

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- Luminance coding error
  - Transform input to uniform scale

$$\mathrm{x}[m,n] = k \bullet \mathrm{x}_o[m,n]^{1/2.2}$$

(Weber-Fechner Law approximation) with the $\mathrm{x}_o[m,n]$ original image

  - Computation of contrast adjusted error

$$\mathrm{e}[m,n] = \mathrm{x}[m,n] - \mathrm{x}_c[m,n]$$

$\mathrm{x}_c[m,n]$ is the contrast adjusted compressed image

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- Spatial frequency weighting of errors
  - Spectral sensitivity of contrast

$$S(\omega) = 1.5e^{-(\sigma^2\omega^2)/2} - e^{2\sigma^2\omega^2}$$

$\sigma=2$, $\omega=(2\pi f)/60$, $f^2 = u^2 + v^2$

u and v are horizontal and vertical frequencies

  - High frequencies attenuation needed to account for CRT transfer function
  - High frequency response is anisotropic

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– High frequency contrast sensitivity

$$S_a(\omega) = S(\omega) \bullet O(\omega,\theta)$$

with

$$O(\omega,\theta) = (1+e^{-\beta(\omega-\omega_o)}cos^4 2\theta)/(1+e^{-\beta(\omega-\omega_o)})$$

where

$$\theta=tan^{-1}(v/u),\ \omega_o=2\pi f_o\ ,\ \beta=8,\ f_o=11.13\ \text{cyc/deg}$$

– Weighted error is contrast adjusted error filtered with spectral sensitivity function

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Random errors and disturbances

- Distortion factor F_1
  - from coding noise

$$e_i[m,n] = x_o[m,n] - x_r[m,n]$$

$$f_1[m,n] = (e_i[m,n] * w_{TV}[m,n])^2$$

$$w_{TV}[m,n] = 1/(1+(f/f_c)^2)$$

f_c=5.56 cyc/deg at viewing distance 4H (height)

  - Computation of F_1

$$F_1 = \frac{\sum_{m,n} f_1[m,n]}{\sum_{m,n} x_o^2[m,n]}$$

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Random errors and disturbances

- Distortion Factor F_2
  - Due to incremental noise in slowly varying regions of images

$$f_2[m,n] = I_T[m,n](e_o[m,n] - s_a[m,n])^2$$

with $s_a[m,n]$ the spatial contrast sensitivity and $I_T[m,n]$ threshold indicator for perceptual visibility

  - Distortion F_2

$$F_2 = \frac{\sum_{m,n} f_2[m,n]}{\sum_{m,n} x_r^2[m,n]}$$

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Structured and localized errors and disturbances

- Distortion Factor F_3 (blocking errors)
  - Along horizontal (h) and vertical (v) edges

$$f_{3h}[m,n] = I_h[m,n](e_w[m,n] - e_w[m,n\text{-}1])^2$$

$$F_{3h} \frac{1}{\sum_{m,n} I_h[m,n]} \sum_{m,n} f_{3h}[m,n]$$

  - Final distortion composed of horizontal and vertical factors

$$F_3 = \sqrt{F_{3h}^2 + F_{3v}^2}$$

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Structured and localized errors and disturbances

- Distortion Factor F_4 (correlated errors)
  - Localized to a windowed area (w)

$$f_4[m,n] = \sum_{(k,l)\in W; l=k\neq 0} |r(m,n,k,l)|^{0.25}$$

$$r(m,n,k,l) = \frac{1}{w-1}\left[\sum_{i,j} e_w[i,j]e_w[i+k,j+l] - \frac{1}{w}\sum_{i,j} e_w[i,j]\sum_{i,j} e_w[i+k,j+l]\right]$$

  - Distortion F_4

$$F_4 = \frac{1}{MN}\sum_{m,n} f_4[m,n]$$

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Structured and localized errors and disturbances

- Distortion Factor F_5 (masking)
  - In horizontal (S_h) and vertical (S_v) directions

$$S_h[m,n] = e^{\left\{-0.04\left(\frac{|x_o[m,n-1]-x_o[m,n+1]}{2}\right)\right\}}$$

$$f_5[m,n] = I_M[m,n]\cdot|e_w[m,n]|\cdot(S_h[m,n] + S_v[m,n])$$

  - Final distortion

$$F_5 = \frac{1}{N_K}\sum_{m,n} f_5[m,n]$$

N_K, number of 3x3 Kirsch edge $k(m,n) \geq K$, K=400

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Principal component analysis

- Quantify combined distortion factors
  - With covariance (COV) matrix

$$C_F = COV(F) = E\{(F - \mu_F)\,(F - \mu_F)^T\}$$

where $F = (F_1, F_2, F_3, F_4, F_5)^T$ is a vector of distortion factors with μ_F is the its mean

  - Derivation of principal components (Z)
    - Obtain eigenvectors of C_F to determine individual contribution of distortion factors (F_1 to F_5)
    - De-correlation of eigenvectors of C_F
      - More effective and robust for quality assessment

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Computation of PQS

- PQS defined as linear combination of principal components

$$PQS = b_0 + \sum_{j=1}^{J} b_j Z_j$$

where b_j is the partial regression coefficient of the Multiple Regression Analysis (MRA)

- Regression analysis
  - performed on mean opinion score (MOS)
    - collected through subjective experiments

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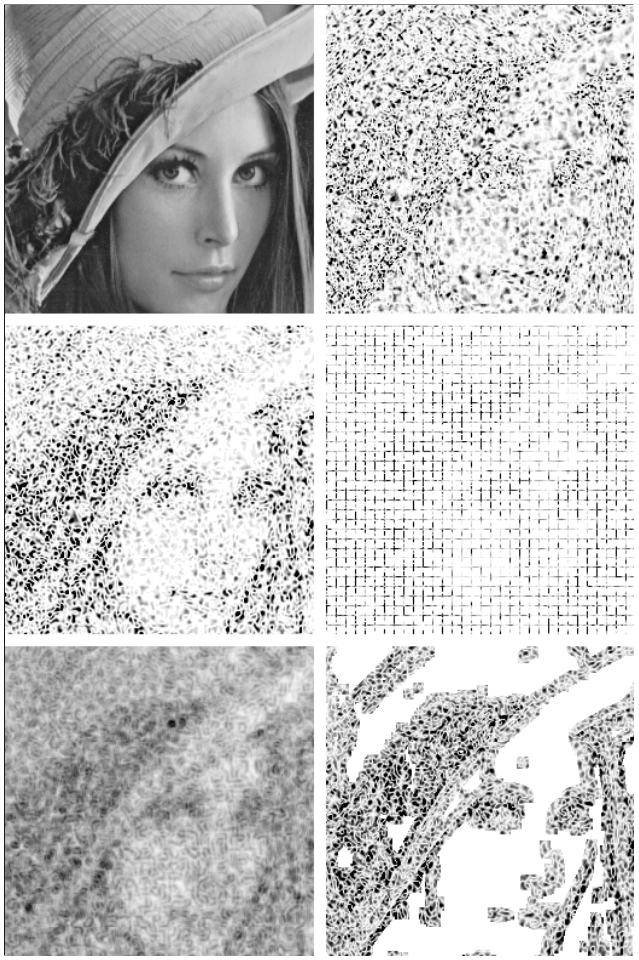
PQS distortion factor images from a JPEG coded image with quality factor = 15



From left to right, top to bottom:

1. Original
2. $f_1[m,n]$
3. $f_2[m,n]$
4. $\sqrt{f_{3h}^2[m,n]+f_{3v}^2[m,n]}$
5. $f_4[m,n]$
6. $f_5[m,n]$

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6.4.1 Visual Assessment Test

- Follow ITU-R bt.500 recommendations
  - General experimental conditions
  - Subjective scale
  - Specific conditions
    - Test image resolution 256 x 256 pixels
    - 4 times image height viewing distance
    - Trained non-expert subjects
    - Grading of quality in half step increments
  - 9 subjects with 675 evaluations from 75 encoded images

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Impairment scale (left) and experimental conditions (right)

Scale	Impairment
5	Imperceptible
4	Perceptible, but not annoying
3	Slightly annoying
2	Annoying
1	Very annoying

Ratio of viewing distance to picture height	4
Room illumination	None
Peak luminance on the screen	42.5 (cd/m^2)
Lowest luminance on the screen	0.23 (cd/m^2)
Time of observation	unlimited
Number of observers	9 (expert observers)

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Test images. Clockwise from top left: *Church, Hairband, Weather, Barbara and Cameraman*

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- Coding engines
  - DCT, Subband and Wavelet coders
- Collation of data
  - Mean Opinion Score (MOS)
    - Mean score for each of the 75 encoded images
- Data analysis
  - Compute covariance matrix
  - Compute eigenvalues and eigenvectors

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Covariance matrix (top) and eigenvalues with corresponding eigenvectors (bottom)

	F_1	F_2	F_3	F_4	F_5
F_1	1.0000	0.9967	0.9753	0.8391	0.5823
F_2	0.9967	1.0000	0.9743	0.8231	0.5682
F_3	0.9753	0.9743	1.0000	0.8749	0.5696
F_4	0.8391	0.8231	0.8749	1.0000	0.6714
F_5	0.5823	0.5682	0.5696	0.6714	1.0000

Principal component analysis

λ_1	λ_2	λ_3	λ_4	λ_5
4.19165	0.59144	0.19021	0.02392	0.00278

ℓ_1	ℓ_2	ℓ_3	ℓ_4	ℓ_5
0.47500	-0.24449	0.27083	-0.38709	0.70100
0.47198	-0.26829	0.32384	-0.31044	-0.70993
0.47526	-0.24723	0.01921	0.84271	0.04966
0.45058	0.10598	-0.86219	-0.20065	-0.04604
0.35030	0.89213	0.27936	0.05793	-0.00216

Multiple Regression Analysis

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- Observations of covariance matrix
  - High correlation between F_1 and F_2
    - Expected since both evaluate random errors
  - High correlation between F_3 and F_2/F_2
    - Unexpected between blocking and random errors
    - Appears to track one another as coding parameters change
- Observation of Eigenvalues
  - 99.5% of energy concentrated in λ_1, λ_2 and λ_3
    - Image quality mainly depends on F_1, F_2 and F_3

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- Principal Component Analysis
  - Transformation from $\mathrm{F_i}$ to Z_i

$$\begin{bmatrix} Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \\ Z_5 \end{bmatrix} = \begin{bmatrix} 0.47500 & 0.47198 & 0.47526 & 0.45058 & 0.35030 \\ -0.24449 & -0.26829 & -0.24723 & 0.10598 & 0.89213 \\ 0.27083 & 0.32384 & 0.01921 & -0.86219 & 0.27936 \\ -0.38709 & -0.31044 & 0.84271 & -0.20065 & 0.05793 \\ 0.70100 & -0.70993 & 0.04966 & -0.04604 & -0.00216 \end{bmatrix} \begin{bmatrix} \mathrm{F}_1 \\ \mathrm{F}_2 \\ \mathrm{F}_3 \\ \mathrm{F}_4 \\ \mathrm{F}_5 \end{bmatrix}$$

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- Multiple Regression Analysis
  - Two expressions

$$PQS = 5.632 - 0.068Z_1 - 1.536Z_2 - 0.0704Z_3$$

$$PQS = 5.797 + 0.035F_1 + 0.044F_2 + 0.01F_3 - 0.132F_4 + 0.135F_5$$

  - Existing regression coefficient lack robustness
    - Consequently, may not operated well outside test images

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Evaluation of PQS

- PQS matched well with MOS
  - Better fit in mid-range MOS than extremeties
  - Correlation coefficient $\rho = 0.928$
  - For WMSE and MOS, $\rho = 0.57$
    - Calculated with F_1 alone
  - PQS absolute error about the regression line
    - Within 0.5 with 70% probability

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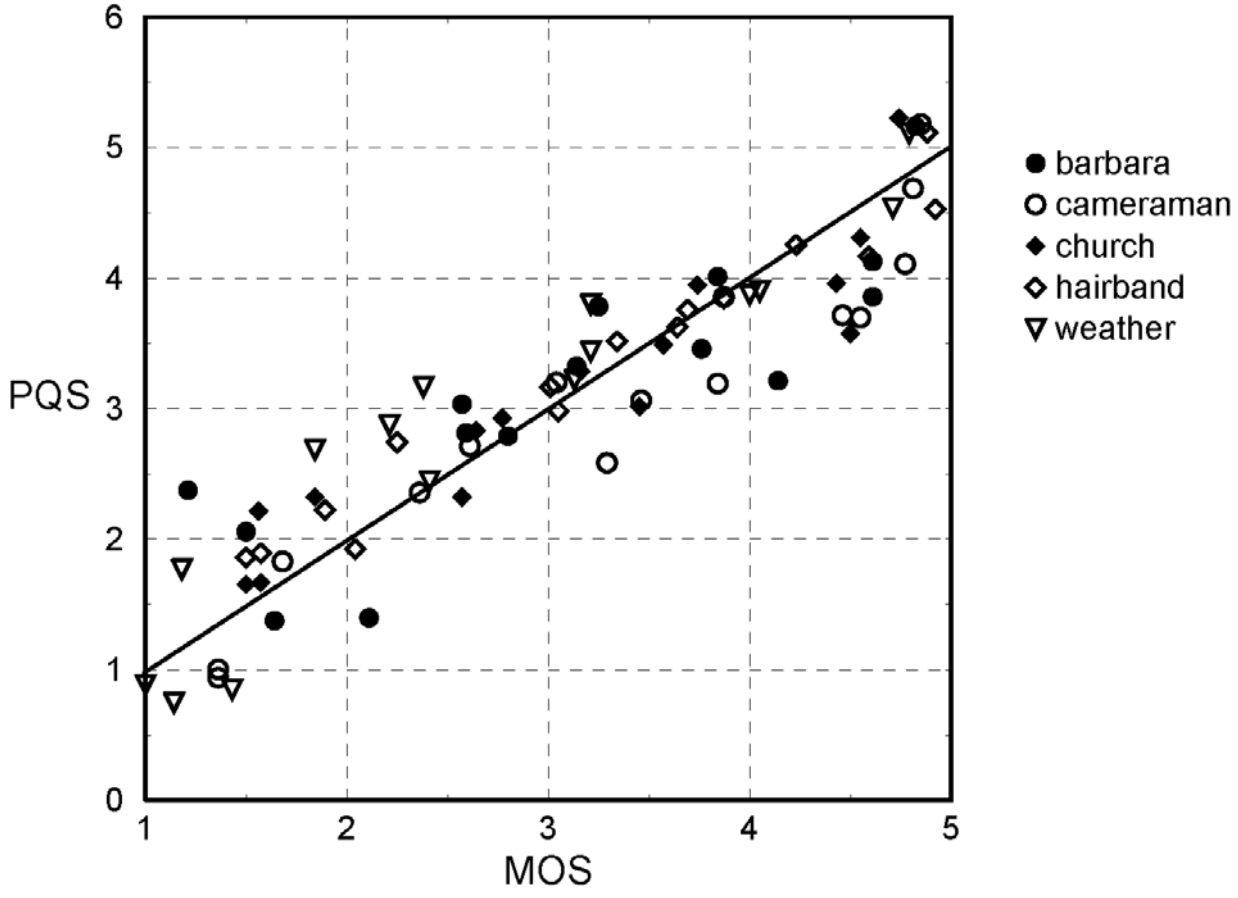
PQS vs MOS scatter diagram



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- PQS vs PSNR
  - PQS captures differences missed by PSNR between JPEG and wavelet coders
- PQS Generality and robustness
  - Some variations relative to coding technique
    - PQS evaluation slightly dependent on coding techniques

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6.1.6 Key Distortion Factors

- Analyse distortion factors F_i
  - Determine if individual F_i is a key distortion factor
- Overall distortion characterized by
  - Z_1: the amount of error
  - Z_2: the location of error
  - Z_3: the structure of error
- PQS a linear combination of 3 errors

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Correlation between PQS and MOS

Factors					ρ	ρ^*	$E\{\|error\|\}$
1					0.5665	0.5582	0.8347
	2				0.5373	0.5282	0.8510
		3			0.5714	0.5633	0.8269
			4		0.7426	0.7384	0.6551
				5	0.8985	0.8971*	0.4268
1	2				0.5547	0.5461	0.8418
1		3			0.5729	0.5564	0.8289
1			4		0.7499	0.7417	0.6362
1				5	0.9001	0.8972	0.4206
	2	3			0.5779	0.5616	0.8222
	2		4		0.7539	0.7459	0.6336
	2			5	0.8991	0.8962	0.4236
		3	4		0.7600	0.7522	0.6302
		3		5	0.9015	0.8986	0.4144
			4	5	0.9180	0.9156*	0.3773
1	2	3			0.5716	0.5550	0.8265
1	2		4		0.7516	0.7435	0.6352
1	2			5	0.8996	0.8967	0.4220
1		3	4		0.7600	0.7522	0.6302
1		3		5	0.9015	0.8986	0.4144
1			4	5	0.9271	0.9239	0.3536
	2	3	4		0.7600	0.7522	0.6302
	2	3		5	0.9015	0.8986	0.4144
	2		4	5	0.9302	0.9271*	0.3460
		3	4	5	0.9279	0.9247	0.3551
1	2	3	4		0.7600	0.7522	0.6302
1	2	3		5	0.9015	0.8986	0.4144
1	2		4	5	0.9285	0.9253*	0.3501
1		3	4	5	0.9279	0.9247	0.3551
	2	3	4	5	0.9279	0.9247	0.3551
1	2	3	4	5	0.9279	0.9247	0.3551

- Different combination of PQS distortion factors and their associated correlation to MOS

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- Contribution of distortion factors
  - F_5 may operate by itself
    - Perhaps for evaluating high quality pictures
  - F_1, F_2 and F_3 are insufficient by themselves
- Other distortion factors to consider
  - Jagged distortions

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6.1.7 Discussion

- Limitations
  - Assigning single quality score may not reflect picture quality clearly
- ITU-R bt.500 scales and methods
  - 5 point scale lack resolution
  - Need for anchor images
- Modelling human vision
  - Importance of visual characteristics for quality metrics

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- Specialization of PQS
  - Can calibrated to evaluate specific coding systems
- PQS of colour picture coding
  - Evaluates colour distortions in addition to the usual distortions
- Applications for PQS
  - Adaptive coders with quality feedback loop

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6.2 Application of PQS to a Variety of Electronic Images

- Categories of electronic media
  - Conventional TV
  - High Definition TV
  - Extra high quality images
    - Digital cameras, specialized image capture devices
  - Handheld devices
    - cellular phones, PDA
  - Computers (computer graphics)

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- Subjective picture evaluation
  - Purpose of evaluation. Measure what?
    - Fidelity, impairment or picture quality
  - Picture spatial resolution and viewing distance
  - Constancy of viewing distance
    - Viewing distance as a function of display height
  - Viewing angle between adjacent pixels
  - Other viewing conditions
    - Ambient light, noise, etc

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6.3 Various Categories of Image Systems

- Standard TV
  - NTSC, PAL, SECAM
- HDTV and Super HDTV
  - 1000 x 1600 pixel HDTV
  - 2000 x 4000 pixel super HDTV
- Extra High Quality Images
- Cellular Phone type
- Personal computer

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Encoding parameters of digital TV for studios

Encoding parameter values for the 4:2:2 of the family

Parameters	525-line, 60 field/s systems	625-line, 50 field/s systems
1. Coded signals	*Y, R-Y, B-Y*	
2. Number of samples per total line: - luminancd signal (*Y*) - each colour-difference signal (*R-Y, B-Y*)	 858 429	 864 432
3. Sampling structure	Orthogonal, line, field and picture repetitive. *R-Y*and *B-Y* samples co-sited with odd(1st, 3rd, 5th, etc.) *Y* samples in each line.	
4. Sampling frequency: - luminancd signal - each colour-difference signal	 13.5 MHz 6.75 MHz	
5. Form of coding	Uniformly quantized PCM, 8bits per sample, for the luminance signal and each colour-difference signal	
6. Number of samples per digital active line: - luminance signal - each colour-difference signal	 720 360	
7. Correspondence between video signal levels and quantization levels: - luminance signal - each colour-difference signal	 220 quantization levels with the black level corresponding to level 16 and the peak white level corresponding to level 235 224 quantization levels in the centre part of the quantization scale with zero signal corresponding to level 128	

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6.4 Study at ITU

- Some recent Recommendations
  - J.143
  - J.133
  - J.147
  - J.148

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Recommendation J.143

- Move towards standardization of assessment models
  - Full Reference (FR)
  - Reduced Reference (RR)
  - No Reference (NR)
- FR
  - Compares between processed and reference
  - Intended for TV standard evaluations
  - May be deploy on handheld devices in future

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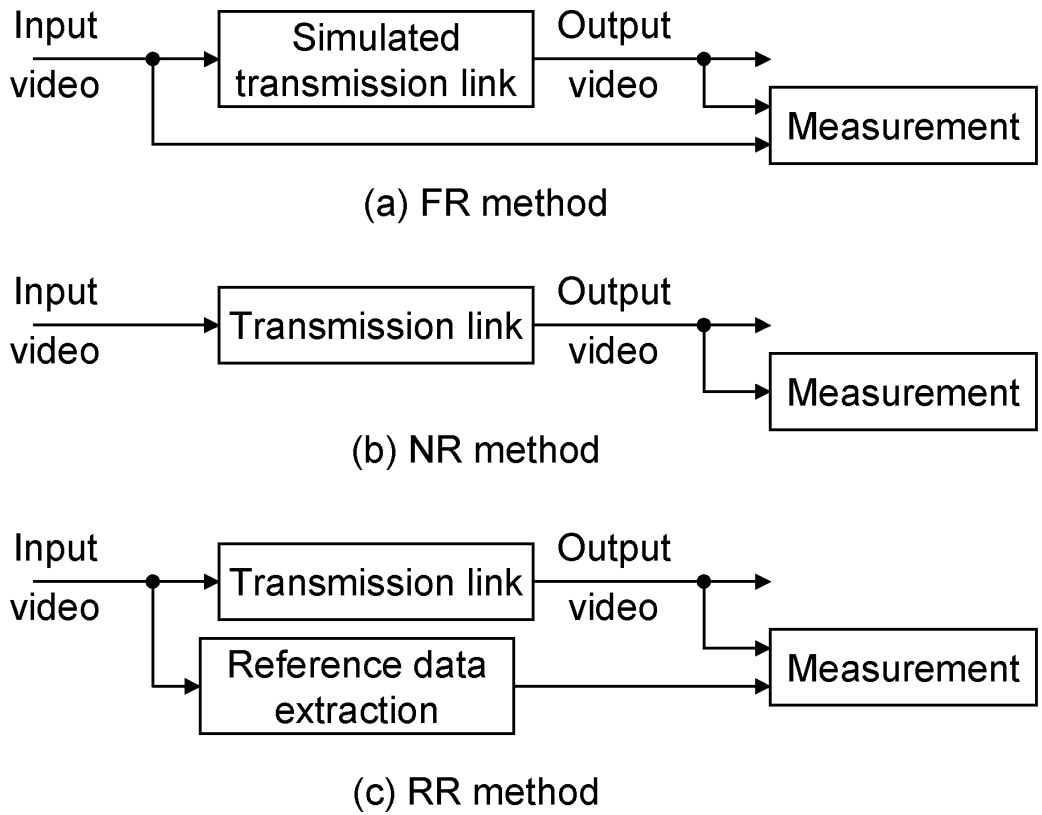
Concept of FR, NR and RR methods



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- NR
  - Evaluates based on processed only
  - No effective generic NR metric has been established
- RR
  - Evaluation based on extracted feature of reference pictures
  - Intended for monitoring TV transmission

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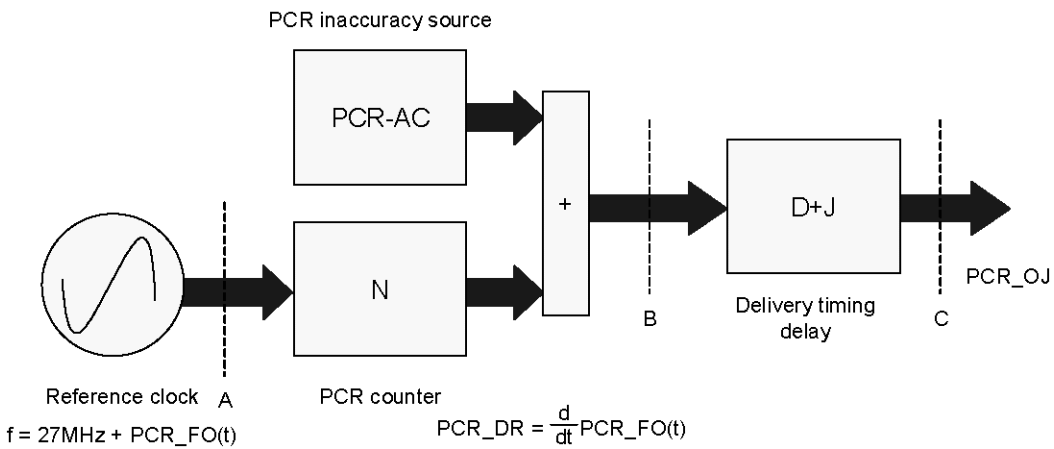
Recommendation J.133

- Measurement of MPEG-2 transport stream in networks
  - For television transmission

Below: concept of J.133. PRC (program reference clock)



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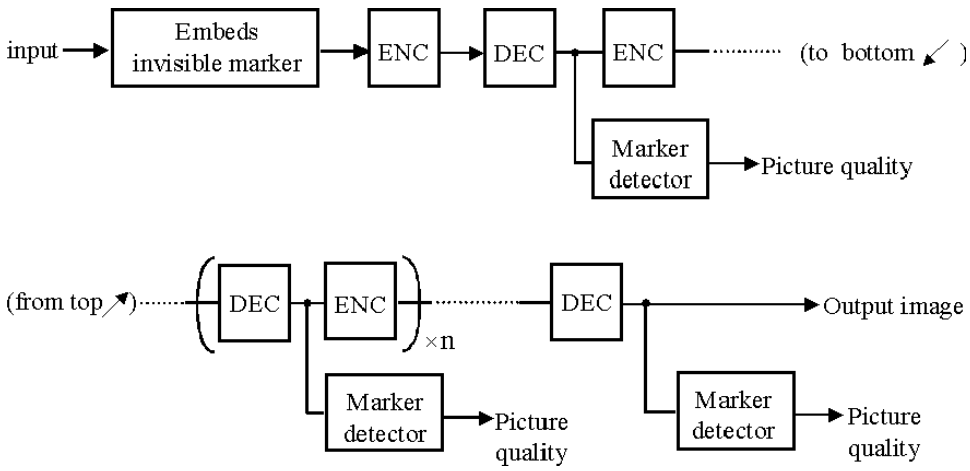
Recommendation J.147

- Objective picture quality measurement method by use of in-service test signals
  - Can operate in either FR, RR or NR modes

Below: Concept of J.147



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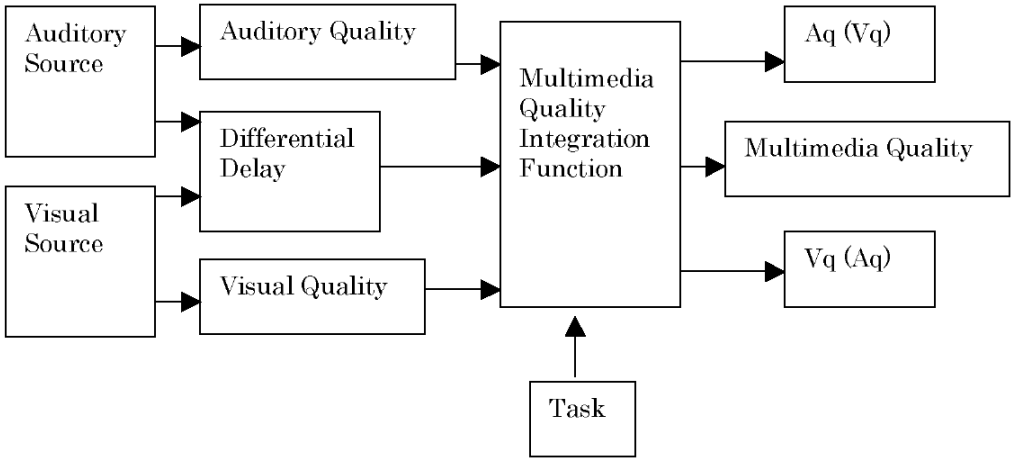
Recommendation J.148

- Requirements for an objective perceptual multimedia quality model
  - Considers both audio and video

Below: Concept of J.148



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6.5 Conclusion

- Picture quality evaluation is a difficult task
  - Subjectively - *perception, viewing conditions, time factor, etc*
  - Objectively – *Modelling/prediction issues*
- PQS: an objective quality assessment
  - For still images, but extendable to video
  - Operates on 5 or 7 point scale
  - Quantifies different types of distortions
  - Correlates well with MOS

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- Moves in standardization bodies
  - Moves towards perceived picture quality
  - Enhancing picture evaluation tools
    - According to applications
      - FR, NR and RR metrics

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7. Structural Similarity Based Image Quality Assessment

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Chapter 7 Outline

7.1 Structural Similarity and Image Quality

7.2 The Structural SIMilarity (SSIM) Index

7.3 Image Quality Assessment Based on the SSIM Index

7.4 Discussions

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Introduction

- Properties of images
  - Highly structured
    - Due to strong spatial dependency of pixels
    - Holds important information of objects
- Structural Similarity assessment
  - Assumes the HVS is adaptive to structural information
  - Consequently, quantifying structural similarity should account for perceived quality

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7.1 Structural Similarity and Image Quality

- Discussions centred on Full Reference (FR) metric
  - Test image evaluated based on a reference
    - Reference image is assumed to have perfect quality
- Classification of statistics based quality measures
  - Error sensitive approach
  - Feature/structural extraction

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- Error sensitive
  - Error signal defined as the difference between test and reference image. e.g. MSE
  - Assumes quality loss as a linear function of error signal
- Feature/structure extraction
  - More attenuated to the HVS
  - Distortion as a function of structural changes
  - Measure structural deterioration

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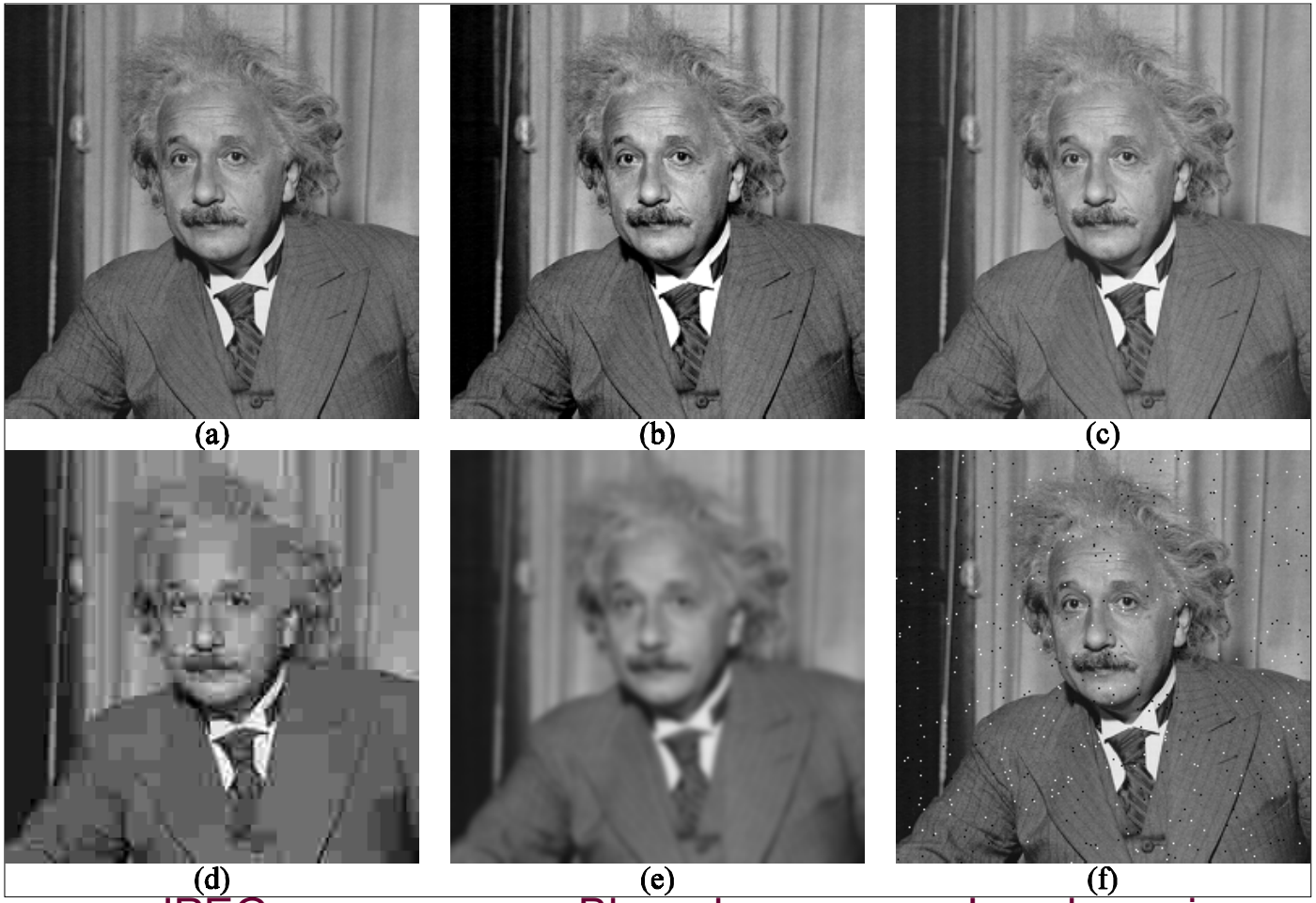
Original Einstein

Contrast stretched
MSE = 144
MSSIM = 0.9884

Mean shifted
MSE = 144
MSSIM = 0.9884



JPEG
MSE = 142
MSSIM = 0.6624

Blurred
MSE = 144
MSSIM = 0.6940

Impulse noise
MSE = 144
MSSIM = 0.8317

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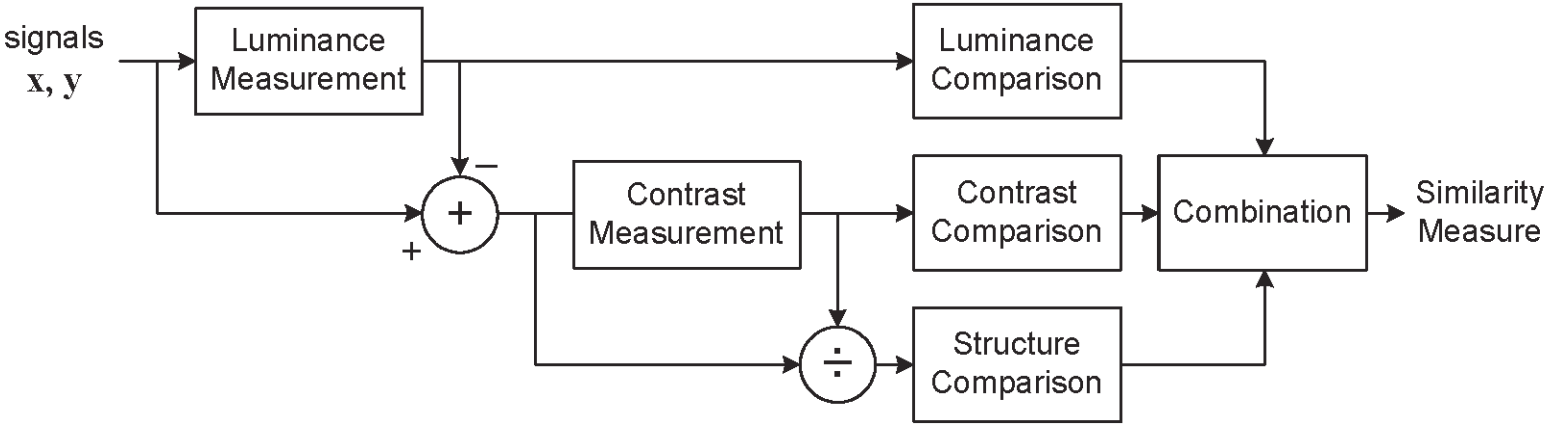
7.2 The Structural SIMilarity (SSIM) Index

- Similarity measurement in 3 components
  - Luminance, Contrast and structure

Below: Illustration of the SSIM system



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- Luminance similarity
  - Mean intensity $$\mu_x = \bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$$
  - Luminance comparison $l(\mathbf{x},\mathbf{y})$ of test and reference signals $\mathbf{x}$ and $\mathbf{y}$, respectively, is

$$l(\mathbf{x},\mathbf{y}) = l(\mu_x,\mu_x)$$

$$\mathbf{x} = \{x_i \mid i = 1,2,\ldots, N\},\ \mathbf{y} = \{y_i \mid i = 1,2,\ldots,N\}$$

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- Contrast similarity
  - Remove mean intensity $\mathbf{x} = \mathbf{x} - \mu_x$
    - Projects of vector $\mathbf{x}$ onto hyperplane
  - Estimate contrast with standard deviation, σ

$$\sigma_x = \left(\frac{1}{N-1} \sum_{i=1}^{N} (x_i - \mu_x)^2 \right)$$

  - Contrast comparison given by

$$c(\mathbf{x}, \mathbf{y}) = c(\sigma_x, \sigma_y)$$

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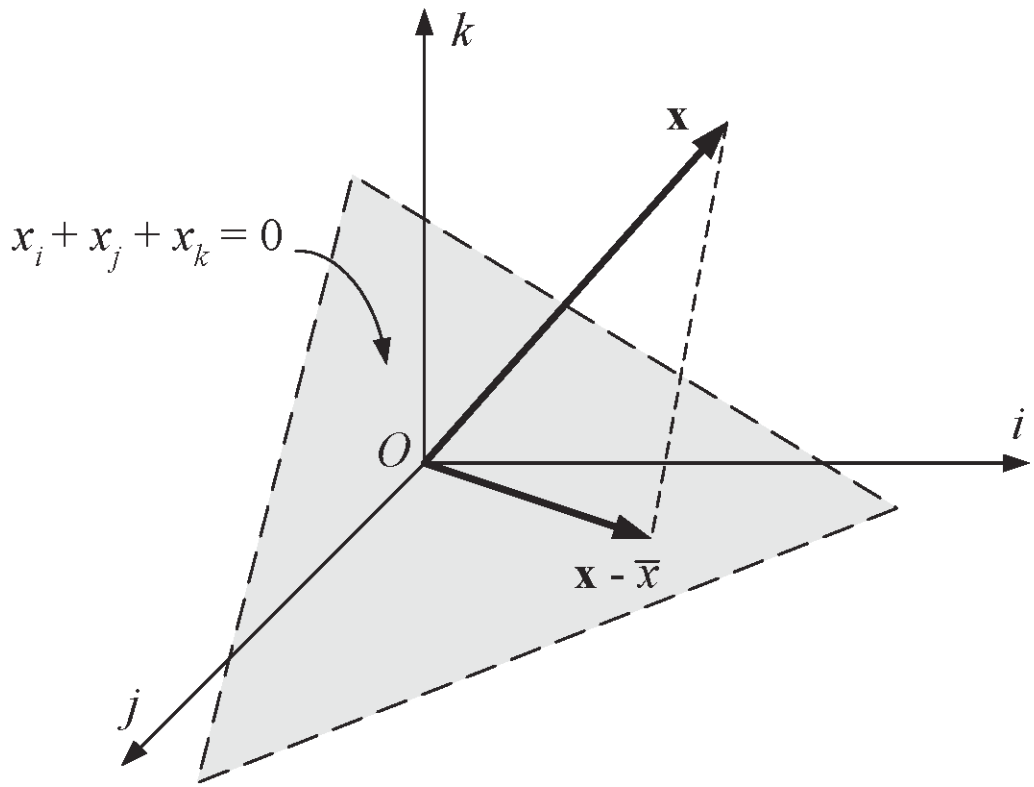
Projection onto hyperplane



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- Structural similarity
  - Normalization by σ (range bounded to 0 - 1)
  - Structural comparison

$$s(\mathbf{x},\mathbf{y}) = s\left(\frac{\mathbf{x}-\mu_x}{\sigma_x}, \frac{\mathbf{y}-\mu_y}{\sigma_y}\right)$$

- Overall similarity measure

$$S(\mathbf{x},\mathbf{y}) = f(l(\mathbf{x},\mathbf{y}),\ c(\mathbf{x},\mathbf{y}),\ s(\mathbf{x},\mathbf{y}))$$

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- Similarity definition $f(\mathbf{.})$
  - Must satisfy 3 conditions
    - Symmetry: $S(\mathbf{x},\mathbf{y}) = S(\mathbf{y},\mathrm{x})$
      - Exchanging order of inputs should not affect output
    - Boundedness: $S(\mathbf{x},\mathbf{y}) \leq 1$
    - Unique maximum: $S(\mathbf{x},\mathbf{y}) = 1$ if and only if $\mathbf{x} = \mathbf{y}$

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- Luminance definition

$$l(\mathbf{x},\mathbf{y}) = \frac{2\mu_x\mu_y + C_1}{\mu_x^2 + \mu_y^2 + C_1}$$

  - C_1 Controls instability when both μ_x and μ_y are close to 0

$$C_1 = (K_1 L)^2$$

  - L is the dynamic range of pixel values (255) and $K_1 << 1$, a small constant

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- $l(\mathbf{x},\mathbf{y})$ is related to Weber's law
- Contrast definition

$$c(\mathbf{x},\mathbf{y}) = \frac{2\sigma_x\sigma_y + C_2}{\sigma_x^2 + \sigma_y^2 + C_2}$$

where $C_2 = (K_2 L)^2$; $C_2 \geq 0$ and $K_2 << 1$

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- Structural definition

$$s(\mathbf{x},\mathbf{y}) = \frac{\sigma_{xy} + C_3}{\sigma_x \sigma_y + C_3}$$

where σ_{xy} is defined as

$$\sigma_{xy} = \frac{1}{N-1} \sum_{i=1}^{N} (x_i - \mu_x)(y_i - \mu_y)$$

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- SSIM definition

$$\mathrm{SSIM}(\mathbf{x},\mathbf{y}) = [l(\mathbf{x},\mathbf{y})]^{\alpha} \cdot [l(\mathbf{x},\mathbf{y})]^{\beta} \cdot [l(\mathbf{x},\mathbf{y})]^{\gamma}$$

Where $\alpha > 0$, $\beta > 0$ and $\gamma > 0$ are gains for individual components

- Setting conditions $\alpha=\beta=\gamma=1$ and $C_3=C_2/2$

$$\mathrm{SSIM}(\mathbf{x},\mathbf{y}) = \frac{2(\mu_x\mu_y + C_1)(\sigma_{xy} + C_2)}{(\mu_x^2 + \mu_y^2 + C_1)(\sigma_x^2 + \sigma_y^2 + C_2)}$$

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- Distortion Contour
  - Geometric projection of distortion in vector space
  - Contours area represents error
  - Distortion contours changes according to the profile of the error functions
    - Shape, size/volume

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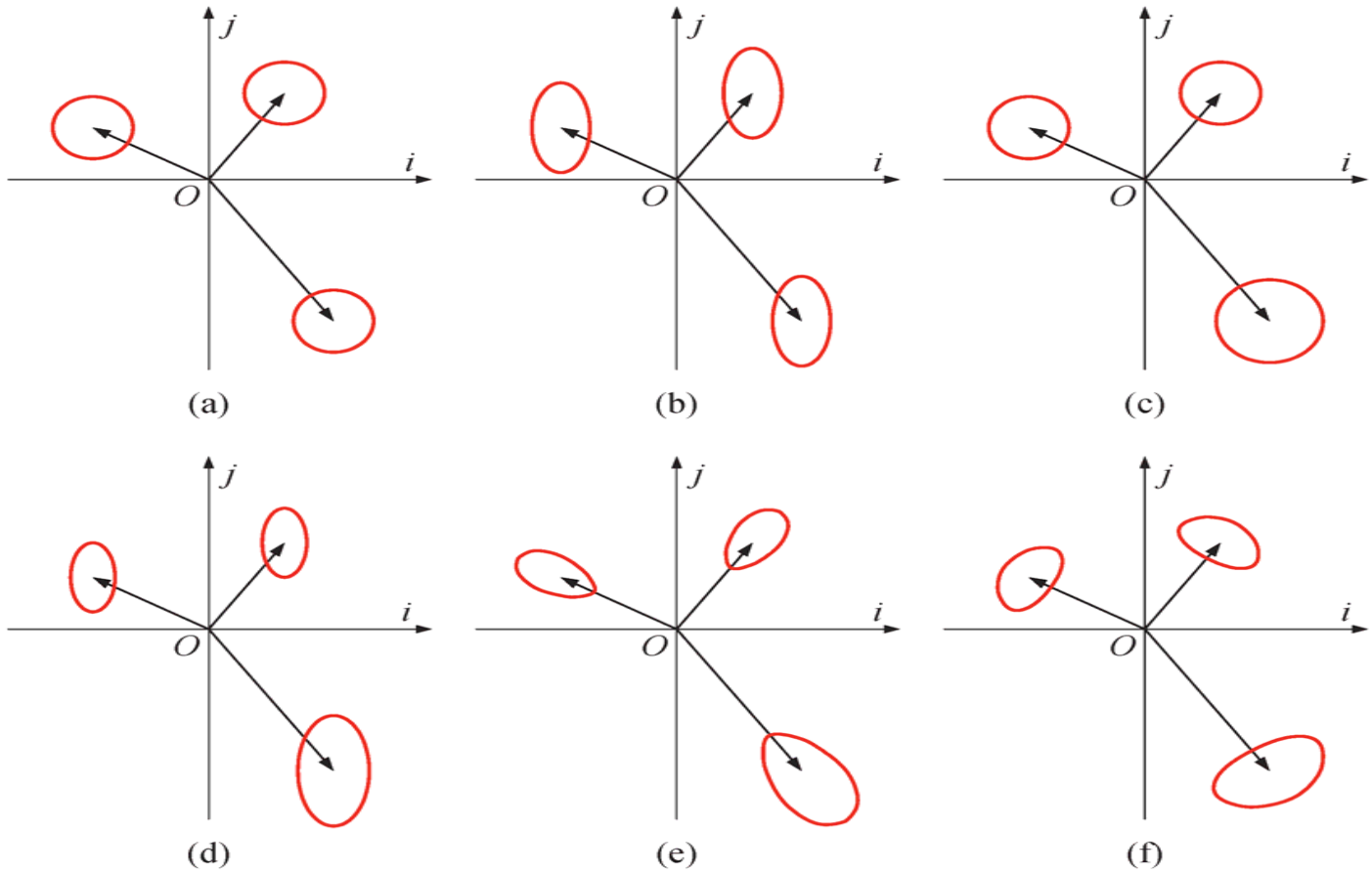
Distortion Contour for Minkowski error

Magnitude weighted Minkowski

Component weighted Minkowski



Magnitude and component weighted Minkowski

SSIM with component emphasis

SSIM with structure emphasis

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7.3 Image Quality Assessment Based on the SSIM Index

- SSIM more effective for localized evaluation
  - Statistical features of images are highly non-stationary
  - Image distortion may be space-variant
  - Focus of the HVS localized on an area
    - Due to viewing angle of the foveal area
  - Provides spatially varying quality maps
    - Different areas with different quality levels

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- SSIM windows
  - Squared 8 x 8 windows
    - Leads to blocking in index map
  - Weighted circular Gaussian window
    - Alleviates blocking problem
    - weights $\mathbf{w} = \{w_i \mid i = 1,2,\ldots, N\}$ bounded by

$$\sum_{i=1}^{N} w_i = 1$$

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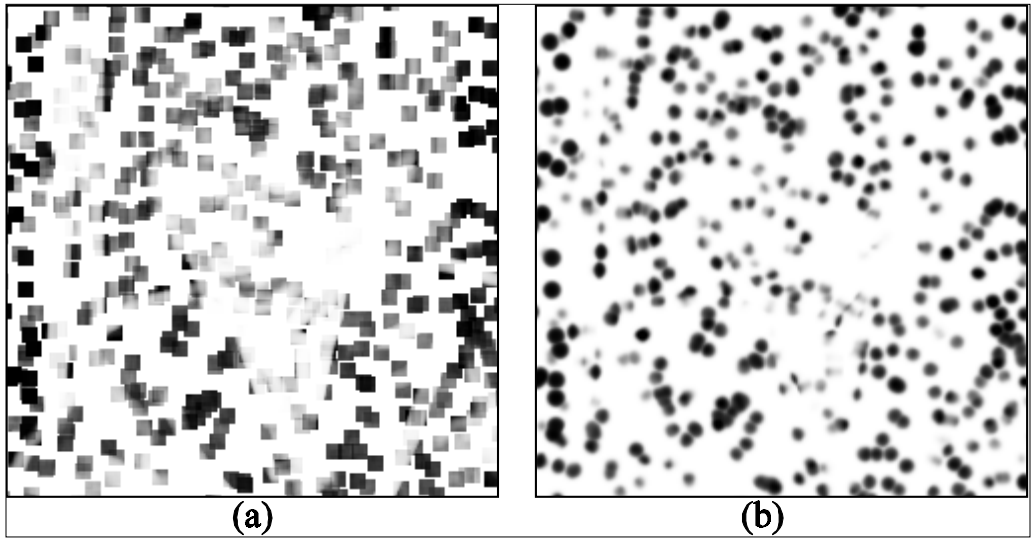
SSIM index maps of impulse corrupted *Einstein* image. a) square window. b) Circular window



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- Weighted mean

$$\mu_x = \sum_{i=1}^{N} w_i x_i$$

- Weighted standard deviation

$$\sigma_x = \left(\sum_{i=1}^{N} w_i (x_i - \mu_x)^2 \right)^{\frac{1}{2}}$$

$$\sigma_{xy} = \sum_{i=1}^{N} w_i (x_i - \mu_x)(y_i - \mu_y)$$

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- Overall quality measure for SSIM

$$\mathrm{MSSIM} = \sum_{j=1}^{M} W_j \cdot \mathrm{SSIM}_j$$

Where the sample weight W_j follows

$$\sum_{j=1}^{M} W_j = 1$$

  – Weighting strategies
    - uniform
    - Region of interest (ROI)
    - Foveal area

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Practical evaluation MSSIM

- Evaluate the performance of SSIM
  - Measure against subjective scores
- Source material
  - 29 colour images from LIVE database
  - Compressed with JPEG and JPEG2000
    - JPEG bitrates 0.150 - 3.336 bpp
    - JPEG2000 bitrates 0.028 – 3.150 bpp
  - Generating 175 coded images

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- Subjective evaluation
  - Quality assessment with 5 point scale
    - Excellent, good, fair, poor and bad
  - Subject numbers
    - 13 to 20 for JPEG coded images
    - 25 for JPEG 2000 coded images
  - Screening for outliers in data
  - Data normalized to range of 1 -100

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- MSSIM operation
  - Calculation based on downsampled image
    - ¼ resolution image
- Performance observations
  - Colour components has little impact on MSSIM performance
  - MSSIM more consistent with perceived quality
  - Better prediction than PSNR

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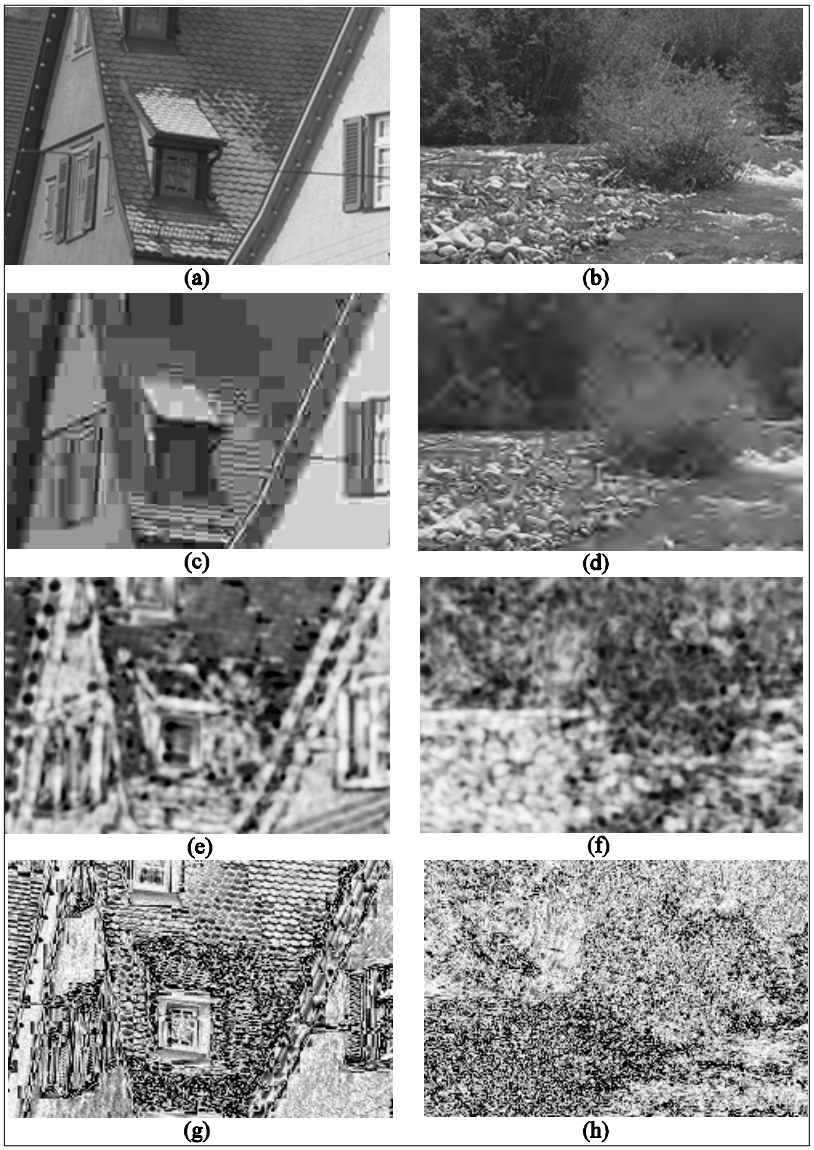
Original *Buildings* image

Original *Stream* Image



JPEG Coded @ 0.2673 bpp

JPEG2000 Coded @ 0.1896 bpp

SSIM map

SSIM map

Absolute error map

Absolute error map

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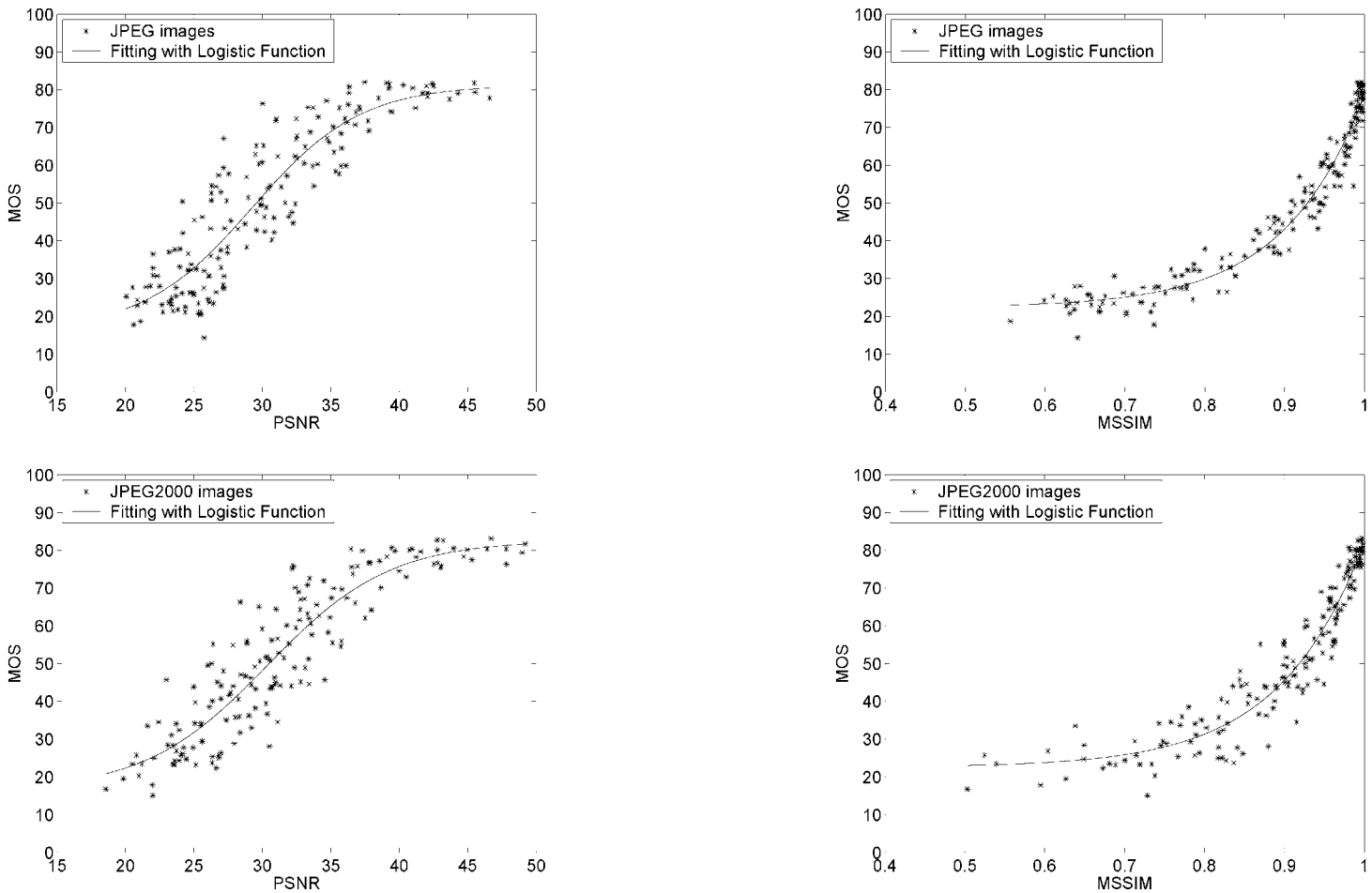
Scatter plots of MOS vs model prediction



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- Quantitative performance evaluation
  - Correlation coefficient (CC)
  - Spearman rand order correlation coefficient (SROCC)
- MSSIM clearly better

Database	JPEG		JPEG2000	
Model	PSNR	MSSIM	PSNR	MSSIM
CC	0.904	0.978	0.910	0.958
MAE	6.769	3.324	6.300	4.352
RMS	8.637	4.176	8.062	5.540
OR	0.200	0.006	0.095	0.024
SROCC	0.893	0.973	0.906	0.955

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7.4 Discussions

- Structural Similarity measurement
  - Different to traditional error sensitive method
    - MSE/PSNR
  - Measures perceived structural information
    - Not perceived error
  - Top-down approach
    - Mimics hypothesized overall HVS functionality

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- SSIM
  - A practical application of the structural similarity philosophy
  - Simple implementation
  - Good prediction results
    - Compared to PSNR

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EGM03	I. Epifanio, J. Hutirrez and J. Malo. Linear transform for simultaneous diagonalization of covariance and perceptual metric matrix in image coding. *Pattern Recognition*, 36(8):1679-1923, Aug. 2003
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RCB03	U. Rajashekar, L.K. Cormack and A.C. Bovik. Image features that draw fixations. In *Proc. IEEE Inter. Conf. Image Processing*, 3:313-316, Sep. 2003
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WLB04	Z. Wang, L. Lu and A.C. Bovik. Video quality assessment based on structural distortion measurement. *Signal Processing: Image Communication*, 19(2):121-132, Feb. 2004. Special issue on video quality metrics
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WYSV97	A.B. Watson, G.Y. Yang, J.A. Solomon and J. Villasenor. Visibility if wavelet quantization noise. *IEEE Trans. Image Processing*, 6(8):1164-1175, Aug. 1997

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8. Vision Model Based Digital Video Impairment Metrics

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Chapter 8 Outline

8.1 Introduction

8.2 Vision Modelling for Impairment Measurement

8.3 Perceptual Blocking Distortion Metric

8.4 Perceptual Ringing Distortion Measure

8.5 Conclusion

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8.1 Introduction

- Proliferation of digital services and applications
  - Digital broadcast, multimedia, camera, etc
  - Rely upon compression
    - Leads to distortions
    - Therefore need to quantify quality of services
- Traditional metrics
  - MSE/PSNR
  - Do not always reflect perceived quality or distortion

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- Vision Model based metrics
  - Emulate mechanism of the *Human Visual System* (HVS)
  - More accurate measurement of perceived quality/distortion
  - Generalized metric
    - Measures overall quality
  - Specialized metric
    - Measures specific impairment. e.g. blurring

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Impairment metrics

- Useful for studying the characteristics of individual impairment
  - May lead to improvements of coding systems
    - e.g. blocking impairment used to design de-blocking algorithms

	impairment	vision model	reference	image/video
Karunasekera et al [KK95]	blocking	Y	full	image
ANSI T1.801.03 [Sec96]	blocking	N	reduced	both [1]
GBIM [WY97]	blocking	Y	no	image
PBDM [YWC00a, YWWC02]	blocking	Y	full	video
PRDM [YWC00b, ZWY+03]	ringing	Y	full	video
Wang et al [WBE00]	blocking	Y	no	image
Bovik et al [BL01]	blocking	Y	no	image

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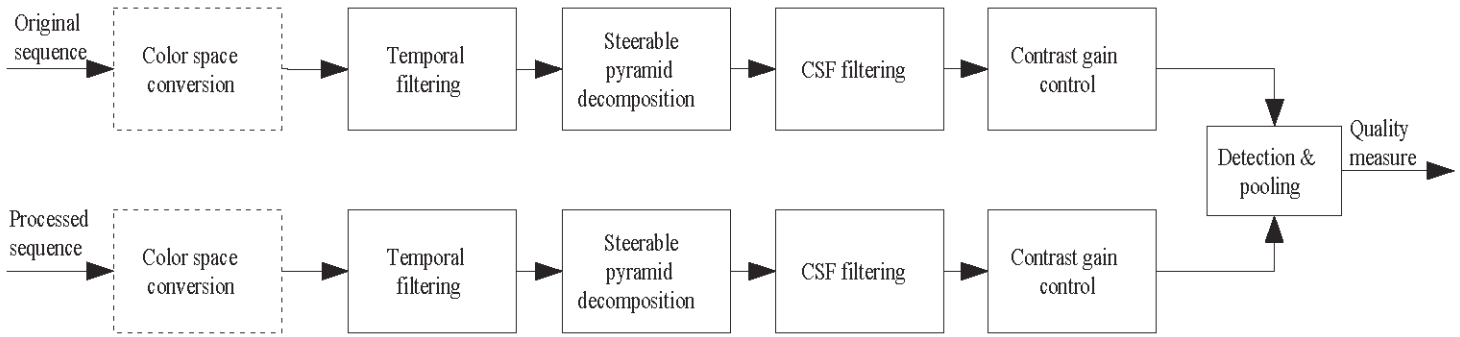
8.2 Vision Modelling for Impairment Measurement



- Key element of vision model (*above*)
  - Colour sensitivity
  - Spatio-temporal contrast sensitivity
  - Contrast gain control

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8.2.1 Colour Space Conversion

- Colour Spaces
  - *RGB*, YC_bC_r, *CIE XYZ*, etc
  - For typical video - YC_bC_r
- *Opponent Colour Space* (OCS)
  - HVS operated in OCS
    - Black-White (BW), Red-Green (RG), Blue-Yellow (BY) colour channels
  - Conversion from YC_bC_r to OCS needed
  - *Y* and *BW* channels have similar properties

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- Sensitivity of colour channels
  - *BW* and *Y* channels contains most information
    - Possible for vision models to operate on colour pictures with luminance channel only with minimal error

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8.2.2 Temporal Filtering

- Temporal channels of HVS
  - Sustained (low pass)
    - Contains majority of information (and distortions)
  - Transient (band pass)

Below: 30 Hz filter coefficients

Filter	a[2] ... a[n_a+1]	b[1] b[2] ... b[n_b+1]
low pass 30Hz	-0.080000	0.800000, 0.120000
band pass 30Hz	0.264560, 0.532900	0.205877, -0.079503, -0.182592, 0.105776
low pass 25Hz	-0.080000	0.859813, 0.060187
band pass 25Hz	0.599392, 0.348100	0.222765, -0.210861, -0.099928, 0.182667

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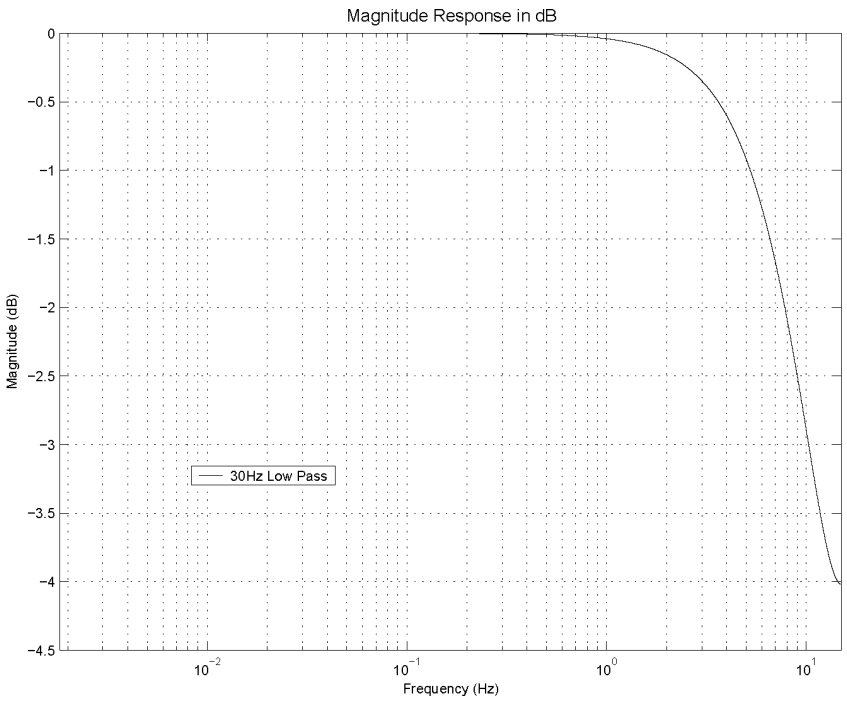
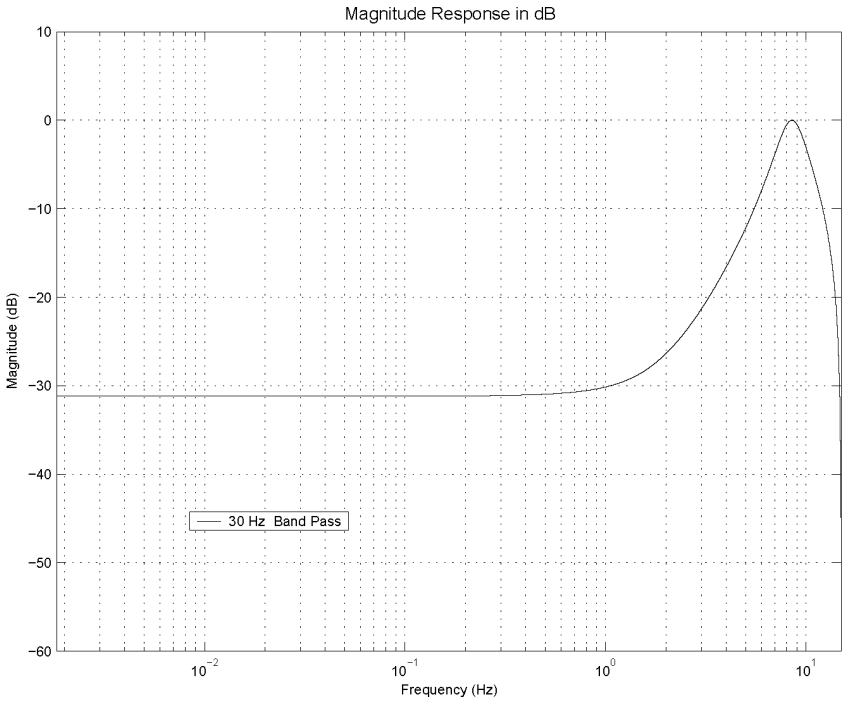
Temporal filters (30 Hz). *Left*: low pass. *Right*: band pass





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8.2.3 Spatial Filtering

- Spatial sensitivity of HVS
  - 4 to 7 bands
  - Frequency with 1 to 2 octaves bandwidth
  - Orientation with 30 to 60 degrees bandwidth
- Practical implementation
  - *Steerable Pyramid Transform* (SPT)
    - 1 isotropic low-pass level
    - 4 band pass levels
      - 4 orientations (0°, 45°, 90° and 135°)
    - 1 isotropic high pass level

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Steerable Pyramid Image of *Claire*

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- Contrast Sensitivity realizations
  - Convolution through filter banks
  - Multiplier through weighting coefficients
    - Simple but coarse approximation
    - One weight for each frequency level

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8.2.4 Contrast Gain Control

- Accounts for masking phenomenon
  - Consist of excitatory and inhibitory given by

$$\tilde{\mathbf{X}}_R[i,f,\theta,k,l] = \sum_{i=1}^{4} w_i \frac{(\mathbf{X}[i,f,\theta,k,l])^2}{\sum_{\phi}(\mathbf{X}[i,f,\phi,k,l])^2 + \gamma_i^2}$$

where $\mathbf{X}[j,f,\theta,k,l]$ is an SPT coefficient at specific frame (j), frequency (f), orientation (θ), vertical (k) and horizontal (l) location

w_i is the scaling constant and γ_i the saturation coefficient. $\Phi = \{0^o, 45^o, 90^o, 135^o\}$ with $i = \{1,2,3,4\}$ representing 4 contrasts mechanisms

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- Multiple contrast mechanism
  - Needed to overcome the rapid saturation of individual mechanism
    - Occurs when STP coefficient $\mathbf{X}[j,f,\theta,k,l]$ is considerably larger than γ_i

Model Parameters	
C_i (CSF)	0.41, 1.25, 1.2, 0.4097, 0.083, 0.001
w_i	1, 1, 1, 1
γ_i	4.4817, 7.3891, 12.1825, 54.5982

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- Isotropic low-pass band
  - Raw magnitude of coefficient are often significantly larger than γ_i
  - Apply mean subtraction to reduce magnitude energy

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8.2.5 Detection and Pooling

- Decimation factor
  - Normalize sensor output for uniform presentation

$$\mathbf{X}_{R_o}[j,f,\theta,k,l] = \frac{\tilde{\mathbf{X}}_{R_o}[j,f,\theta,k,l]}{X_f}$$

$$\mathbf{X}_{R_p}[j,f,\theta,k,l] = \frac{\tilde{\mathbf{X}}_{R_p}[j,f,\theta,k,l]}{X_f}$$

  - $X_f = \{1,4,16,64,256\}$

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- Difference and Pooling operator
  - Squared difference between original (R_o) and processed (R_p)
  - Summation over all variable domains

$$\Delta \mathbf{X}_R = \frac{\sum_{j,f,\theta,k,l} |\mathbf{X}_{R_o}[j,f,\theta,k,l] - \mathbf{X}_{R_o}[j,f,\theta,k,l]|^2}{N}$$

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8.2.6 Model Parameterization

- Calibrate Vision Model Parameters
  - Ensures proper operation of vision model
- Two approaches
  - Vision research experiments
  - Video quality experiment

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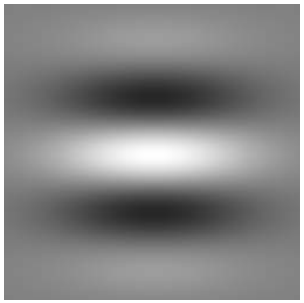
Vision research experiments



- Utilise synthetic test patterns →→
- Target specific aspect of the HVS
  - e.g. contrast sensitivity
- Testing generally at threshold level
  - Appropriate for threshold level assessment
  - Unsuitable for quality assessment
- Modelfest data set
  - Collection of test data for common stimuli

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Video Quality Experiments

- Utilize natural video sequence
- Two phases
  - Collect subjective quality scores associated with test materials
    - e.g. VQEG and ANSI T1A1 sequences
  - Find model parameters which yields the best correlation between prediction and subjective data (Optimization process)

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- Optimization
  - Cost function to measure correlation
    - Spearman rank correlation (r_s)
      - Measures the order of quality/distortion ranking between subjective data and prediction

$$r_s = 1 - \frac{6\sum_l D_l^2}{N(N^2-1)}$$

  - Two tier optimization
    - Coarse search for general search space
    - Refinement stage to locate local optima

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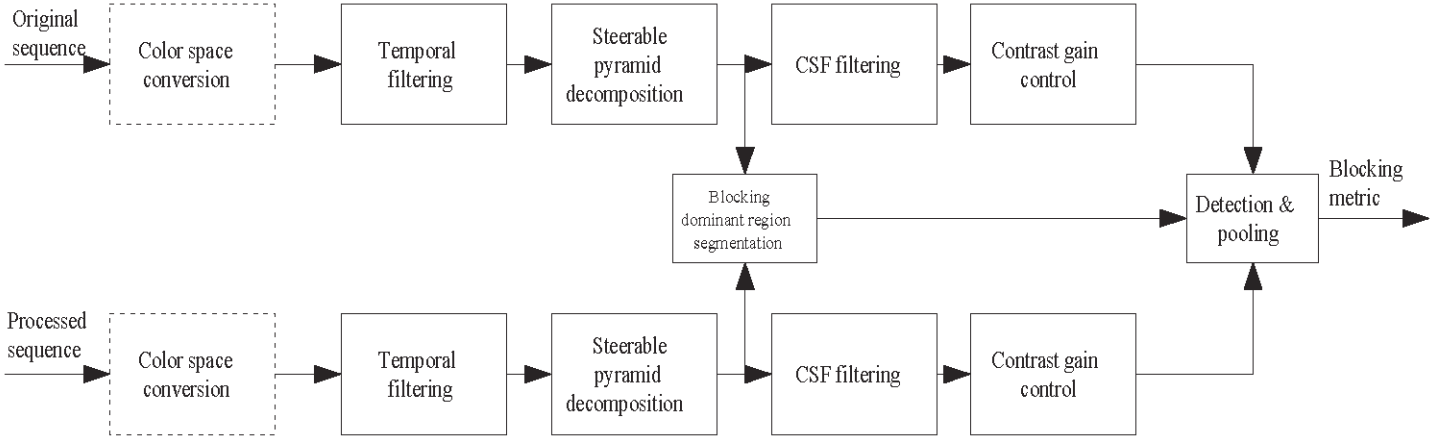
8.3 Perceptual Blocking Distortion Metric (PBDM)

- Blocking distortion from DCT coders
  - Seen as discontinuities at block boundaries
  - Manifest in smooth regions of pictures
  - Quantified with PBDM (below)



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- PBDM Components
  - Blocking dominant region segmentation
    - Vertical and horizontal edge detection
    - Isolate blocking edges from ringing distortions
    - Generate blocking map
  - Quantify distortions in blocking region
    - With vision model in section 8.2
    - Covert distortion to Objective Blocking Rating (OBR) scale

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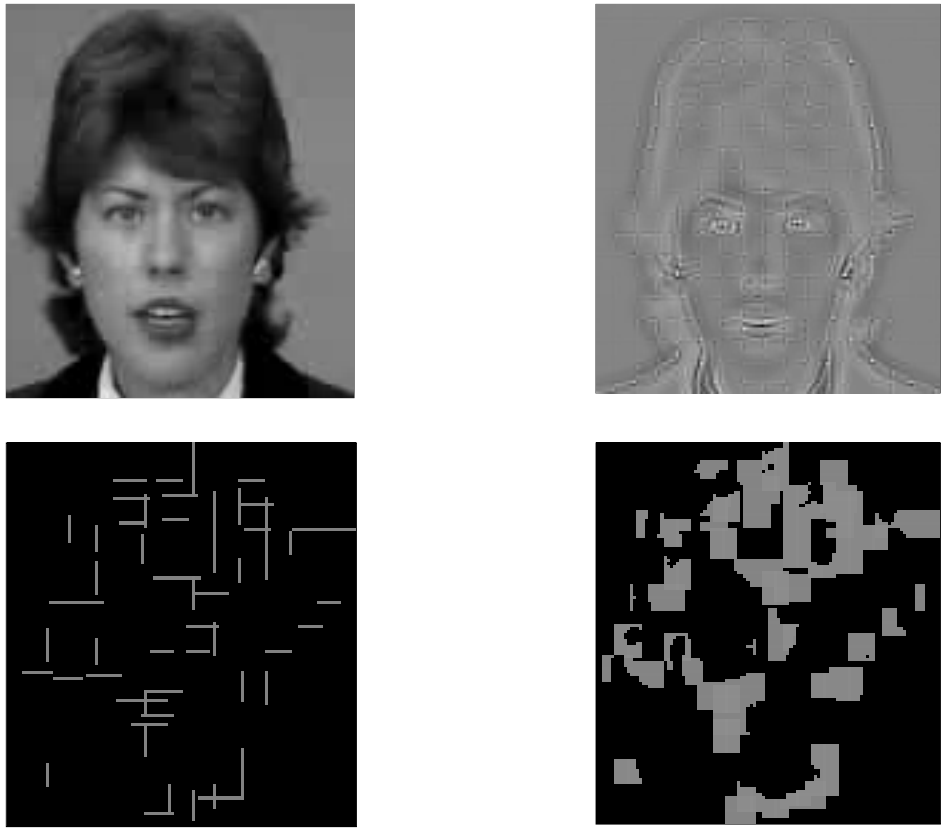
Clockwise from top left. Coded *Claire* frame, high pass SPT image, detected block edges and blocking map



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8.3.3 Performance Evaluation of the PBDM

- Test material
  - ANSI T1A1
    - 5 sequences
    - Coded with MPEG-2 coder at 768 kbps, 1.4 Mbps, 2Mbps, 3Mbps and 5 Mbps
  - VQEG
    - 5 sequences
    - Coded with MPEG-2 coder at 3Mbps and 2Mbps (3/4 resolution)

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- Subjective assessment
  - ITU-R bt.500 recommended test setup
  - Double Stimulus Impairment Scale variant II (DSIS-II) method
  - 5 expert test subjects
- Evaluation with 3 correlation measures
  - spearman rank order correlation
  - Pearson's correlation coefficient
  - Logistic fit

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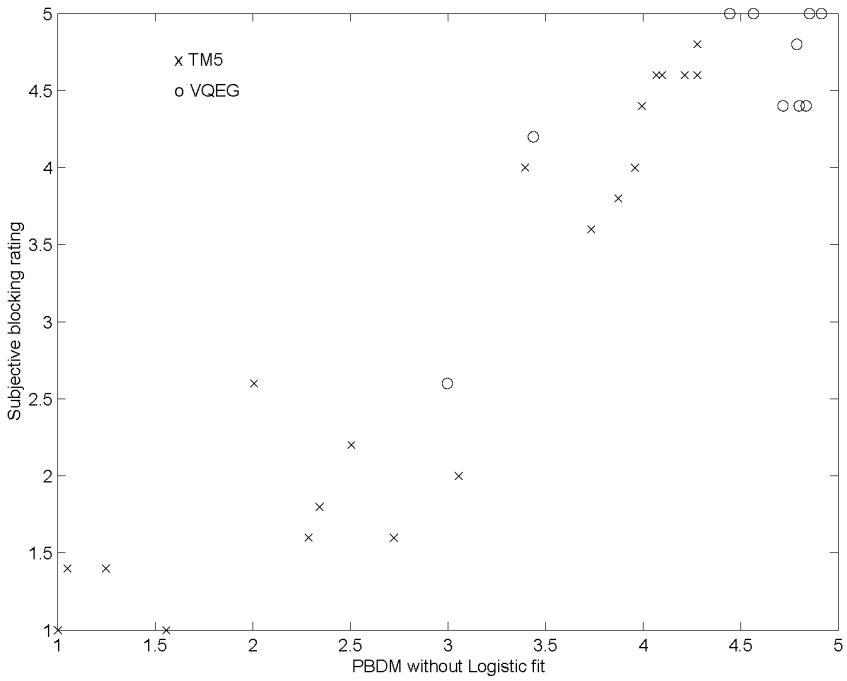
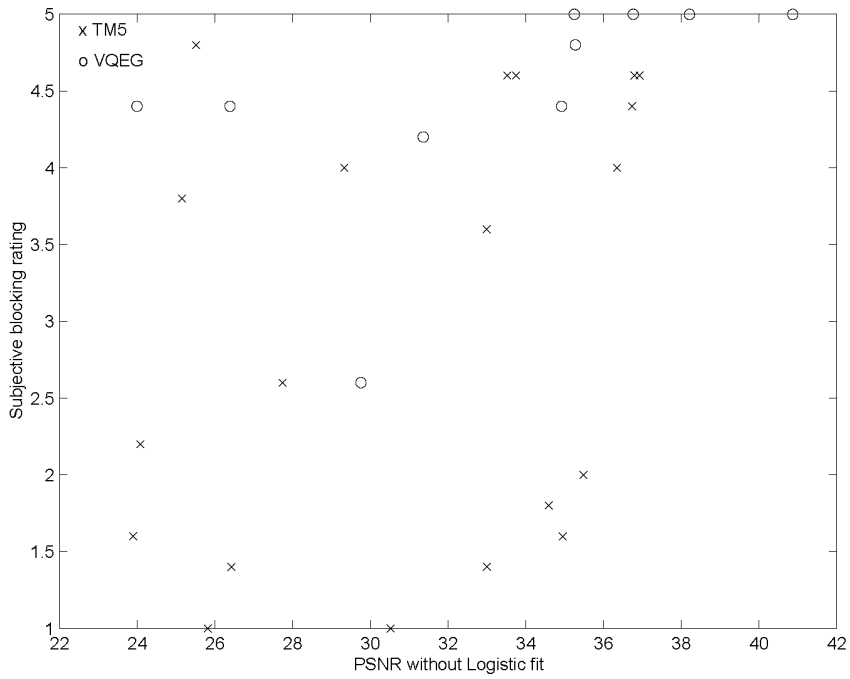
MOS vs PBDM (left) and MOS vs PSNR (right)





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PBDM Evaluation

Metric	Pearson-logistic metric			Spearman	E|*error*|	Average standard deviation in the subjective test data
	Correla-tion	Upper bound	Lower bound			
PBDM	0.961	0.982	0.918	0.910	0.296	0.455
PSNR	0.489	0.726	0.149	0.517	1.038	

- PBDM has excellent correlation to MOS
- PSNR correlation to MOS is poor

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5row1 sequence: MOS: 3.6; PBDM: 3.79; PSNR: 32.99 dB

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Inspec sequence. MOS: 1.4; PBDM: 1.22; PSNR: 33.00 dB

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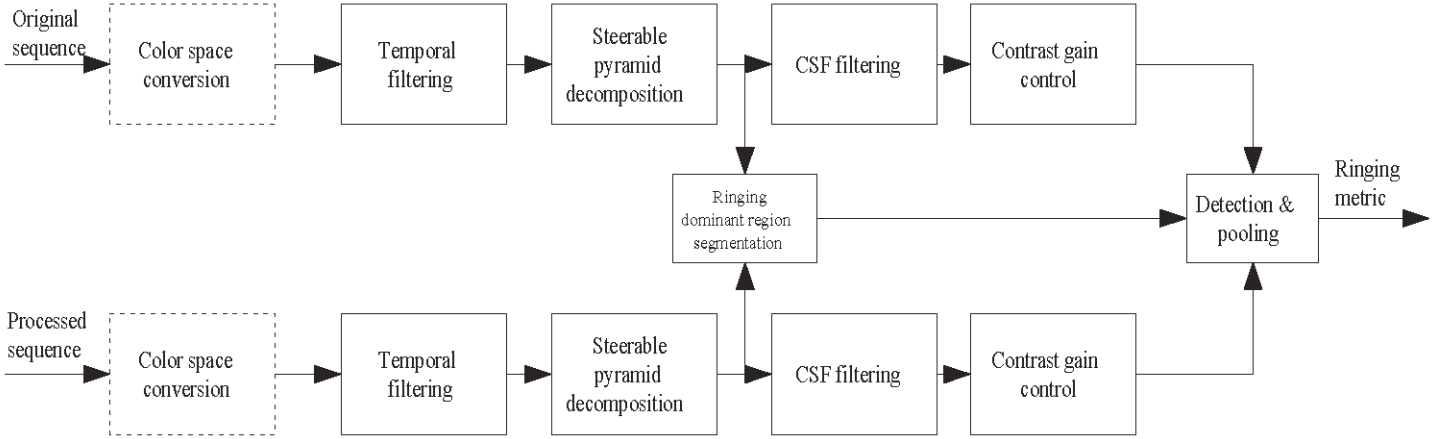
8.4 Perceptual Ringing Distortion Metric (PRDM)

- Ringing distortion
  - Related to Gibb's phenomenon
    - Quantization of transform coefficients leads to high frequency irregularities

Below: PRDM diagram



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- PRDM components
  - Ringing region segmentation
    - Initial classification of regions into 3 categories based on variance
      - Smooth, complex and unknown regions
    - Detection of smooth and complex regions
      - Unknown regions are re-classified into either smooth or complex regions
    - Boundaries of smooth and complex regions are seen as ringing
  - Vision model detection and pooling

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8.4.3 Performance Evaluation of PRDM

- Test material
  - Original sequences
    - Mobile & Calender (MC)
    - Table Tennis (TT)
  - Both sequences coded with MPEG-2 at
    - 1.5, 1.75, 2, 2.25, 2.5, 2.75, 3, 4, 5 and 7 Mbps
- Subjective Assessment
  - DSIS-II
  - 5 expert and 2 non-expert viewers

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Metric	Pearson	Spearman	E$\lvert error \rvert$	Average standard deviation in the subjective test data
PRDM(both)	0.9397	0.9805	0.2651	0.4402
PSNR(both)	0.7674	0.7489	0.5358	
PRDM(MC)	0.9642	1	0.2457	0.4219
PSNR(MC)	0.9341	1	0.6659	
PRDM(TT)	0.9945	1	0.2845	0.4649
PSNR(TT)	0.9709	1	0.4056	

- Results shows excellent correlation between PRDM and MOS
- PSNR correlation to MOS is also good
- DCT coder exhibit limited ringing artifacts

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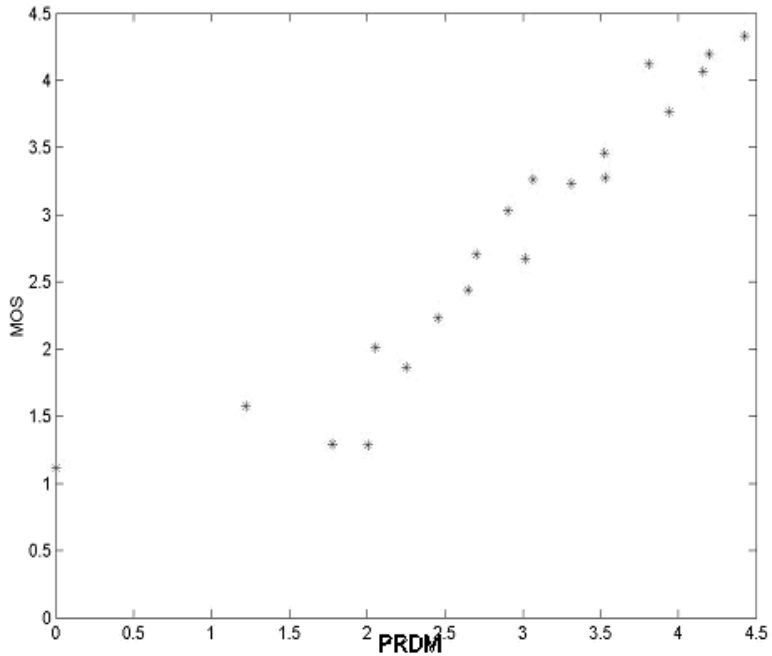
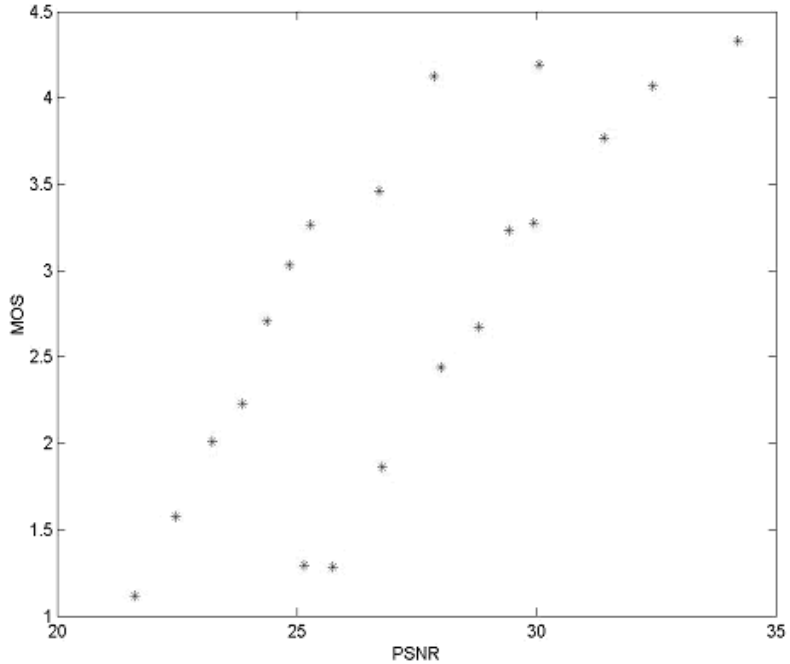
MOS vs PRDM (left) and MOS vs PSNR (right)





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8.5 Conclusion

- Progress have be made in vision model based objective metric
- However, still more work ahead
  - Limited understanding of HVS
    - e.g. temporal masking
  - Other impairment metrics
    - Blurring, temporal fluctuation, etc
  - Improve vision model for NR and RR metrics
  - Application of impairment metrics for picture coding systems development

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9. Modeling Just-noticeable Difference in Visual Signal

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Chapter 9 Outline

9.1 Introduction

9.2 JND with DCT Subbands

9.3 JND with Pixels

9.4 JND Model Evaluation

9.5 Conclusions

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9.1 Introduction

- Digital pictures are ultimately viewed by the *Human Visual System* (HVS)
  - Regardless of operations or applications
- The HVS has limited sensitivity
  - Unable to sense all changes in pictures
    - Note: not all changes equate to distortions
      - e.g. post processing, edge enhancement, etc
  - Advantageous to consider HVS characteristics in picture coding systems

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Just-Noticeable Difference (JND)

- JND definition
  - The visibility threshold below which any change cannot be detected by the HVS
- Factor affection JND
  - local characteristics of images
  - Viewing conditions
  - Individual subject

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9.1.1 Single Stimulus JND Test

- Based upon simple stimuli
  - Varying foreground stimulus over a uniform static background
- Follows Weber-Fechner's Law
  - Just noticeable foreground threshold increases with background luminance above 10 cd/m^2

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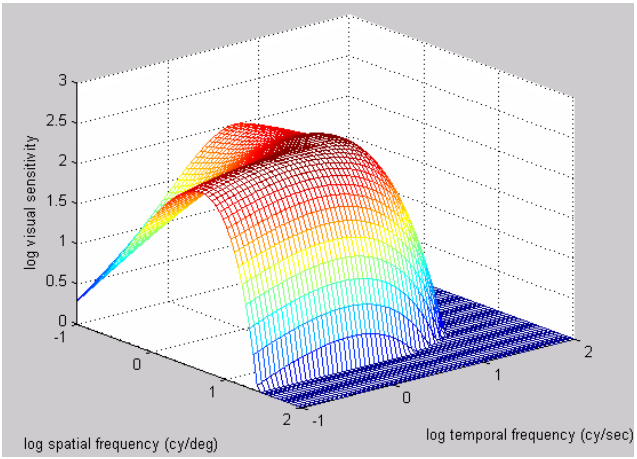
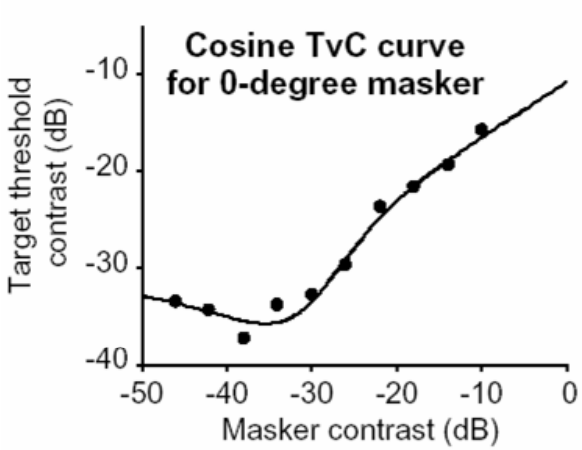
Factors affecting JND threshold levels





– Contrast Sensitivity (*top left*: CSF)
  - JND varies with spatial and temporal frequencies

– Masking and facilitation (*top right*)
  - JND dependent on the interactions between stimulus and its surroundings

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9.1.2 JND Tests with Real-World Images

- Test the JND levels relative to distortions
  - i.e., $x_t = x_o + h(x_d - x_o)$

    where x_o, x_d and x_t original, distorted and test images with h the weighting factor
  - Distortions could be of any form including:
    - Blocking, ringing, blurring, fluctuations, etc
  - JND level determined if 75% of observes could perceive the distortion $(x_d - x_o)$
  - JND can be scaled, i.e., 2-JND, 3-JND, etc

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9.1.3 Applications of JND Models

compression & coding
- quantization/rate control
- motion search
- pre-processing
- filtering of residues/coefficients
- inter-frame replenishment

edge enhancement
- optimum sharpness

quality/distortion metrics
- differentiation
  - near-JND
  - supra-JND
- quantification

watermarking:
- authentication
- error resilience

other visual processing, for
resource savings/allocation
bandwidth, computing power, memory, display/printing resolution
and/or
performance enhancement
picture quality

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Existing Works with JND models

image/video compression	quantizer and rate control Watson'93 Hontsch & Karam'00,02, Yang, *et al.*'05 motion search Yang, *et al.*'03 inter-frame replenishment Chiu & Berger'99 filtering of residues/coefficients Yang, *et al.*'05

visual communication	watermarking Wolfgang, *et al.*'99 self-embedment for error correction unequal error protection Jiang, *et al.*'99 joint source-channel coding

enhancement/ reconstruction	synthesis Ramasubramanian, *et al.*'99 edge-enhancement Lin, *et al.*'05

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JND Estimation

DCT subbands

Ahumada & Peterson'92, Watson'93, Hontsch & Karam'00,02, Zhang, et al.'05

wavelet subbands

Watson, et al.'93

pyramid subbands

Ramasubramanian, *et al.*'99

pixel domain

Chou & Li'95, Chiu &Berger'99, Yang, *et al.*'03

contrast masking

Tong&Venetsanopoulos'98, Zhang, et al.'05

temporal effect

eye motion: Daly'98
frame difference: Chou & Chen'96
temporal CSF:for subbands- Daly'98, Watson, *et al.*'01
for pixel-Zhang'04

Visual-attention modulation

Lu, *et al.*'05

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9.2 JND with DCT Subbands

- Step for determining JND for DCT subbands
  - Base threshold
    - Spatial CSF
  - Luminance adaptation
  - Contrast masking
    - Intra- and inter-band masking
  - Other factors
    - Temporal and colour considerations

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- General formulation in DCT subband

$$s(n,i,j) = t_{s-csf}(n,i,j)\prod_{\xi}\alpha_{\xi}(n,i,j)$$

where n and (i,j) are the DCT block and subband index

- $t_{s\text{-}csf}(n,i,j)$ Base threshold due to spatial CSF
- $\prod_{\xi}\alpha_{\xi}(n,i,j)$ Elevation parameter due to adaptation and masking

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9.2.1 Formulation of Base Threshold

- Base threshold defined as

$$t_{s-csf}(n,k,l) = \frac{G}{\phi_k \phi_l (L_{\max} - L_{\max})} T^o(n,k,l)$$

where $T^o(n,k,l)$ is the DCT domain CSF threshold and

$$\phi_u = \begin{cases} \sqrt{1/N}, & u = 0 \\ \sqrt{2/N}, & \text{otherwise} \end{cases}$$

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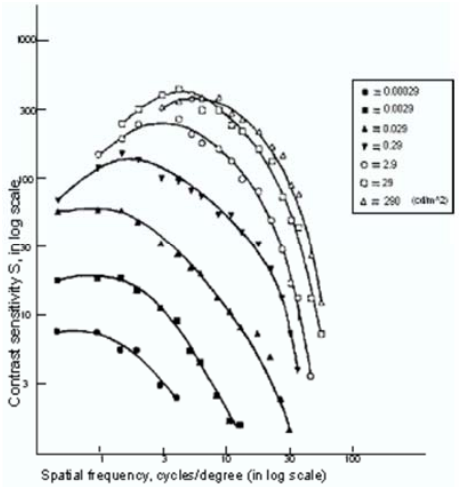
Modelling spatial CSF

- CSF threshold defined as

$$\log T = \log T_{\min} + k(\log f - \log f_p)^2$$

  – From van Nes and Bouman's data (below)



Van Nes & Bouman'67

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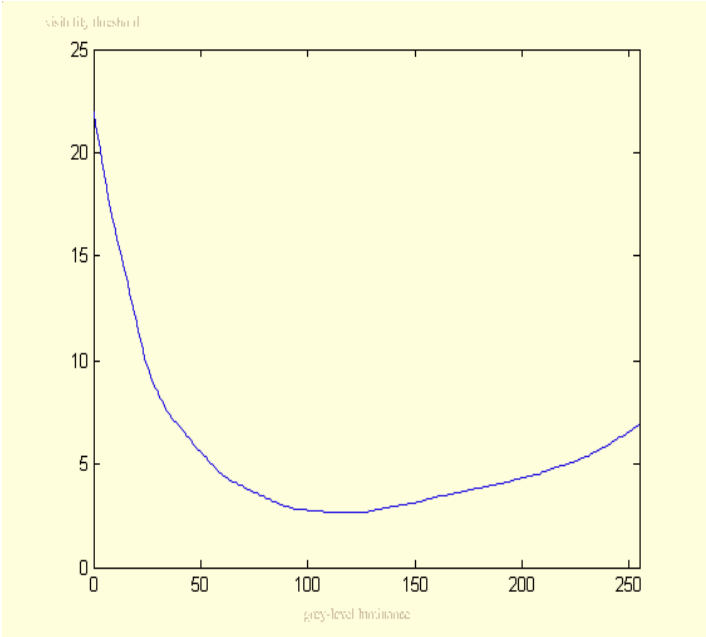
9.2.2 Luminance Adaptation Considerations

- Simple luminance adaptation formulation

$$\alpha_{lum}(n) = \left(\frac{X[n,0,0]}{X_L} \right)^{\varepsilon}$$

$X[n,0,0]$ is DC coefficient at n^{th} block

X_L is the background luminance of DC band



Threshold vs Luminance

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- Realistic adaptation model
  - Needed due to non-monotonic characteristic

$$\alpha_{lum}(n) = \begin{cases} k_1\left(1 - \dfrac{2 \cdot \mathrm{X}[n,0,0]}{G \cdot N}\right)^3, & \mathrm{X}[n,0,0] \le \dfrac{G.N}{2} \\ k_2\left(\dfrac{2 \cdot \mathrm{X}[n,0,0]}{G \cdot N} - 1\right)^2, & \text{otherwise} \end{cases}$$

G is the maximum grey level with K_1 and K_2 fitted parameters

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9.2.3 Contrast Masking

- Intra-band masking (within subband)

$$\alpha_{intra}(n,k,l) = \max\left(1, \left|\frac{X[n,k,l]}{t_{s-csf}(n,i,j)\cdot\alpha_{lum}(n)}\right|^{\zeta}\right)$$

with $0 \le \zeta \le 1$

- Inter-band masking considerations
  - Classification of DCT coefficients
  - Classify subblocks into masking group

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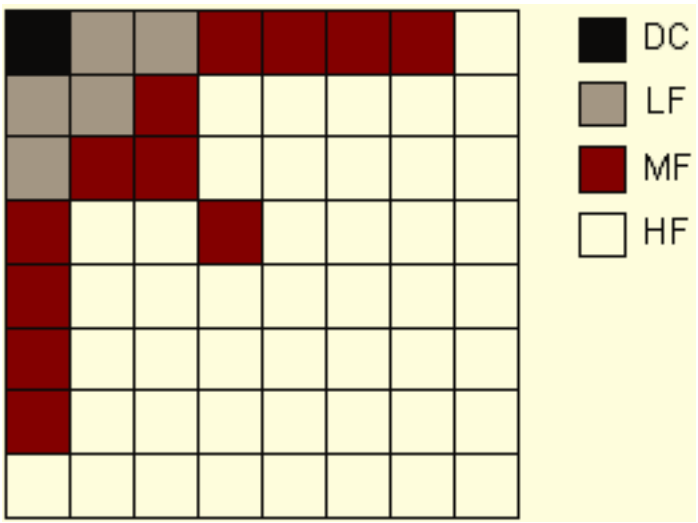
Inter-band masking classification

1. Segregate DCT coefficients into low (LF), mid (MF) and high (HF) frequency groups
2. Calculated absolute energy of each group
3. Classify DCT block to masking group based on energy of HF and MF, (E_{mh}), relative to predefined parameters μ_1, μ_2 and μ_3



DCT Coefficient grouping

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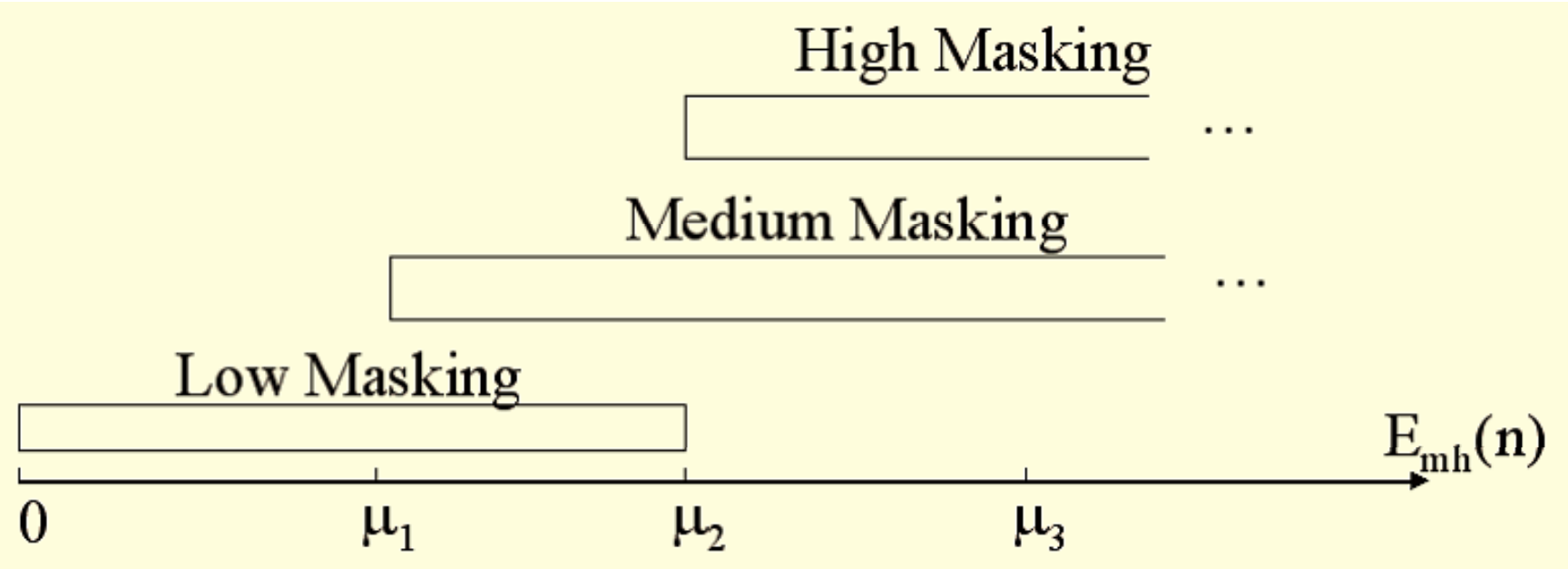
Illustration of low (LM), medium (MM) and high (HM) masking classification of DCT subblocks



μ_1=125, μ_2=290 and μ_3=900

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- Inter-band masking (across subband)

$$\alpha_{inter}(n) = \begin{cases} 1, & LM \\ \delta_1 & MM, E_{ml} \le R_0 \\ \delta_2 & MM, E_{ml} \ge R_0 \\ \left(1 + \dfrac{E_{mh}(n) - \mu_2}{2 \cdot \mu_3 - \mu_2}\right), & otherwise \end{cases}$$

E_{ml} absolute energy of mid and low frequency coefficients, δ_1=1.125, δ_1=1.25 and R=400 are model parameters

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9.3 JND with Pixels

- Considers
  - Luminance adaptation
  - Texture masking
  - Spatial contrast sensitivity
- Spatial JND

$$P(i,j) = T^L(i,j) + T^t(i,j) - C^{Lt}(i,j) \cdot \min\{T^L(i,j), T^t(i,j)\}$$

with $T^L(i,j)$ and $T^t(i,j)$ visibility threshold for luminance adaptation and texture masking.

$0 < C^{Lt} \leq 1(i,j)$ accounts for overlapping masking effect

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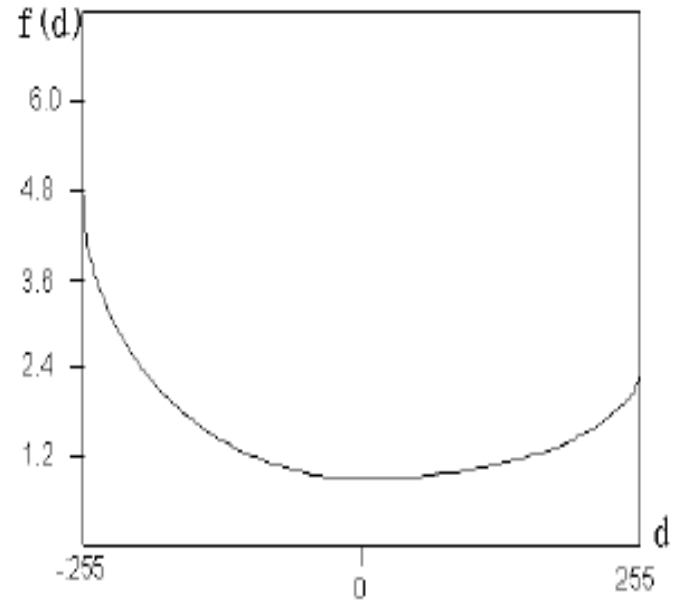
Temporal Masking Effect

Right: masking f(d) vs frame change (d)



- Modelled as

$$P_v(i,j) = f(a(i,j)) \cdot P(i,j)$$

where $f(a)$ is the temporal masking factor defined as

$$a(i,j) = \frac{\mathrm{x}[i,j] - x^p[i,j]}{2} + \frac{L_0 - L_0}{2}$$

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9.3.2 Conversion between Subband and Pixel Based JNDs

- Pixel-wise JND derived from summation of subband JND

$$t_p(n,x,y) = \sum_{u=0}^{N-1}\sum_{v=0}^{N-1} \phi_u \phi_v \cos\left(\frac{u(2x+1)\pi}{2N}\right)\cos\left(\frac{v(2y+1)\pi}{2N}\right)\cdot t'(n,i,j)$$

$$t'(n,i,j) = \begin{cases} sign(\mathrm{X}[n,k,l]\cdot s(n,k,l), & |\mathrm{X}[n,k,l]| \geq s(n,k,l) \\ 0 & otherwise \end{cases}$$

  - Truncation of threshold t' avoids over estimation of smooth region
  - Sign operator eliminates blocking effect

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- Estimation of subband JND

$$s(n,k,l) = [E_p(n) \cdot z(k,l)]^{1/2}$$

with $E_p(n)$, the pixel-wise JND energy in N x N image neighbourhood

$$E_P(n) = \sum_{\zeta=0}^{N-1}\sum_{\eta=0}^{N-1} P^2\left(\zeta + \left(\zeta + \left\lfloor \frac{n \cdot N}{W} \right\rfloor \frac{W}{N}\right) \cdot N, \eta + \left\lfloor \frac{n \cdot N}{W} \right\rfloor \cdot N\right)$$

and z containing the parameter weights (*below*)

$$\sum_{u=0}^{N-1}\sum_{v=0}^{N-1} z(u,v) = 1$$

0.0211	0.0197	0.0273	0.0445
0.0211	0.0261	0.0365	0.0581
0.0396	0.0464	0.0626	0.0954
0.0865	0.0990	0.1286	0.1865

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9.4 JND Model Evaluation

- Noise shaping in image/video
  - i.e., inject noise into images/videos and see if the noise level is noticeable
  - Pixel domain noise shaping

$$\tilde{\mathrm{x}}[i,j] = \mathrm{x}[i,j] + q \cdot S^{random}(i,j) \cdot P(i,j)$$

  - Transform domain noise shaping

$$\tilde{\mathrm{X}}[n,k,l] = \tilde{\mathrm{X}}[n,k,l] + q \cdot S^{random}(n,k,l) \cdot s(n,k,l)$$

S^{random} takes ± 1 with $P(i,j)$ and $s(n,k,l)$ the pixel and transform domain JND

q < 1 shapes the noise at perceptual lossless quality

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Noise injected *Cameraman* images. MSE = 144.
Left: DCT domain JND. *Right*: Pixel domain JND

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- For same total error energy
  - Accuracy of JND model improves with perceptual quality of noise-injected images/video
- For same perceptual visual quality
  - Accuracy of the JND model dictates the amount of noise that could be embedded into images/video

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9.5 Conclusions

- JND models
  - Pixel domain
  - Transform (DCT) domain
- JND domain conversion
  - from pixel to DCT and vice versa
- Evaluation of JND models
  - Systematic JND-guided noise injection approach

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- Applications of JND models
  - Perceptual quality/distortion metric
  - Picture compression
  - Data hiding
  - Error concealment

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AK01	A.J. Ahumada and W.K. Krebs. Masking in color images. *Proc. of SPIE Human Vision and Electronic Imaging VI*, 4299:187-194, Jan. 2001
AP92	A.J. Ahumada and H.A. Peterson. Luminance-model-based DCT quantization for color image compression. *SPIE Proc. Human Vision, Visual Processing and Digital Display III*, 3665-374, 1992
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CC96	C.H. Chou and C.W. Chen. A Perceptually Optimized 3-D Subband Image Codec for Video Communication over Wireless Channels. *IEEE Trans. Circuits and System for Video Technology*, 6(2):143-156, 1996
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HK02	I. Höntsch and L.J. Karam. Adaptive image coding with perceptual distortion control. *IEEE Trans. on Image Processing*, 11(3):214-222, Mar. 2002
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ITU00	ITU. Methodology for the subjective assessment of the quality of television pictures. *ITU-R Recommendation 500-10*, Geneva, Switzerland, 1998
JJS93	N. Jayant, J. Johnston and R. Safranek. Signal compression based on models of human perception. *Proc. IEEE*, 81:1385-1422, Oct. 1993
LDX03	W. Lin, L. Dong and P. Xue. Discriminative Analysis of Pixel Difference Towards Picture Quality Prediction. *Proc. IEEE ICIP*, 3:193-196, Sept. 2003

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LF80	G.E. Legge and J.M. Foley. Contrast masking in human vision. *J. Opt. Soc. Am.*, 70(12):1458-1471, 1980
MGE+01	J. Malo, J. Gutierrez, I. Epifanio, F. Ferri and J.M. Artigas. Perceptual feedback in multigrid motino estimation using an improved DCT quantization. *IEEE Trans. Image Processing*, 10(10):1411-1427, Oct. 2001
Nad00	M.J. Nadenau. *Integration of Human Color Vision Models into Hight Quality Image Compression*. Ph.D. thesis, EPFL, Lausanne, 2000
NH88	A.N. Netravali and B.G. Haskell. Digital Pictures-Representation, Compression. *Proc. SPIE Human Vision, Visual Processing and Digital Display VI*, 1998
OT86	L.A. Olzak and J.P. Thomas. Seeing spatial patterns, vol. 1. In *Handbook of Perception and Human Performance*. New York: John Wiley and Sons, 1986
PAW93	H.A. Peterson, A.J. Ahumada and A.B. Watson. An improved detection model for DCT coefficient quantization. *Proc. SPIE Human Vision, Visual Processing and Digital Display VI*, 1913-191-201, 1993

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PPMP91	H.A. Peterson, H. Peng, J.H. Morgan and W.B. Pennebaker. Quantization of color images components in the DCT domain. *Proc. SPIE Human Vision, Visual Processing and Digital Display II*, 1453:210-222, 1991
RPG99	M. Ramasubramanian, S.N. Pattanaik and D.P. Greenberg. A perceptually based physical error metric for realistic image synthesis. *Computer Graphics*, 73-82, Aug. 1999
Saf94	R.J. Safranek. A JPEG compliant encoder utilizing perceptually based quantization. *Proc. SPIE Human Vision, Visual Processing and Digital Display V*, 2179:117-126, Feb. 1994
SJ89	R.J. Safranek and J.D. Johnston. A perceptually tuned sub-band image coder with image dependent quantization and post-quantization data compression. *Proc. IEEE International Conference on Acoustic, Speech and Signal Processing*, 1945-1948, 1989
TS96	T.D. Tran and R. Safranek. A locally adaptive perceptual masking threshold model for image coding. *Proc. IEEE International Conference on Acoustic, Speech and Signal Processing*, 4:1883-1886, 1996

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TV98	H.Y. Tong and A.N. Venetsanopoulos. A perceptual model for JPEG applications based on block classification, texture masking and luminance masking. *Proc. IEEE ICIP*, 3:428-432, 1998
vNB67	F.L. van Nes and M.A. Bouman. Spatial modulation transfer in the human eye. *Journal of the Optical Society of America*, 57:401-406, Mar. 1967
Wat93	A.B. Watson. DCTune: A technique for visual optimization of DCT quantization matrices for individual images. *Society for Information Display Digest of Technical Papers XXIV*, 946-949, 1993
Wat00	A.B. Watson. Proposal: Measurement of a JND Scale for Video Quality. Submission to the IEEE G-2.1.6 Subcommittee on Video Compression Measurements Meeting on August 7th, 2000
WHMI01	A.B. Watson, J. Hu and J.F. McGowan III. DVQ: A digital video quality metric based on human vision. *Journal of Electronic Imaging*, 10(1):20-29, January 2001.
WPD99	R.B. Wolfgang, C.I. Podilchuk and E.J. Delp. Perceptual Watermarks for Digital Images and Video. *Proc. IEEE*, 87(7):1108-1126, July, 1999

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WYSV97	A.B. Watson, G.Y. Yang, J.A. Solomon and J. Villasenor. Visibility of wavelet quantization noise. *IEEE Trans. on Image Processing*, 6(8):1164-1175, Aug. 1997
YLL+03a	X. Yang, W. Lin, Z. Lu, E.P. Ong and S. Yao. Just-noticeable-distortion profile with nonlinear additivity model for perceptual masking in color images. *Proc. IEEE ICASSP*, 3:609-612, 2003
YLL+03b	X.K. Yang. W. Lin, Z.K. Lu, E.P. Ong and S.S. Yao. Perceptually-adaptive Hybrid Video Encoding based On Just-noticeable-distortion Profile. *SPIE 2003 Conference on Video Communication and Image Processing*, 5150:1448-1459, 2003
YW98	M. Yuen and H.R. Wu. A survey of hybrid MC/DPCM/DCT video coding distortions. *Signal Processing*, 70:247-278, 1998
Zen99	W. Zeng. Visual Optimization in Digital Image Watermarking. *Proc. ACM Multimedia Workshop on Multimedia and Security*, 1999
Zha04	X.H. Zhang. Just-noticeable distortion estimation for images. Master's thesis, School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, Feb. 2004

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ZLX03	X.H. Zhang, W.S. Lin and P. Xue. A new DCT-based just-noticeable distortion estimator for images. *Proc. Joint Conference of 4th International Conference on Information Communication and Signal Processing and 4th IEEE Pacific Rim Conference on Multimedia*, 2003, Singapore

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10. No-Reference Quality Metric for Degraded and Enhanced Video

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Chapter 10 Outline

10.1 Introduction

10.2 State-of-the-Art for No-Reference Metrics

10.3 Quality Metric Components and Design

10.4 No-Reference Overall Quality Metric

10.5 Performance of the Quality Metric

10.6 Conclusions and Future Research

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10.1 Introduction

- Objective Image Quality (OIQ) Metric
  - Predict standard subjective quality ratings
  - Substantial work carried out by VQEG
    - Supported by ITU and broadcast industry
    - Work focused on quality measures for broadcasting applications
      - Should consider enhancements as well as distortions
      - Must be applicable along any point of broadcast chain
        - » Including points with no references
        - » Need for No-Reference Metric

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- No-Reference Objective Quality Metrics (NROQM)
  - Application areas
    - Video coding system development
    - Embedded monitoring and control of quality
    - Evaluation of picture display (coding) systems
  - Evaluations picture features
    - e.g. sharpness, contrast, distortions, etc
  - Incorporates aspects of the HVS

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10.2 State-of-the-Art for No-Reference Metrics

- Digital Video Quality (DVQ) Analyzer
  - Measure blocking distortions in video
    - Measurements account for motion and spatial masking
- Picture Appraisal Rating (PAR)
  - Estimates PSNR from quantized data
- Tektronix's PQM300
  - Blocking distortion metric for video

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10.3 Quality Metric Components and Design

- Centred on feature measurement
- Two aspects to feature quantification
  - Desirables which adds to quality
    - Sharpness, contrast, etc
  - Undesirables that impedes quality
    - Impairments, e.g., blurring, blocking, etc

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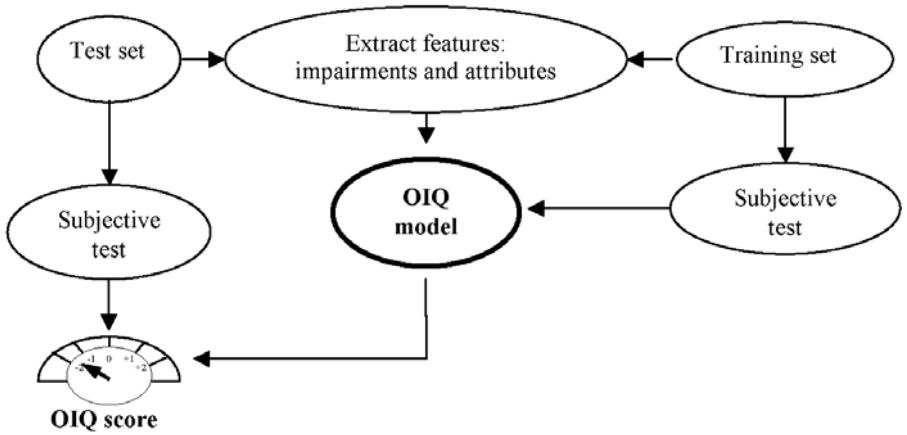
Framework for the development of no-reference metric (*above*)



- Train the model to predict subject responses
  - Gather subjective data associated with images/videos
  - Optimize model with test images/videos to produce the best prediction match with subjective data

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10.3.1 Blocking Artifacts

- Due to coarse quantization of DCT coefficients
- Occurs along block boundaries of blocks
- Need to differentiate between blocking edges and content edges
  - Threshold measurements
    - Assumes blocking edges below certain threshold
      - Measure magnitude of discontinuities or
      - Calculate extrapolated discontinuities of blocks

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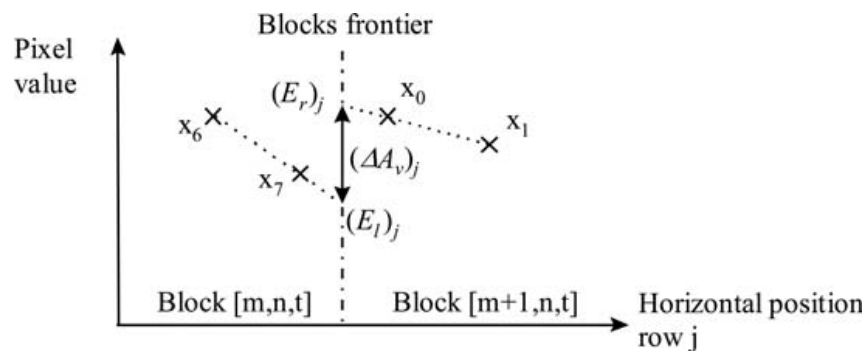
Extrapolation for blocking detection



- $(E_r)_j$ and $(E_l)_j$ are extrapolated values from adjacent blocks
- Discontinuity is the difference between all extrapolated values $(E_r)_j$ and $(E_l)_j$ along the block boundary

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10.3.2 Ringing Artifacts

- Ringing definition
  - Shimmering effect around high contrast edges
- Manifests as edge doubling
- Ringing and blocking not necessarily correlated
  - Ringing depends on the strength of edges in images
  - Blocking depends on presence smoothly varying areas

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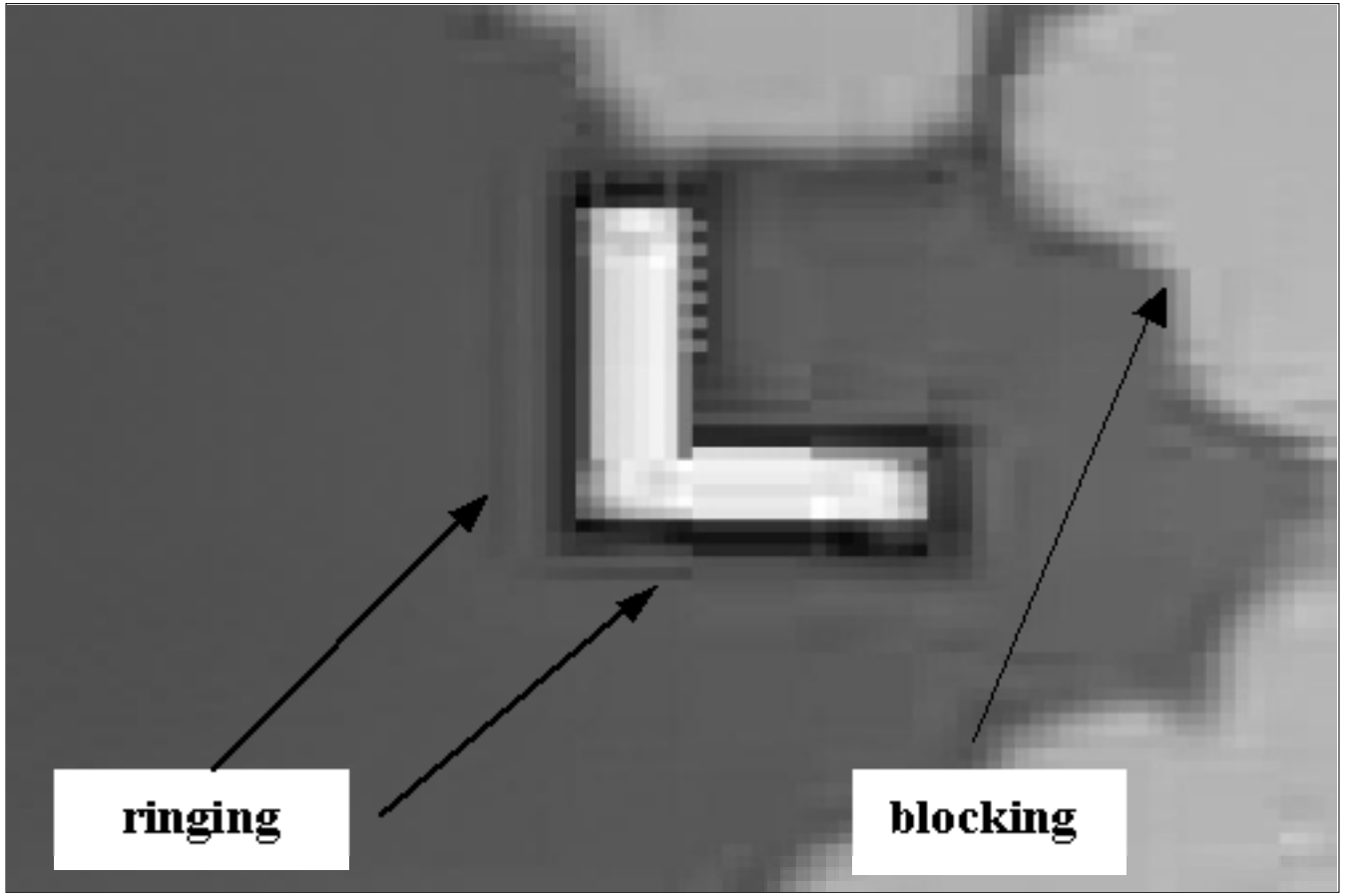
Blocking and ringing artifacts



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- General ringing detection strategy
  - Edge detection
  - Spatial activity measurement around edges
    - Usually based on the variance of a windowed area
  - Classify ringing pixels relative to variance
  - Examples metric
    - Visible Ringing Measure (VRM)
      - Also employ morphing operations for detection

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10.3.3 Clipping

- Truncation of pixel/coefficient magnitude due to the arithmetic precision process
  - Leads to aliasing artifacts
  - Introduced during picture coding and processing
    - e.g. “peaking”, a sharpness enhancement process may lead to clipping when enhancement pictures overshoots its dynamic operational range
- General clipping measures
  - Quality the number of clipped pixels

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10.3.4 Noise

- Random variation in spatial and temporal dimension
  - Introduced during transmission or picture generation
  - May enhance or degrade picture quality
  - Most noticeable in relatively smooth regions
    - Appears as speckle in spatial domain
    - Fluctuation in temporal domain

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- Noise measurement
  - Generally reliant of variance
    - To classify noisy regions
  - Assumes noise to be considerably weaker then image signals
    - Isolated noise (or signal) with low pass or band pass filtering
    - Quantify isolated noise

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10.3.5 Contrast

- The difference in luminance between a pixel and its background
- Contrast dependent on
  - Object in question, background, mean luminance and colour
- Simple Measurement of contrast levels
  - Compute luminance histogram
  - Calculated the difference (in luminance energy) between the upper and lower halves of the histogram

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10.3.6 Sharpness

- Quantify by the clarity of details in images
  - Through preservation/definition of edges
- Sharpness depends on
  - Resolution, content, contrast and noise
- Sharpness metric with local edge kurtosis
  - Generate edge image
    - Partition edge image into blocks
  - Apply 2-D kurtosis to individual blocks
    - Sharpness is the average 2-D kurtosis

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Edge detection and block assignment of *Doll* sequence for sharpness measurement

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10.4 No-Reference Overall Quality Metric (NROQM)

- Consists of components described in section 10.3
  - Contrast, noise, clipping, sharpness, blocking and ringing
- Model Optimization
  - Find a set of NROQM parameters that best match subjective data
  - Incremental heuristic knowledge approach
    - More precise calibration of metric components

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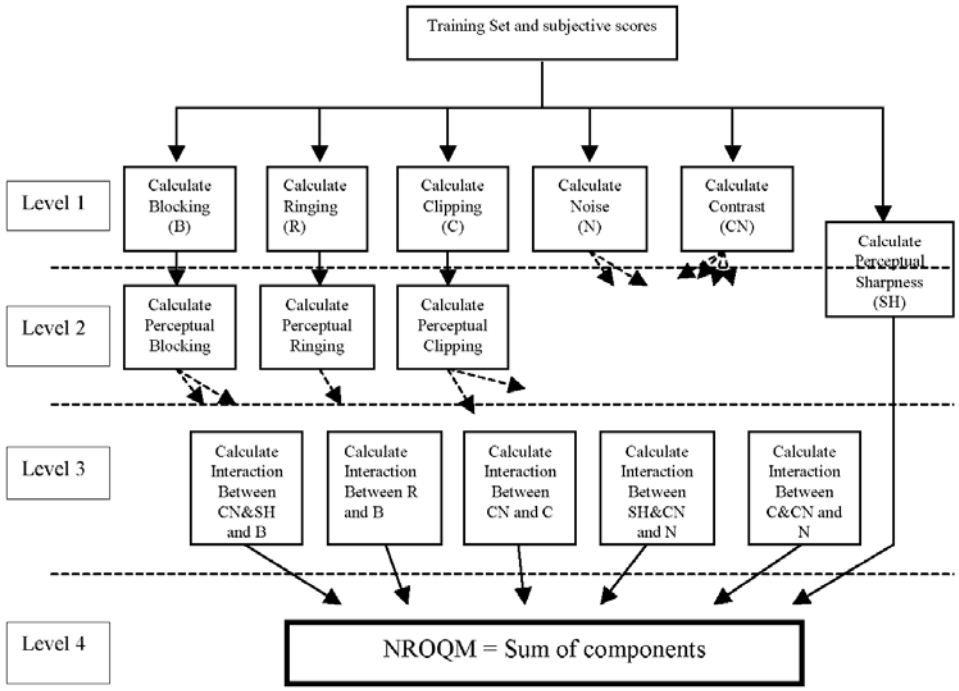
Operational flowchart of the NROQM



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10.5 Performance of the Quality Metric

- Evaluated with 65 sequences
  - With various level of processing
    - Coding, sharpness enhancement and noise reduction
  - Derived from 3 sequences
    - *Doll, Dolphins and Lawnmowerman*
  - Subjective assessment
    - 20 non-expert subjects
    - 7-point scale comparative test
  - Correlation: NROQM=0.85, PSNR=0.399

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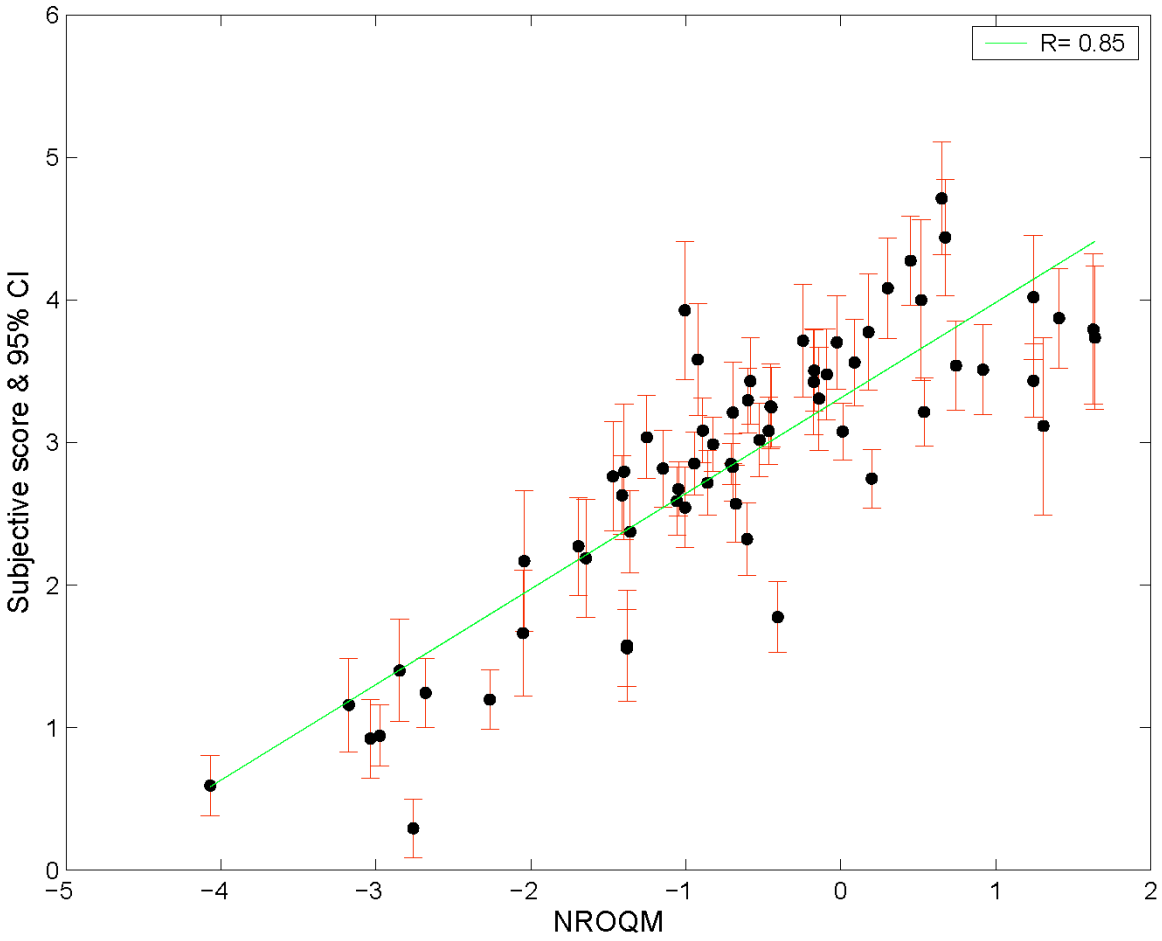
Performance of NROQM



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- Additional evaluations
  - With different sequences (*Fade* and *Boat*)
    - Correlation: 0.848 (*Fade*) and 0.943 (*Boat*)
  - Expert viewers
    - Extreme enhancement of test material
      - NROQM operating outside operational range
        - » Not calibrated for extreme enhancement
    - Resulting evaluation uncovers some deficiencies
      - High clipping
      - Sharpness in high contrast areas
      - Over sharpening

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10.6 Conclusions and Future Research

- NR metric has practical applications
  - picture quality and impairment measurement
  - Quality assessment for coding system development
  - Real-time monitoring and control of picture quality
- NROQM an example of NR metric
  - Demonstrated operability/applicability
  - Potential for improvement

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- Areas for future development
  - Motion field smoothness
  - Mosquito noise
  - IBP frame drift
  - Judder
    - Unnatural modulation of smooth motion

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Can86	T. Canny. A computational approach to edge detection. *IEEE Trans. Pattern Analysis Machine Intelligence*, 8(6):679-698, Nov. 1986
CDGR00	J.E. Caviedes, A. Drouot, A. Gesnot and L. Rouvellou. Impairment metrics for digital video and their role in objective quality assessment. In *Proc. VCIP 2000*, 791-800, perth, Australia, June 2000
CG02	J.E. Caviedes and S. Gurbuz. No-reference sharpness metric based on local edge kurtosis. In *Proc. ICIP*, 3:53-56, Rochester, NY, Sept. 2002
CJ01	J.E. Caviedes and J. Jung. No-reference metric for a video quality control loop. In *Proc. SCI2001*, 290-295, Orlando, FL, July 2001
dH00	G. de Haan. *Video Processing for Multimedia Systems*. Eindhoven: University Press Facilities, 2000

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Eng00	P.G. Engeldrum. *Psychometric Scaling: A Toolkit for Imaging Systems Development*. Winchester, MA: Imcotek Press, 2000
Fai99	M.D. Fairchild. A victory for equivalent background – on average. In *Proc. IS&T/SID 7th Color Imaging Conference*, 87-92. Scottsdale, AR, 1999
GEN	Genista Corp. (http://www.genista.com)
GPLL99	C. Glassman, A. Peregoudov, A. Logunov and V. Lichahov. Video compression artifacts: predicting the perceptual ratings. In *Proc. IBC*, 560-564, Amsterdam, 1999
Inc97	T. Inc. A guide to picture quality measurements for modern television systems, Beaverton, OR, 1997. (http://www.tektronix.com)
ITU00	ITU. Methodology for the subjective assessment of the quality of television pictures. *ITU-R Recommendation 500-0*, Geneva, Switzerland, 2000
ITU03	Objective perceptual video quality measurement techniques for standard definition digital broadcast television in the presence of a full reference, 2003. Draft New Recommendation ITU-T BT.[Doc. 6/39]

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JF00	G.M. Johnson and M.D. Fairchild. Sharpness rules. In *Proc. IS&T/SID 8th Color Imaging Conference*, 24-30, Scottsdale, AR, November 2000
KK95	S.A. Karunasekera and N.G. Kingsbury. A distortion measure for blocking artifacts in images based on human visual sensitivity. *IEEE Transaction on Image Processing*, 4(6):713-724, June 1995
Ogu99	S.H. Oguz. *Morphological post-filtering of ringing and lost data concealment in generalized lapped orthogonal transform based image and video coding*. Ph.D. thesis, University of Wisconsin, Madison, WI, 1999
PIX	Pixelmetrix Corporation (http://www.pixelmatric.com)
ROH	Rohde & Schwarz (http://www.rohde-schwarz.com)
SDZ96	B. Spehar, J.S. DeBonet and Q. Zaidi. Brightness induction from uniform and complex surrounds: A general model. *Vision Research*, (36):1893-1906, July 1996
SNE	Snell & Wilcox (http://www,snellwilcox.com)
TCC02	D.S. Turaga, Y. Chen and J.E. Caviedes. No-reference PSNR estimation for compressed pictures. In *Proc. ICIP*, 3:61-64, Rochester, NY, Sept. 2002

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VQE	The Video Quality Experts Group (http://www.vqeg.org)
VQE03	VQEG. Final report from the Video Quality Experts Group on the validation of objective models of video quality assessment – Phase II, Aug. 2003
vZA01	K. von Zon and W. Ali. Automated video chain optimization. *IEEE Trans. on Consumer Electronics*, 47(3):593-603, Aug. 2001
WL01	A. Worner and J. Lauterjung. A real time single ended algorithm for objective quality monitoring of compressed video signals. In *Proc. Of SCI2001*, 13:329-334, Orlando, FL, July 2001
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WYSV97	A. Watson, G. Yang, J. Solomon and J. Villasenor. Visibility of wavelet quantization noise. *IEEE Trans. on Image Processing*, 6:1164-1175, Aug. 1997

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YHTN01	S. Yang, Y. Hu, D. Tull and T. Nguyen. Maximum likelihood parameter estimation for image ringing artifact removal. *IEEE Trans. On CSVT*, 11(8):963-973, August 2001
YWC00	Z.Yu, H.R. Wu and T. Chen. Perceptual blocking distortion measure for digital video. In *Proc. VCIP2000*, 4067:4067:768-779, Perth, Australia, 2000

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11. Video Quality Experts Group

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Chapter 11 Outline

11.1 Formation

11.2 Goals

11.3 Phase I

11.4 Phase II

11.5 Continuing Work and Directions

11.6 Summary

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1.1 Formation

- VGEG formed in 1997
  - To address standardized objective methods for picture quality measurement
  - From ITU Tele-communication and Radio-communication sectors
    - ITU-R SG-11
    - ITU-T SG-12 and SG-9

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11.2 Goals

- To develop recommendation for objective picture quality assessment
  - Basic requirement
    - Objective metric should provide adequate equivalent subjective assessment of picture quality
    - Must be effective for evaluating standardized video coding schemes, e.g. MPEG-2, H.263, etc
      - At various bitrates from 768 kbps to 36 Mbps
      - At varying spatial and temporal information
        - » interlaced/non-interlaced, PAL/NTSC, etc

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- Plan
  - Model verification process
    - Solicit objective models to be include for verification leading to recommendation
    - Develop of objective and subjective test plan
    - Objective test for evaluating proposed models
    - Subjective test for acquiring subjective data
    - Analyze objective test results and subjective data
  - Present report to ITU

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11.3 Phase I

- Selection of source material
- Selection of test conditions (HRC)
  - e.g. coding rate
  - *Hypothetical Reference Circuits* (HRC)
- Subjective test
  - Follows ITU-R bt.500 recommendations
    - Double Stimulus Continuous Quality Scale (DSCQS) method
  - 20 sequences x 16 HRCs

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- Subjective test (continue)
  - Undertaken is 4 parts
    - 50 Hz Low and High Quality
    - 60 Hz Low and High Quality
  - Run in multiple laboratories
    - CRC (Canada), RAI (Italy), CCETT (France), NHK (Japan), DCITA (Australia), Berkom (Germany) and FUB (Italy)

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- Objective test
  - Ran by individual proponent of each model
  - Proponent results (10%) verified by independent labs
    - CRC (Canada), FUB (Italy), IRT (Germany) and NIST (USA)

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Proponents of objective measures

- [po] Peak Signal to Noise Ratio (PSNR)
- [p1] CPqD (Brazil)
- [p2] Tektronix/Sarnoff (USA)
- [p3] NHK/Mitsubishi Electric Corp. (Japan)
- [p4] KDD (Japan)
- [p5] EPFL (Switzerland)
- [p6] TAPESTRIES (European Union)
- [p7] NASA (USA)
- [p8] KPN Research (The Netherlands)/Swisscom CIT (Switzerland)
- [p9] NTIA/ITS (USA)

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- Comparison metrics
  - Measures a number of attributes between subjective and objective data
    - Prediction accuracy
      - Correlation measures, e.g. Pearson's, Spearman, etc
    - Monotonicity
    - Consistency
    - Variation

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Phase I conclusions

- No objective measurement system could replace subjective testing
- No one objective model outperforms the other in all cases
- Objective assessment methods have improved considerably, but
- No method for ITU recommendation can be made
- Data set generated is uniquely valuable

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11.4 Phase II

- More discriminating than Phase I test
  - More precise area of interest
  - Focused on secondary distribution of digitally coded television quality video
  - Two experiments
    - 525-line and 625-line video covering a wide range of qualities
  - Proponents required to submit video calibration parameters
    - Spatial and temporal registration, gains, etc

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- Laboratories
  - 525-line test - CRC (Canada) and Verizon (USA)
  - 625-line test - FUB (Italy)
- Proponents
  - 10 initially
  - 8 began testing
  - 6 completed testing
  - PSNR included as baseline metric

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- Final proponents
  - A. NASA (USA)
  - D. British Telecom (UK)
  - E. Yonsei University/Radio Research Lab./SK Telecom (Korea)
  - F. CPqD (Brazil)
  - G. Chiba University (Japan)
  - H. NTIA/ITS (USA)

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- Results
  - 625 and 525 results were similar, not identical
  - For 525
    - Models D and H performed better than other models
    - D and H statistically equivalent in performance
  - For 625
    - Models A, E, F and H are statistically equivalent in performance and are better than remaining models
  - PSNR performance is mid range

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- ITU directions
  - Draft standard for estimating perceived video quality
    - 4 model following VQEG Phase II results
      - British Telecom
      - Yonsei University/Radio Research Lab./SK Telecom
      - CPqD
      - NTIA/ITS
  - Eventually recommend only one normative full reference method

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11.5 Continuing Work and Directions

- Continuing work
  - with Full Reference Metric
- Future
  - Reduced Reference Metric
  - No-Reference Metric

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11.6 Summary

- VQEG
  - Purpose
    - Develop a unified an objective video quality measurement method for standardization
  - Existing work
    - Phase I and II test
      - has a number of proponents
      - for applications in broadcasting
      - Produced valuable data for future quality metric work
  - Future
    - Unified FR metric, work in NR and RR metric

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ISO94	ISO/IEC 13818. Information technology – generic coding of moving pictures and associated audio information. Technical report, ISO/IEC, Nov. 1994
ITU98a	ITU. ITU-R BT.500-9, methodology for the subjective assessment of the quality of television pictures. *ITU-T BT*, 1998
ITU98b	ITU-T Video Coding Experts Group. Video coding for low bit rate communication. ITU-T recommendation H.263, Jan. 1998
RH96	K.R. Rao and J.J. Hwang. *Techniques and Standards for Image, Video and Audio Coding*. Upper Saddle River, NJ: Prentice Hall, 1996
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VQE00b	VQEG, *VQEG Objective Test Plan*. VQEG, Jan. 2000
VQE00c	VQEG, *VQEG Objective Test Plan*. VQEG, Jan. 2000

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VEQ03	VQEG. *Final Report form the Video Quality Experts Group on the Validation of Objective Models of Video Quality Assessment, Phase II*. VQEG, August 2003
Wor03	Working Group 6Q. *Objective perceptual video quality measurement techniques for standard definition digital broadcast television in the presence of a full reference*, ITU-R, Oct. 2003. Working Group 6Q draft new recommendation ITU-R BT.[DOC. 6/39]

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III. Perceptual Coding and Processing of Digital Pictures

12. HVS Based Perceptual Video Encoders

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Sarnoff Corporation Inc., USA

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Chapter 12 Outline

12.1 Introduction

12.2 Noise Visibility and Visual masking

12.3 Architectures for Perceptual based Coding

12.4 Standard-Specific Features

12.5 Salience/Maskability Pre-Processing

12.6 Application to Multi-Channel Encoding

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12.1 Introduction

- Video encoders
  - Traditional approach with MSE type metric
  - HVS based utilizing perceptual metric
- MSE metric
  - Fast computation, simple implementation
  - Poor correlation with perceived distortion
- Perceptual metric
  - Good correlation with subjective data
  - Computationally intensive

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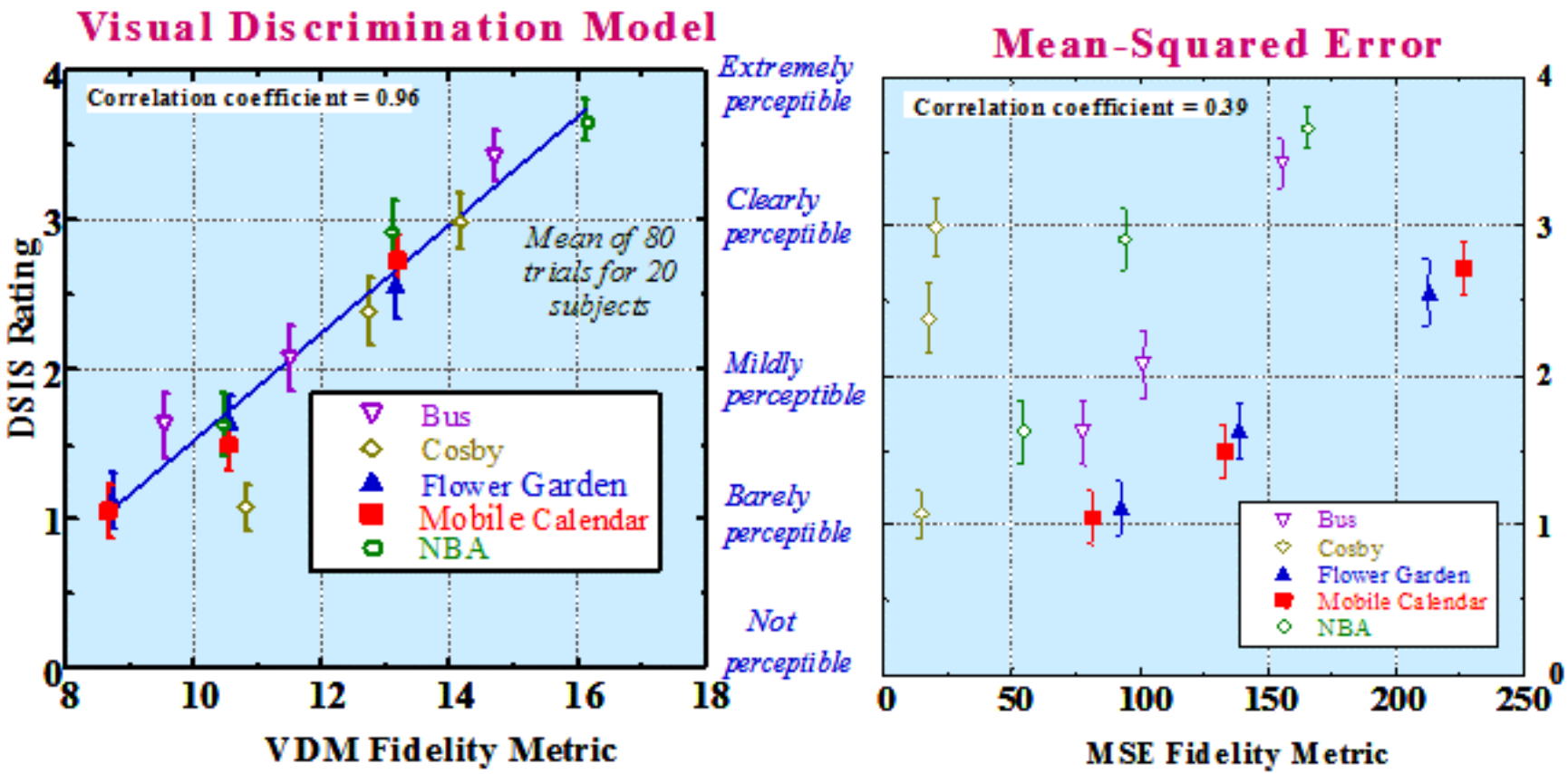
Performance of HVS (*left*) and non-HVS (*right*) based objective metrics



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12.2 Noise Visibility and Visual masking

- Lossy coding systems
  - Introduce distortion to pictures
  - So, how to minimize visible distortions?
- Characteristics of distortions
  - Structural in appearance
    - Manifestation has consistent structure
  - Appearance dependent on image content
    - Certain area of images may hide distortions

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Visibility of noise. *Left*: Gaussian (MSE: 27.1). *Right*: DCT quantization (MSE: 21.3)

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- Block based DCT coders
  - Used for video coding (MPEG standards)
  - Blocking distortions prominent
    - Due to quantization
- Discrete Wavelet Transform (DWT) coder
  - No blocking distortions
  - Ringing distortions at low bitrates

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Images coded at 0.25 bpp. *Left*: DCT (JPEG). *Right*: DWT (JPEG2000)

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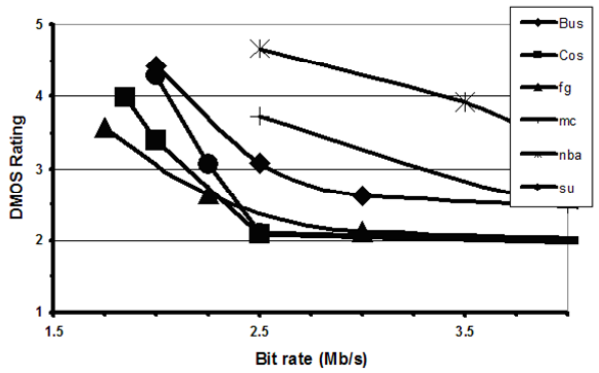
12.3 Architectures for Perceptual based Coding

- The Rate-Distortion (R-D) Curve (*Below*)
  - Regulates distortions relative to bitrates
  - Profile of R-D curves are content dependent
    - i.e., different picture have different R-D curve



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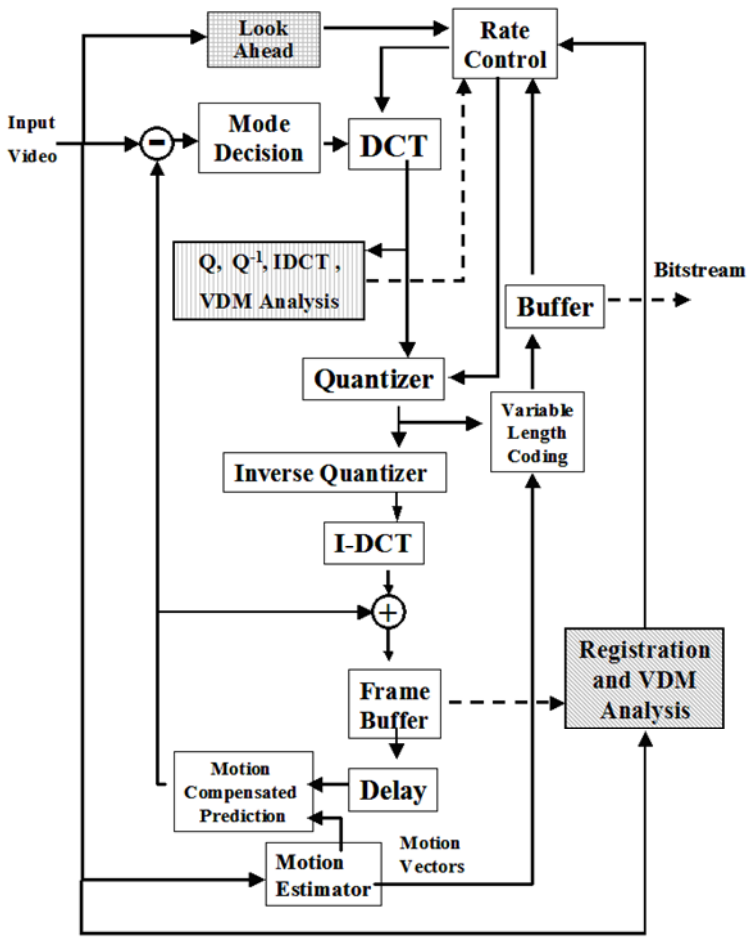
MPEG-2 coder with 2 possible application points (shaded boxes) for R-D optimizer



- Estimated R-D
  - Look-ahead technique
  - Outside coding loop
- Computed R-D with multi-pass coding scheme
  - 1st pass for R-D curve
  - 2nd pass for coding
  - Inside coding loop

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- Latency issue
  - Estimated R-D outside coding loop has high latency
    - may not cope well with rapidly changing content
  - Computed R-D inside coding loop has low latency
    - Distortion levels can be controlled by in-built distortion metric
    - Coding rate is then adjusted to the desired quality level with the R-D curve

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12.3.1 Masking Calculations

- Masking regions
  - High contrast edges
    - e.g., textured area such as grass
  - Occasionally around visually salient features with broad frequency coverage
    - Some salient features attract more visual attention
      - Therefore, special treatment required to minimize visibility of artifacts

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- Spatio-temporal masking
  - Laplacian pyramid decomposition of frames
    - Into different resolutions, i.e., ½ and ¼
  - Sum of energy across local spatio-temporal frequency and orientation bands
    - Regions of **high** saliency removed from calculations
  - Calculate the local contrast
    - Sum of local energy normalized by the maximum luminance

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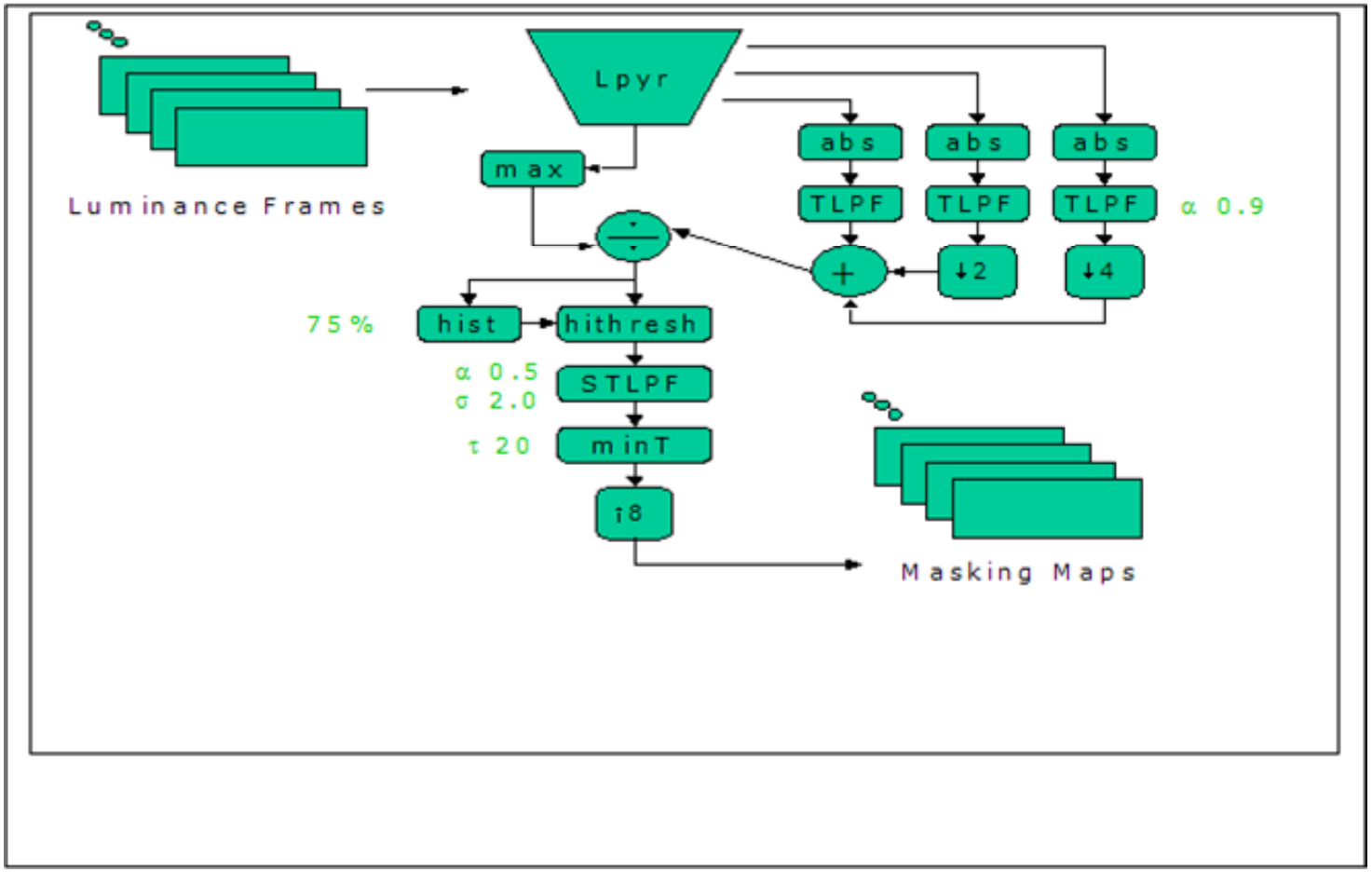
Maskability model with salient feature rejection



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- Saliency rejection
  - Construct histogram of local contrast energy for each frame
  - Region above percentile threshold are rejected
    - Threshold is a free parameter set to 75%
- Temporal saliency considerations
  - Object based with motion tracking

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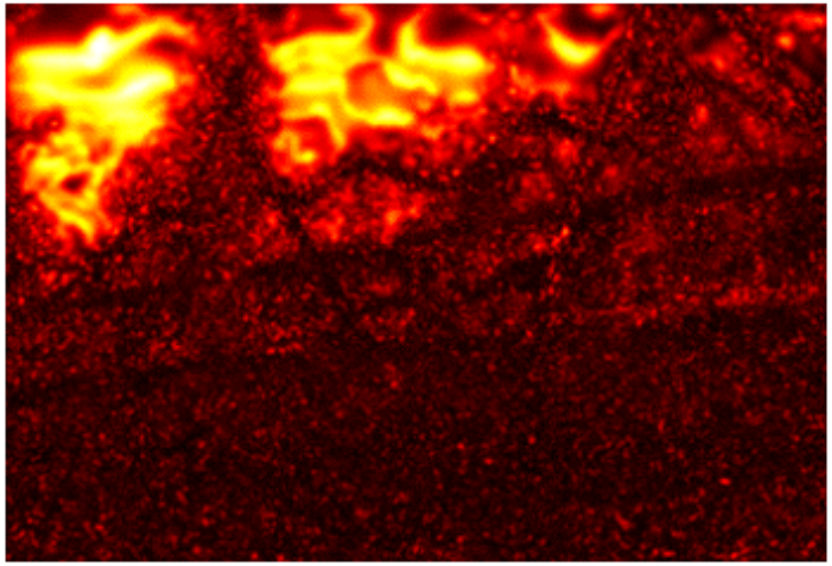
Flowergarden sequence (*Left*) and its masking map (*right*). Bright area indicates low masking.



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12.3.2 Perceptual Based Rate Control

- Perceptual metric in rate control at:
  - Macroblock level (block size limitation)
    - Only provides relative estimates of distortions
  - Picture level (pre-assigned bitrate for frame)
    - Good account of visible distortion
    - Uniform distribution of distortion over frame
  - GOP level (pre-assigned bitrate for GOP)
    - Utilize full vision model, i.e., temporal mechanism
    - Uniform distortion distribution over GOP
    - With VBR enables constant quality video

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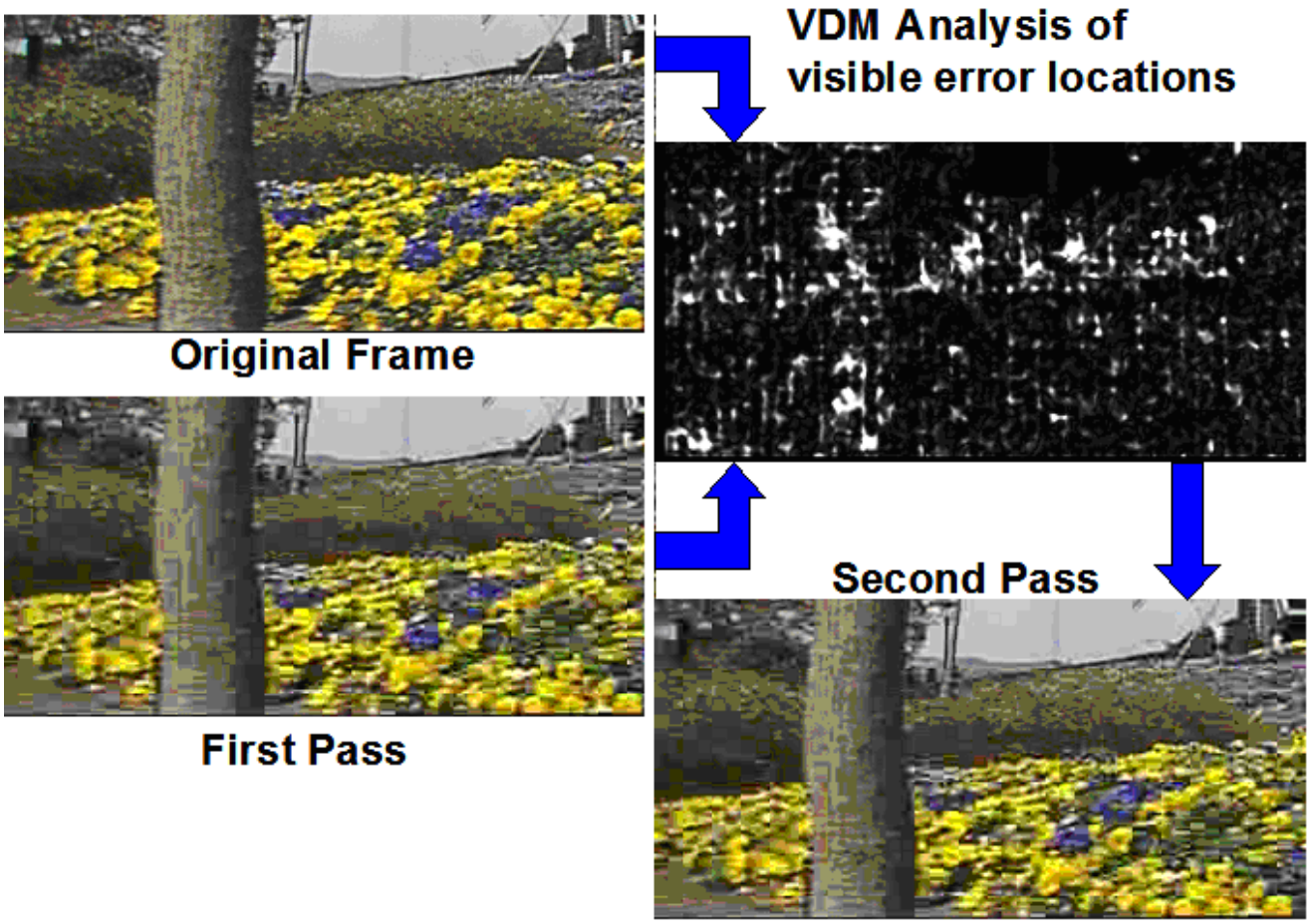
Macroblock bit allocation with the *Visual Discrimination Model* (VDM)



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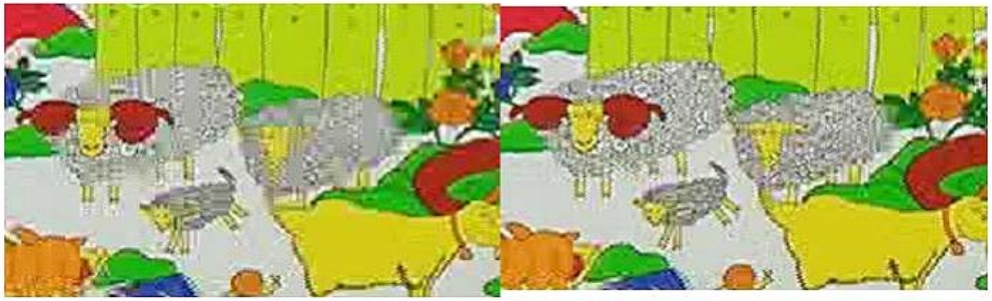
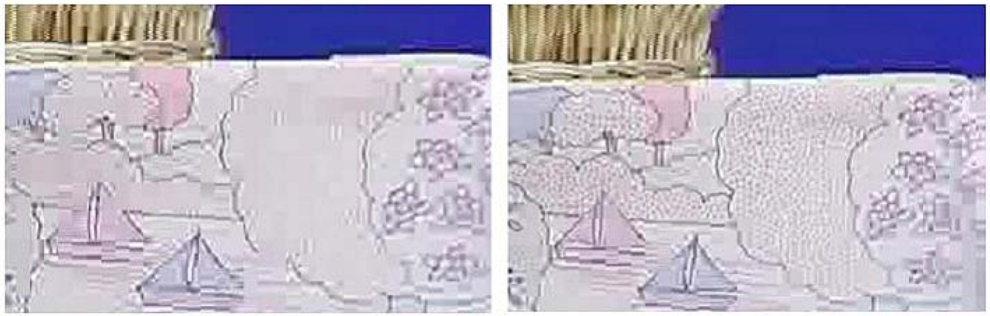
Example of vision based coding with DVC (incorporating VDM) compared to MPEG TM5

Baseline Encoder-TM5



DVC Encoder

Baseline Encoder-TM5



DVC Encoder

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- Look Ahead R-D curve
  - Estimate R-D curves based on sample videos
    - Acquire distortions of sample videos at various bitrates (quantization level)
    - Estimate R-D curve for different video profiles
      - i.e., different GOP
  - Interpolate points in curve for R-D estimation
  - Generally used as the first pass for a multi-pass coding scheme

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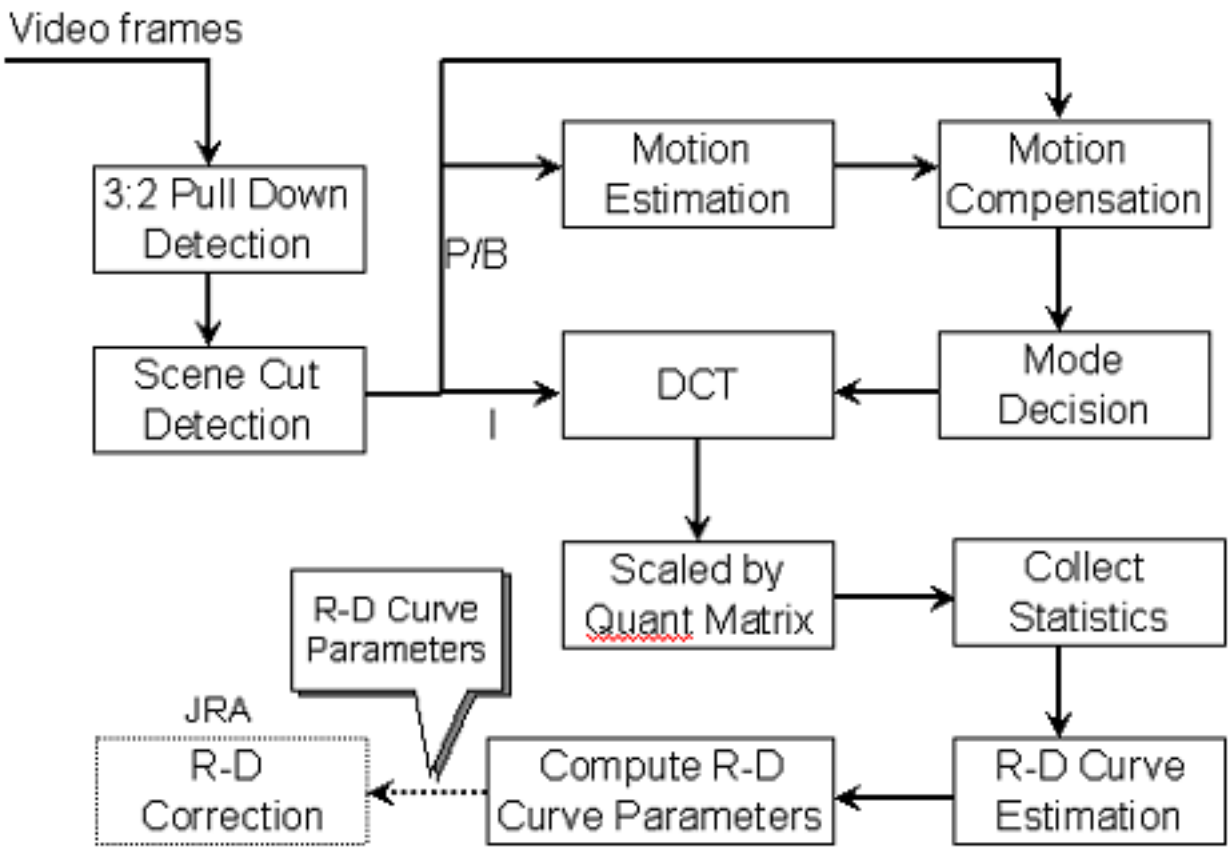
Illustration of Sarnoff look-ahead R-D curve estimation (JRA: Joint Rate Allocation)



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- Sarnoff Look-Ahead rate allocation
  - Real-time implementation
  - Picture level rate allocation
  - Operation depends on frame type
    - i.e., I-frame, P-frame or B-frame
  - Histogram approach
  - Utilise Visual MSE to compute error
    - Visual MSE = MSE/(Visual mask)

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12.4 Standard-Specific Features

- Block sizes (block based coding)
  - Blocking artifacts
    - Due to coarse quantization
    - Dependent on picture content
      - More visible in smooth areas than highly textured areas
    - Dependent on motion activity and prediction
    - Affected by viewing distance (visual acuity)
      - Blocking diminishes as viewing distance increases
    - Block size affects visibility of blocking effect
      - H.264/MPEG-4 AVC uses 4x4 DCT block

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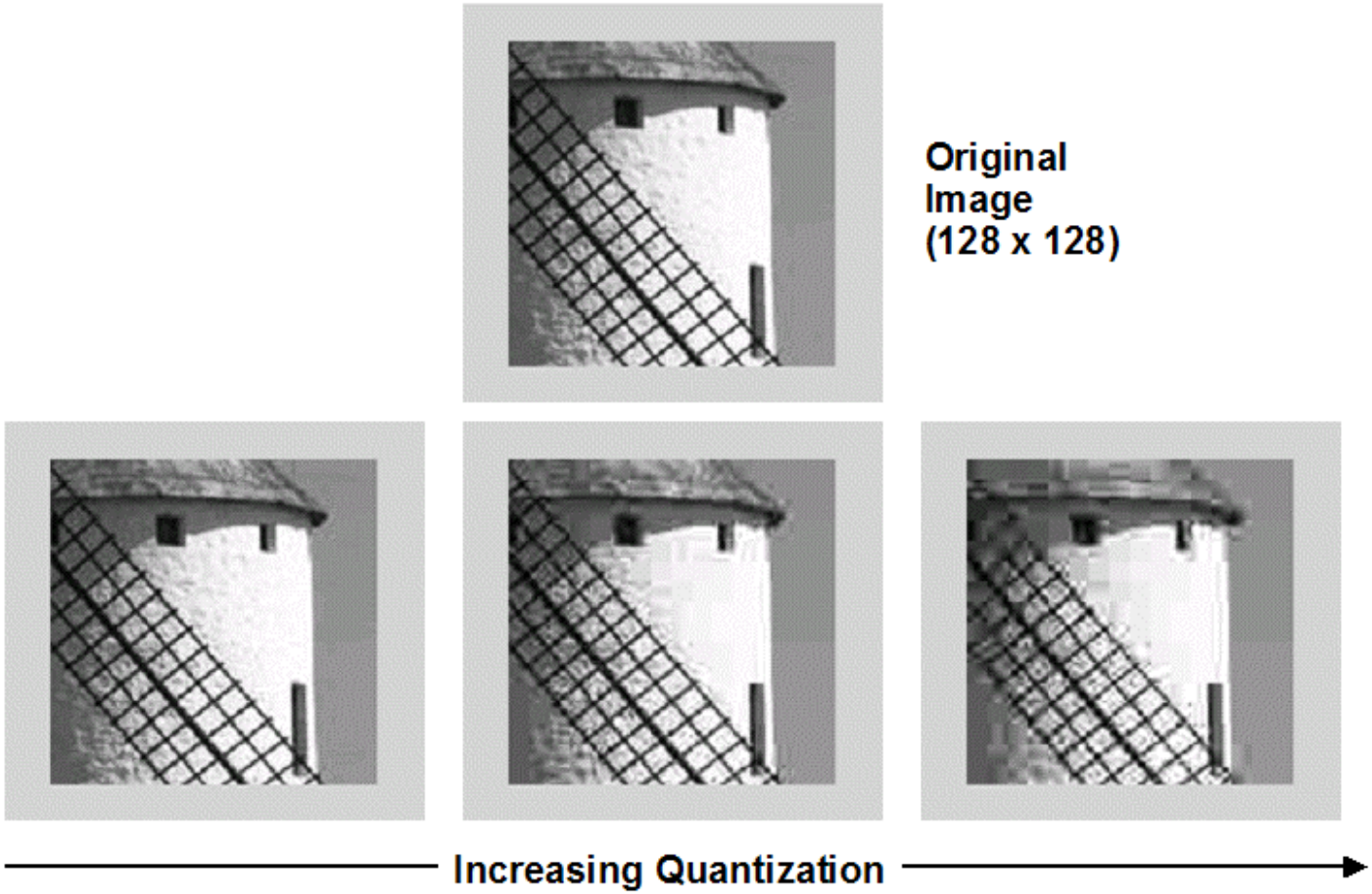
Impact of quantization on blocking distortion



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Visibility of blocking artifacts in smooth and textured areas

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12.4.2 In-Loop Filtering

- For de-blocking
  - Reduces visibility of block
  - Eliminates the need for post-filtering at decoder
- De-blocking filters used in
  - H.261, H.263 and H.264/MPEG-4 AVC
- Reduction of blocking in H.264/MPEG-4 AVC attributed (in part) to
  - 4x4 DCT and de-blocking filter

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12.4.3 Perceptual-Based Scalable Coding Schemes

- Scalable coding
  - Multi-layered with one base and additional enhancement layers
  - Scalable modes
    - Temporal/spatial resolutions and SNR
  - MPEG-4 Fine Granularity Scalability (FGS)
    - DCT coefficients encoded in layers
      - Allows precise rate control
    - Applications in video streaming

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12.5 Salience/Maskability Pre-Processing

- Pre-filtering can be adapted to any coding system
- Saliency rejection
  - Histogram strategy
  - Coherence of local motion
    - Targets local regions with same/similar motion speed and direction
      - indicative of coherent moving objects

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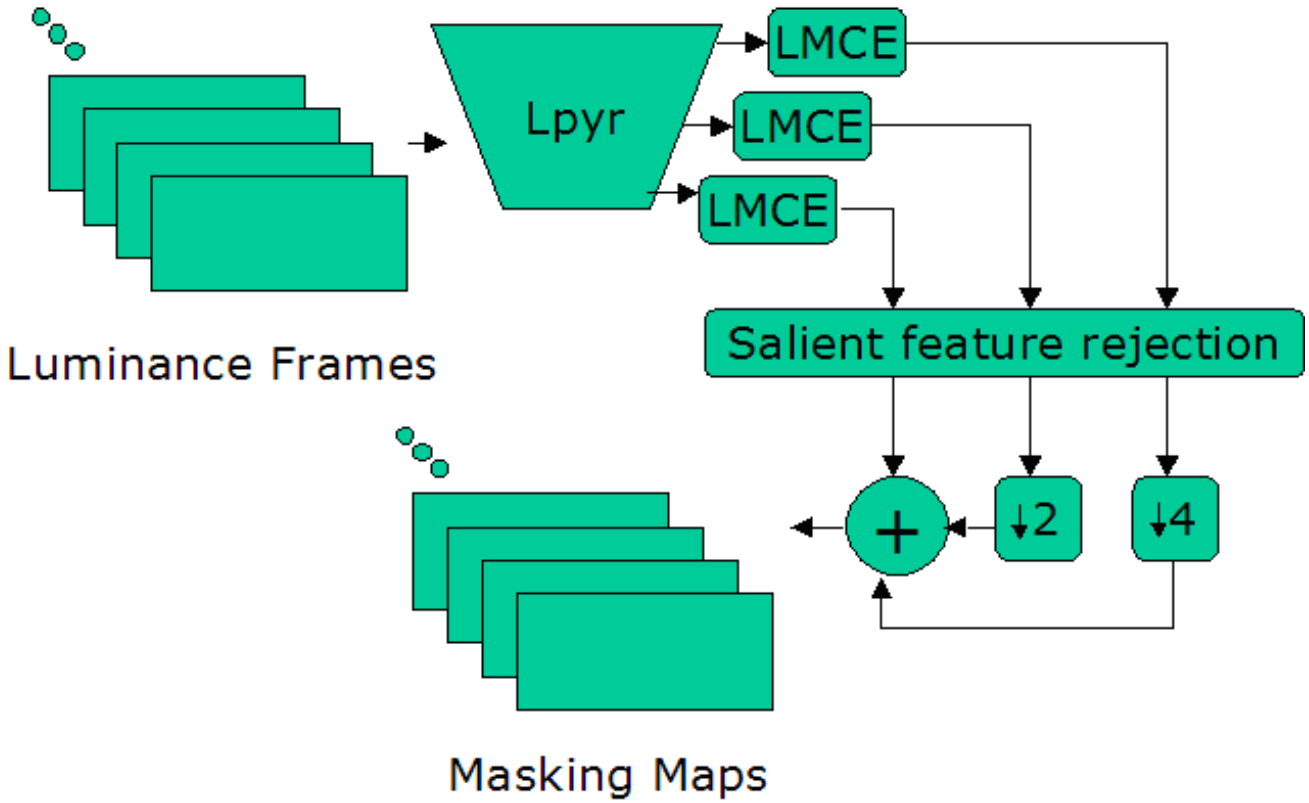
Pre-processor based maskability model with salient feature rejection



LME: local motion contrast energy detectors

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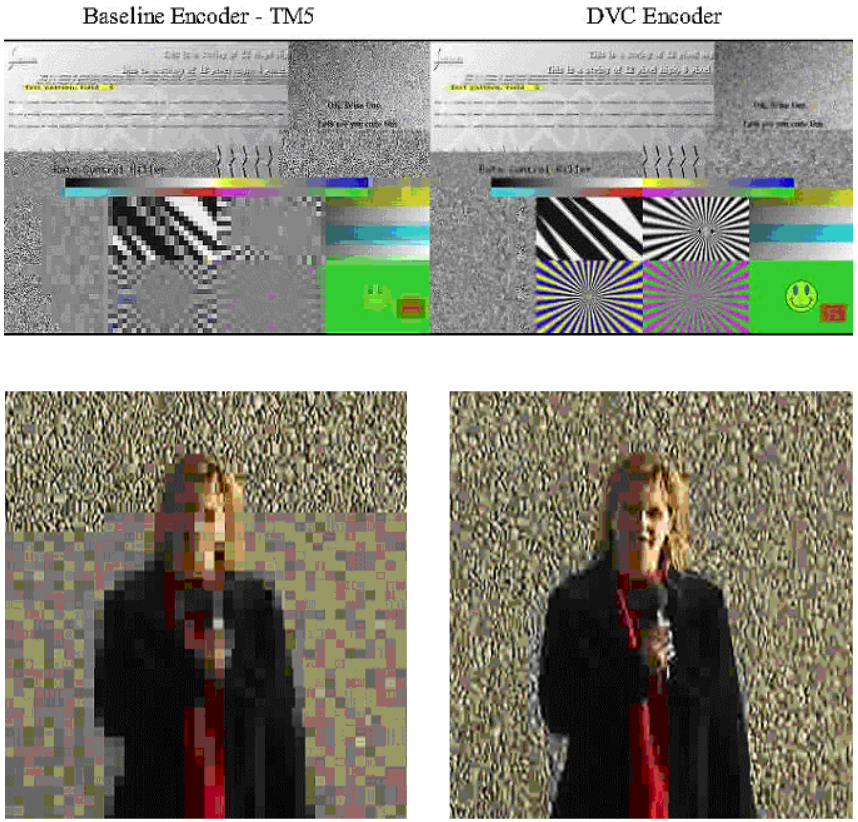
Illustration of pre-filtering. *Left*: MPEG-2 TM5 coded images. *Right*: DVC coded with pre-filtering



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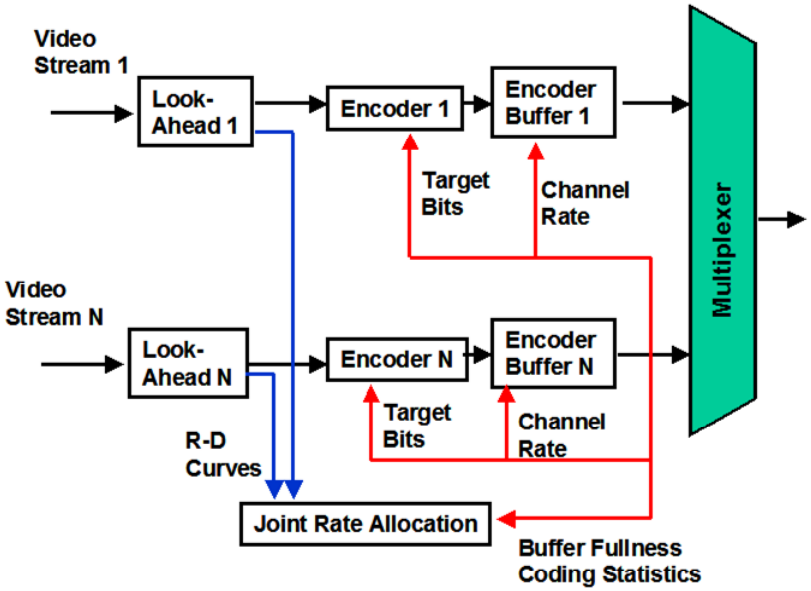
12.6 Application to Multi-Channel Encoding

- Multiplexed video streams
  - 8-12 programs in a 30 Mbps transport stream
  - Suited for Look-Ahead rate control scheme
    - *Join Rate Allocation* (JRA) equalizes distortions over all video streams



Multi-channel encoder

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PM93	W.B. Pennebaker and J. Mitchell. *JPEG Still Image Data Compression Standard*. Norwell, MA: Van Nostrand Reinhold, 1993

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Ric03	I. Richardson, *H.264 and MPEG-4 Video Compression*. Hoboken, NJ: Wiley, 2003
RJ02	M. Rabbani and R. Joshi. An Overview of the JPEG 2000 Still Image Compression Standard. *Signal Processing: Image Communincation*, 17:3-48, 2002
RY90	K.R. Rao and P. Yip. *Discrete Cosine Transform: Algorithms, Advances, Applications*. New York: Academic Press, 1990
SCE01	A. Skodras, C. Christopoulos and T. Ebrahimi. The JPEG 2000 Still Image Compression Standard. *IEEE Signal Processing Magazine*, 18:36-58, Sept. 2001
TM02	D. Taubman and M. Marcellin. *JPEG2000: Image Compression Fundamentals, Standards and Practices*. Boston, MA: Kluwer, 2002

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13. Perceptual Image Coding

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Chapter 13 Outline

13.1 Introduction

13.2 A Perceptual Distortion Metric Based Image Coder

13.3 Model Calibration

13.4 Performance Evaluation

13.5 Perceptual Lossless Coder

13.6 Summary

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13.1 Introduction

- Redundancies in picture data
  - Statistical
    - Correlation between pixel data
  - Psychovisual
    - Information which the eye and mind cannot see
    - Removal does not impede image quality but
    - Leads to better compression performance

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Human Visual System (HVS) Based Coders

- Common implementation through
  - Quantization (most common)
  - Coefficient weighting
    - Performed prior to quantization
  - Post- and/or pre-filtering
  - *Region Of Interest* (ROI) coding
    - Identify visually significant region and encode at higher quality

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- Some HVS Based coders
  - Watson's *DCTune*
  - Safranek and Johnton's Subband Image Coder
  - Höntsch and Karam's *APIC*
  - Chou and Li's Perceptually Tuned Subband Image Coder
  - Taubman's EBCOT with visual masking
  - Zeng et al's Point-Wise Extended Visual Masking

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13.2 A Perceptual Distortion Metric Based Image Coder

- Utilize EBCOT (*Embedded Block Coding with Optimized Truncation*) architecture
  - Modular *Rate-Distortion* (R-D) component
    - Any distortion metric may be embedded in the R-D function
      - Perceptual distortion metric replaces MSE
  - Bitstream compliance maintained
    - No additional side information
    - No other alteration to bitstream

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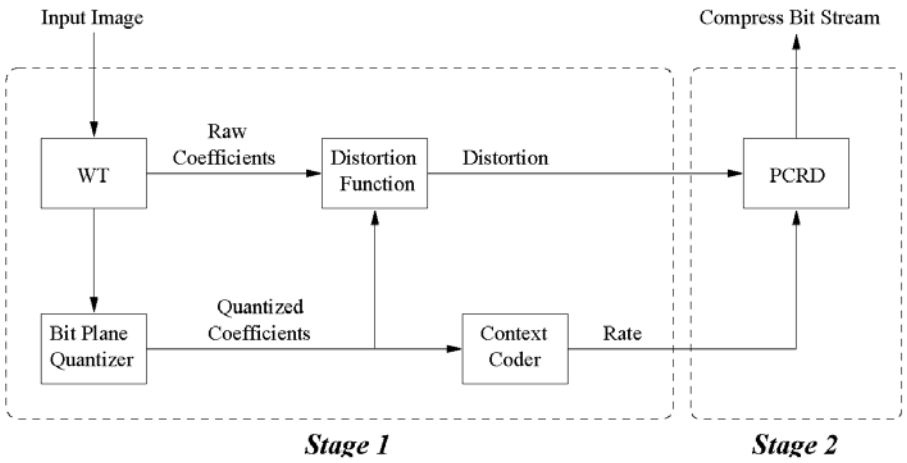
13.2.1 Coder Structure



- Basic EBCOT framework (*below*)
  - transform
    - 5 level transform
    - Bi-orthogonal 9/7 filters

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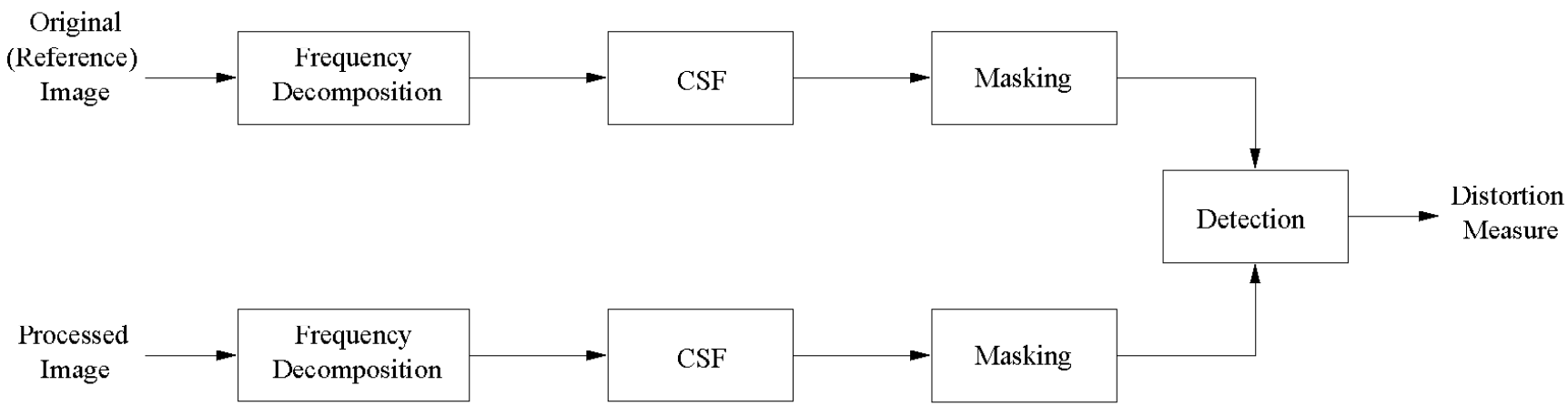
13.2.2 Perceptual Image Distortion Metric (PIDM)



- Contrast Gain Control (CGC) (*above*)
  - Frequency transform (with 9/7 filter)
  - CSF weighting
  - Masking + detection

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13.2.3 EBOCT Adaptation

- Perceptual distortion calculation
  - Localized to individual block
  - Each bitplane has *n* number of coding passes
    - Hence up to *n* number of quality layers
    - Perceived distortion calculated between layers
- Neighbourhood size for masking
  - Variable size neighbourhood
    - Dependent on resolution level
      - The higher the resolution, the larger the window

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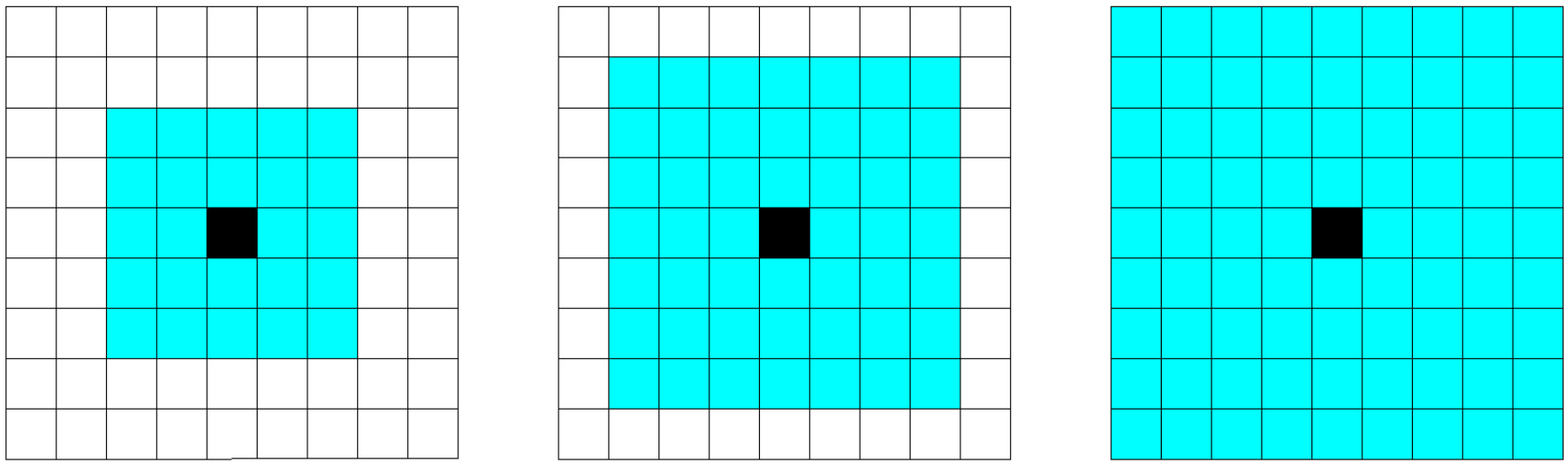
Masking neighbourhood size. Left to right: level 2, level 3 and level 4.



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13.3 Model Calibration

- Calibrate vision model responses to subjective data
- Test material
  - 11 source images
  - Distorted derived from bitplane filtering of source images in the transform domain
    - Covers a wide range of quality levels

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- Subjective test
  - DSCQS method from ITU-R bt.500
  - 3H viewing distance
  - 14 to 19 subjects
- Optimization of model paramters
  - In three stages
    - Parametric, algorithmic and manual optimization
  - Correlation measure
    - pearson’s correlation coefficient

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- Parametric
  - Brute force search
  - Coarse approximation of model parameters
- Algorithmic
  - More detail search for optimum parameters
- Manual tuning at coder level
  - Parameters are tuned relative to performance of encoded images
    - Requires subjective input

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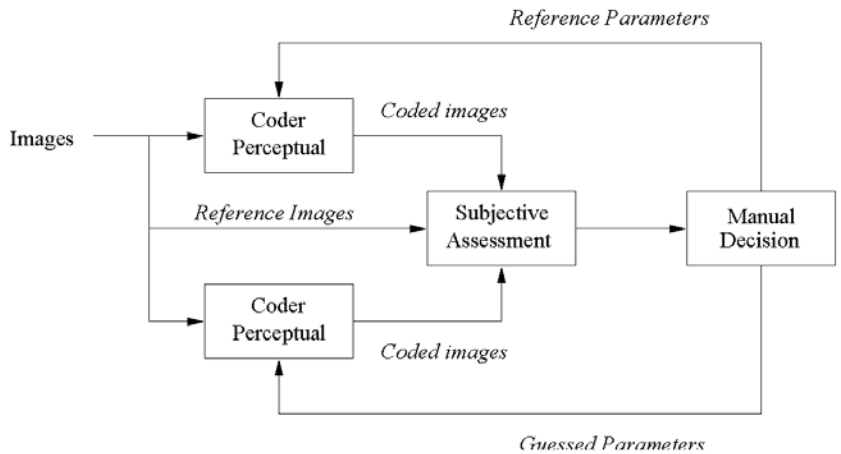
Illustration of manual optimization



- Necessity of manual optimization
  - Subjective data provide overall quality of images
  - PIDM operates at coefficient/block level and require more refined subjective data

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13.4 Performance Evaluation

- Comparison with benchmark coders
  - EBCOT with MSE
  - EBCOT-CVIS
    - Taubmans's spatial masking model
  - EBCOT-XMASK
    - Zeng et al's spatial masking model
- Assessment material
  - 8 images of which 5 have been used for model calibration

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- Methods of evaluation
  - Objective
    - PSNR and *Universal Image Quality Index* (UIQI)
  - Subjective
    - Randomized comparative test
      - Dichotomous 2 images with 2 choices: *left* or *right*
      - Trichotomous 2 images with 3 choices: *left*, *right* or *either*
- Range of evaluation
  - Each image is coded to 4 bitrates
    - 0.0625 bpp, 0.125 bpp, 0.25 bpp and 0.5 bpp

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Objective Results

- Overall
  - PSNR
    - Best performer EBCOT-MSE (no surprise)
    - EBCOT-PIDM 2nd and EBCOT-CVIS 3rd
    - Worst performer EBCOT-XMASK
  - UIQI
    - All metrics about the same except for EBCOT-XMASK
      - Worst performer below 0.25 bpp
      - Best performer at 0.5 bpp

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Subjective Results

- Overall
  - PIBM vs CVIS (13 subjects)
    - Dichotomous: 81% of test images for PIBM
    - Trichotomous: 66% of test images for PIBM,
  - PIBM vs XMASK (7 subjects)
    - Dichotomous: 78% of test images for PIBM
    - Trichotomous: 78% of test images for PIBM,
  - PIBM vs MSE (15 subjects)
    - Dichotomous: 72% of test images for PIBM
    - Trichotomous: 57% of test images for PIBM

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Barbara

512x512

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0.25bpp

MSE

PC

CVIS

XMASK

© H.R. Wu

0.25bpp

MSE

PC

CVIS

XMASK

Wu &

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0.25bpp

MSE

PC

CVIS

XMASK

Wu &

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0.25bpp

MSE

PC

CVIS

XMASK

Wu &

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13.5 Perceptual Lossless Coder

- Encodes images at imperceptible level
  - Between coded and original
  - Constant quality coder at the *Just Not-Noticeable Level* (JNND)
- Visual Pruning Function (VPF)
  - Equivalent pre-filtering operator that removes visually redundant information
  - Operates in the spectral domain

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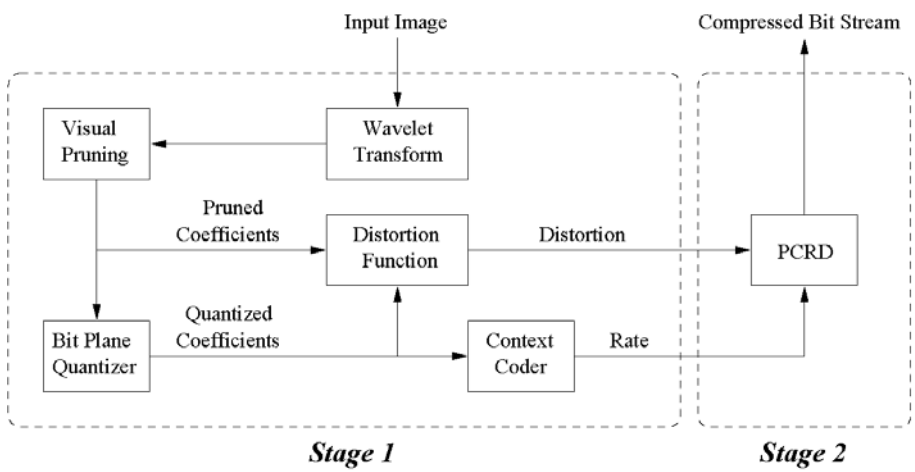
13.5.1 Coding Structure (*below*)

- EBCOT with embedded VPF
  - Utilize similar vision model as the PIDM
  - Perceptual distortion of vision model calibrated to JNND threshold



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13.5.2 Performance Analysis

- Compression performance
  - Compared with 2 benchmark coders
    - LOCO (LOw COmplexity coder)
      - JPEG-LS core
    - nLOCO (near-lossless LOCO)
      - With maximum pixel difference of 2 (d=2)
- Subjective Test for indifference
  - Trichotomous test
    - Randomized presentation of images
    - 2 images, 3 choices: *left*, *right* or *identical*

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Compression performance of PLC and benchmark coders

Image	Dimensions	bpp		
		VLGI Coder	LOCO (LS)	LOCO (D2)
Actor	512x512	2.990	5.267	3.012
Barbara	512x512	1.986	4.733	2.552
Boat	512x512	1.866	4.250	2.149
Bridge	512x512	3.256	5.500	3.278
Butterfly	512x512	1.500	3.822	1.888
Couple	512x512	2.039	4.262	2.141
Crowd	512x512	1.910	3.914	2.065
Elaine	512x512	2.633	4.898	2.668
Goldhill	512x512	2.424	4.712	2.495
House	512x512	1.904	4.097	2.115
Lake	512x512	2.677	4.983	2.755
Lena	512x512	1.796	4.244	2.097
Mandrill	512x512	3.556	6.036	3.727
Peppers	512x512	2.152	4.489	2.270
F16 Jet	512x512	1.582	3.793	1.830
Sail	512x512	2.810	5.212	2.968
Tank	512x512	2.577	4.808	2.565
Tiffany	512x512	2.309	4.672	2.469
Tulip	512x512	1.841	4.176	2.127
Washington	512x512	2.047	4.129	2.112

- PLC is ahead
  - Up to 50% more compression than LOCO
  - Up to 10% more compression than nLOCO

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Subjective results. *Left*: PLC vs Original. *Right*: PLC vs nLOCO

Image	Selection counts			No. of Subjects
	PLC	ORG	NEU	
Actor	10	5	2	17
Barbara	8	1	1	10
Boats	4	4	2	10
Bridge	8	6	2	16
Butterfly	3	4	6	13
Couple	5	4	2	11
Crowd	2	1	2	5
Elaine	4	2	1	7
Goldhill	4	0	5	9
House	5	3	2	10
Lake	1	3	4	8
Lena	7	6	2	15
Mandrill	6	1	9	16
Peppers	4	4	3	11
F16 Jet	5	7	3	15
Sail	4	1	7	12
Tank	4	4	2	10
Tiffany	2	4	2	8
Tulip	2	1	2	5
Washington	4	1	2	7
Total	92	62	61	215

Image	Selection counts			No. of Subjects
	PLC	nLC	NEU	
Actor	1	5	3	9
Barbara	8	3	1	13
Boats	5	4	3	12
Bridge	6	5	2	13
Butterfly	5	5	2	12
Couple	8	3	2	13
Crowd	4	4	8	16
Elaine	5	8	2	15
Goldhill	5	6	2	13
House	3	3	0	6
Lake	6	3	3	12
Lena	2	7	3	12
Mandrill	1	7	2	10
Peppers	2	4	3	9
F16 Jet	8	2	0	10
Sail	2	3	5	10
Tank	2	4	3	9
Tiffany	3	4	2	9
Tulip	8	2	3	13
Washington	1	8	6	15
Total	85	90	55	230

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- Raw subjective results
  - Apparently PLC is better than original
    - Neutral indicative of differences
    - Preferred selection favours PLC
    - Perhaps PLC has an enhancement effect
  - PLC and nLOCO are similar
    - Neutral selection is not indicative similarity, but
    - Preferred selection is split almost evently
      - Raw preference is 5.5% apart

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Original

PLC

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PLC

nLOCO

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13.6 Summary

- Perceptual Image coding
  - Enables further compression gains over pure statistical coders
  - Allows for graceful degradation of perceived quality relative to bitrate constrains
  - Enables constant (perceived) quality coding
    - e.g. constant quality at the JNND level (PLC)

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- PIDM Coding structure
  - Start-of-the-art EBCOT architecture
    - Hierarchical progressive bitplane coder
    - Scalable in rate and resolution
  - PIDM used for R-D function for rate control
    - Measures perceived distortion resulting from bitplane encoding
  - Fully bitstream compliant with EBCOT/JPEG2000
    - No additional side information needed

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YZF99	K.H. Yang, W. Zhu and A.F. Faryar. Perceptual Quantization for Predictive Coding in Images. In *Proc. of IEEE ICIP*, 2:381-385, 1999

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14. Foveated Image and Video Coding

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Chapter 14 Outline

14.1 Foveated Human Vision and Foveated Image Processing

14.2 Foveation Methods

14.3 Scalable Foveated Image and Video Coding

14.4 Discussions

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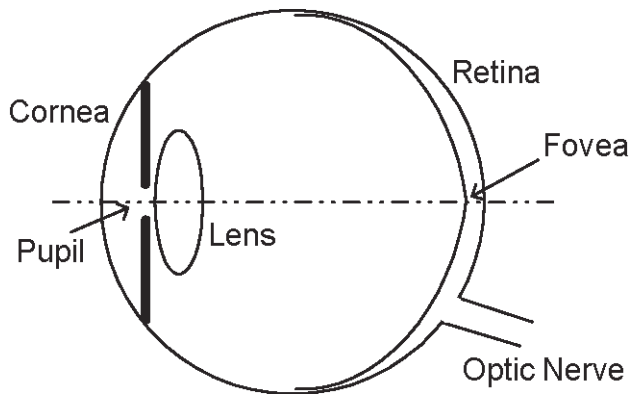
14.1 Foveated Human Vision and Foveated Image Processing



- Anatomy of the human eye
  - Photoreceptor: *Cones* and *Rods*
    - Populates the retina (focal point fovea)
    - Non-uniform distribution of photoreceptors in retina

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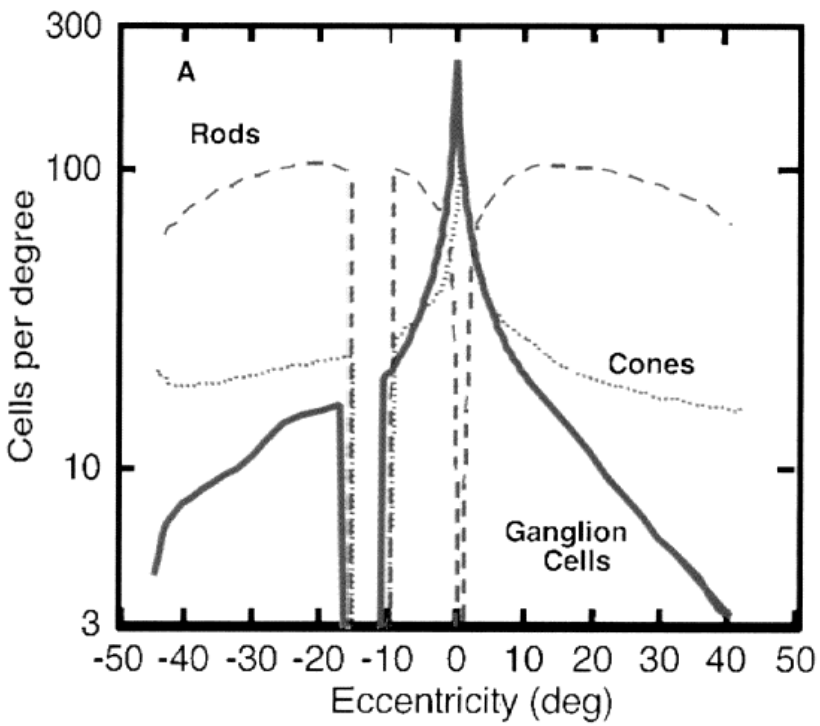
Distribution of rods, cones and ganglion cells relative to eccentricity (central point of fovea)



- Cone concentrates falls off sharply from fovea
- No rods in fovea
- No photoreceptor in the area occupied by the optic nerve (blind spot)

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- Basic operation of the eye
  - Light is captured by photoreceptors
    - Cones responsible for photopic vision
    - Rods handle scotopic vision
  - Ganglion cells integrates visual stimuli captured by photoreceptors
    - Some preliminary processing of visual signals
  - Integrated signal transmitted to cortex via visual pathways

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- Foveated image processing and coding
  - Focused on the fovea
    - Point of fixation
  - Major redundancies in peripheral vision
    - Improve compression

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Goldhill Image. a) original. b) foveated

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14.2 Foveation Methods

- Geometric methods
  - Three approaches
    - Direct application of to uniform resolution image
      - Underlying image is mapped onto new coordinate system (1 to 1 mapping)
    - Superpixel method
      - Pixels are grouped and mapped into superpixel block (many to 1 mapping)
    - Foveated retinal geometry
      - Image mapped to foveal sensor grid

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Foveation coordinate transform. a) original images. b) transformed image

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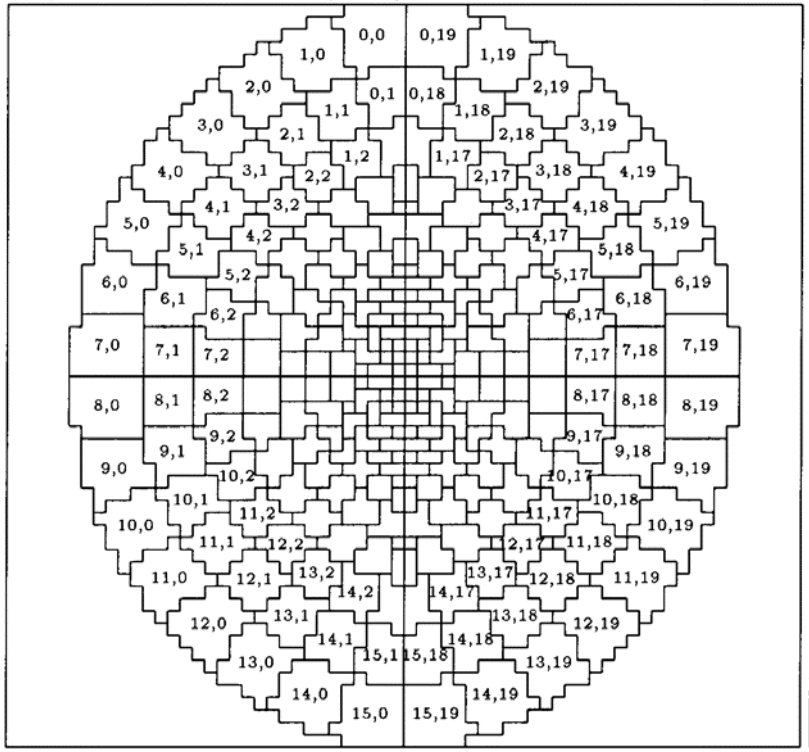
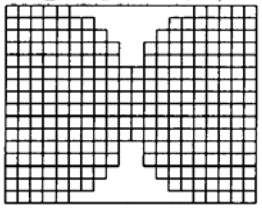
Longmap superpixel representation

Logmap lookup tables (S, R) for 60 by 64 TV image.



Logmap array (16 by 20)



(15,19)

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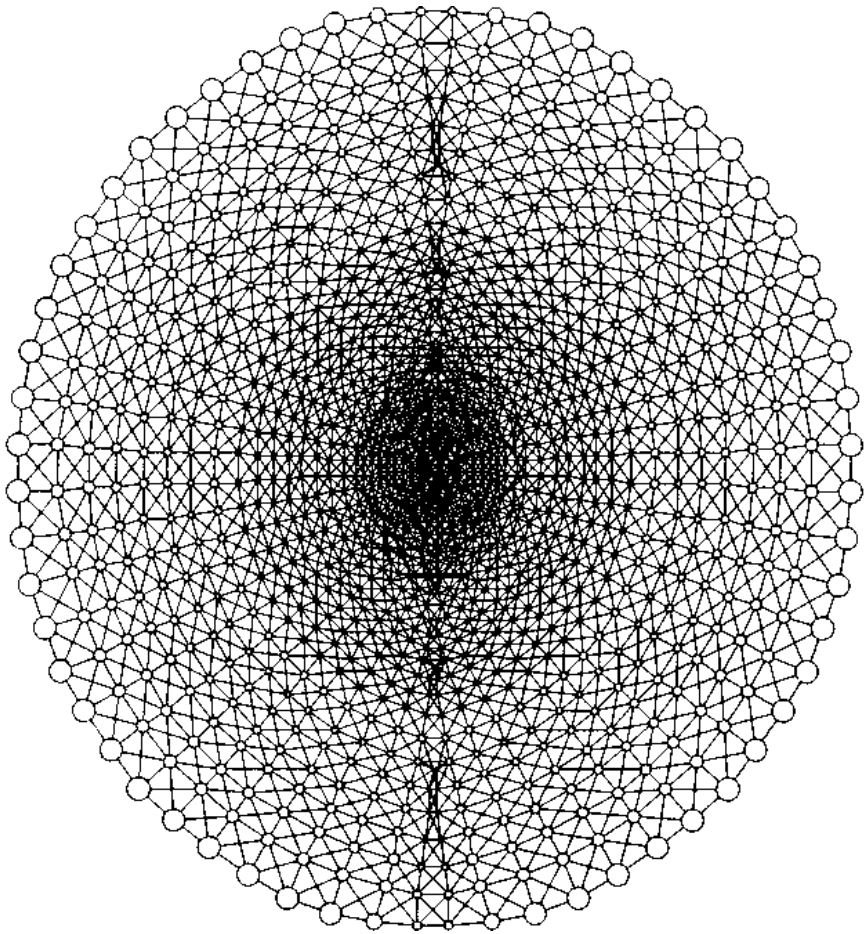
Foveated sensor distribution



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14.2.2 Filtering Based Methods

- Foveal processing
  - Shift-invariant low-pass filtering
    - Cut-off frequency determined by retinal sampling density
- Foveation implementation
  - Multi-channel Filter banks
    - Decomposition into different spectral bands
    - Foveal image obtained with space-invariant combination of spectral images
      - dependent on retinal sampling density

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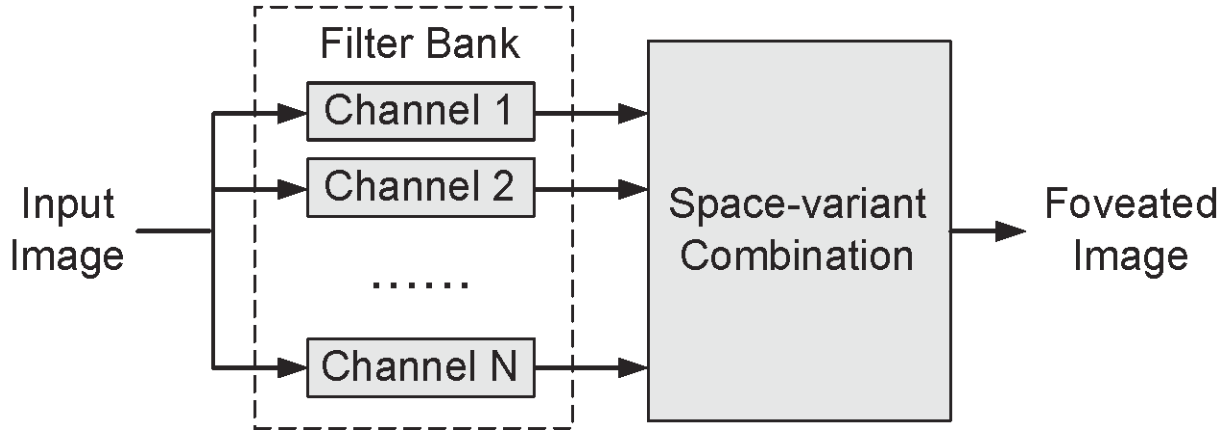
Filter bank foveation method



- Filter design considerations
  - Low-pass, band-pass or both
  - Filter type: IIR or FIR
  - Characteristics
    - Band size, ripple size

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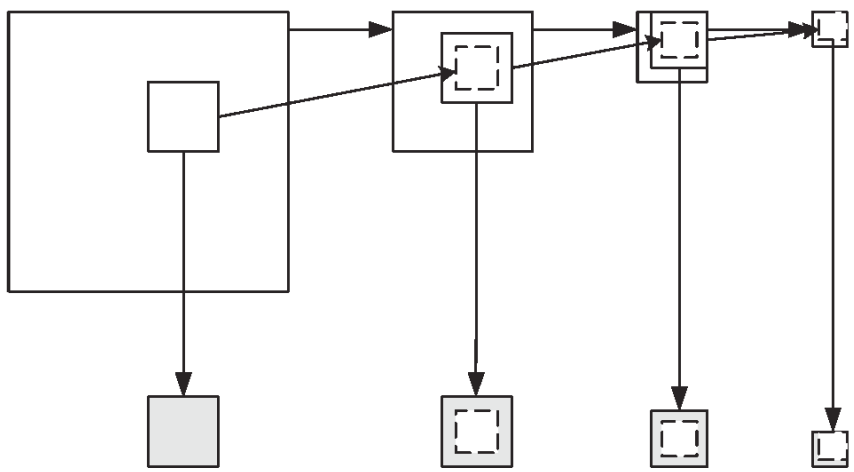
14.3.2 Multiresolution Methods

- Image projected into different resolutions
  - Combines both geometric and filtering-based methods



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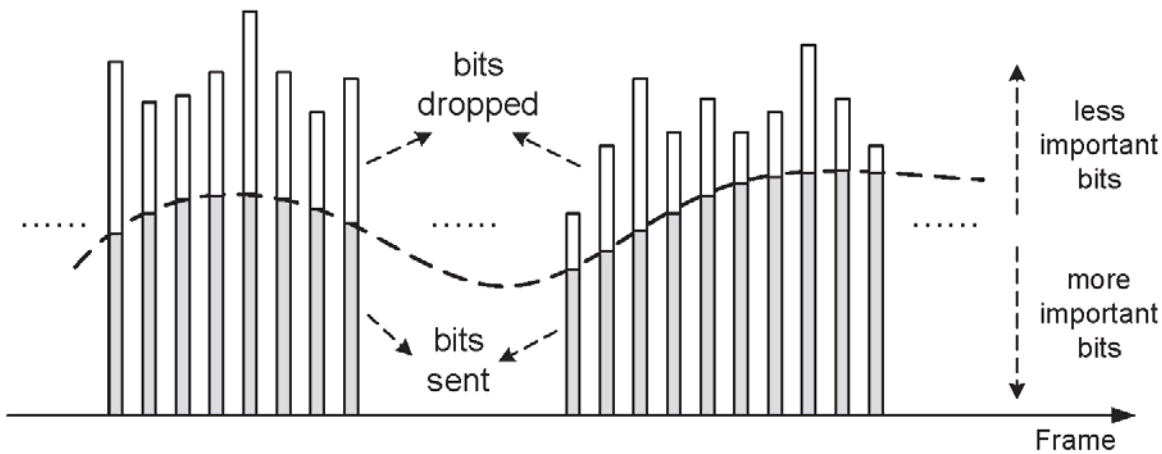
14.3 Scalable Foveated Image and Video Coding

- Scalable video coding
  - Compressed stream layered to different quality levels
  - Quality tailored to user requirements



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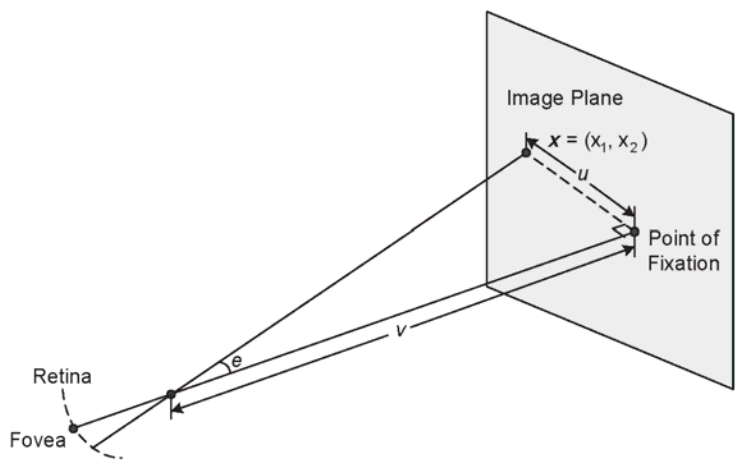
14.3.1 Foveated Perceptual Weighting Model

- Contrast sensitivity measured as a function of retinal eccentricity
  - Dependent of viewing distance (*below*)
    - Assuming constant fixation point (*u*), as viewing distance increases (*v*), angle of eccentricity (*e*) decreases



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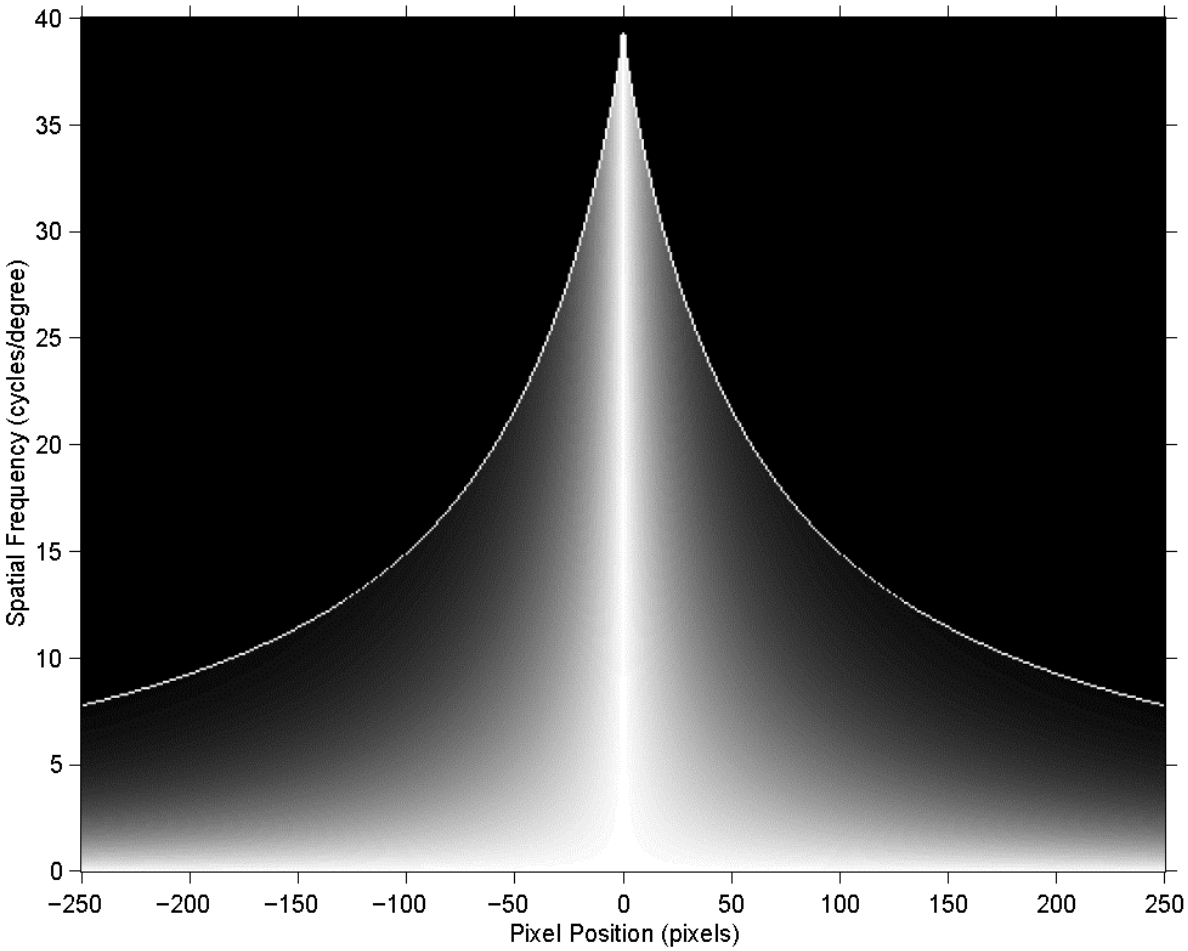
Normalized contrast sensitivity



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- Foveal weights in the wavelet domain
  - Determine visible threshold in the wavelet domain
    - Devise error model from data fitting of threshold level noise experiments in the wavelet domain
  - Formulate error detection function from error model
  - Adjust error detection function according to contrast sensitivity

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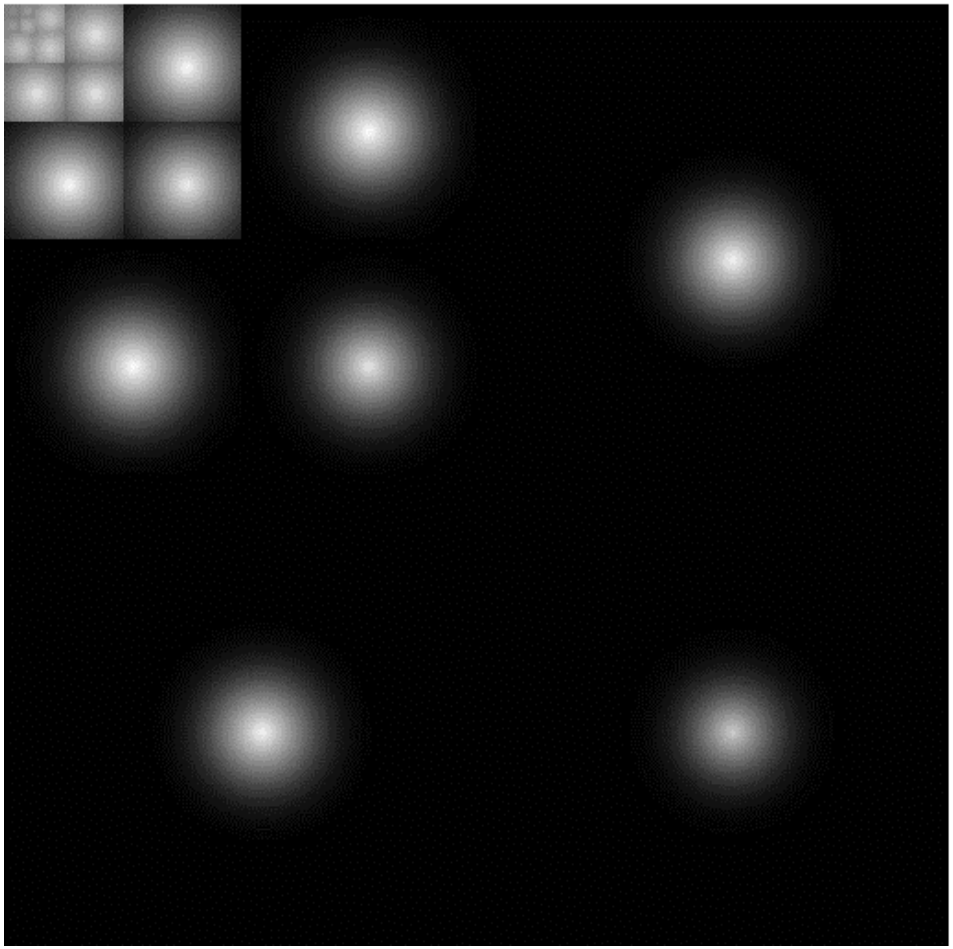
Wavelet domain weighting mask of a signal foveation point



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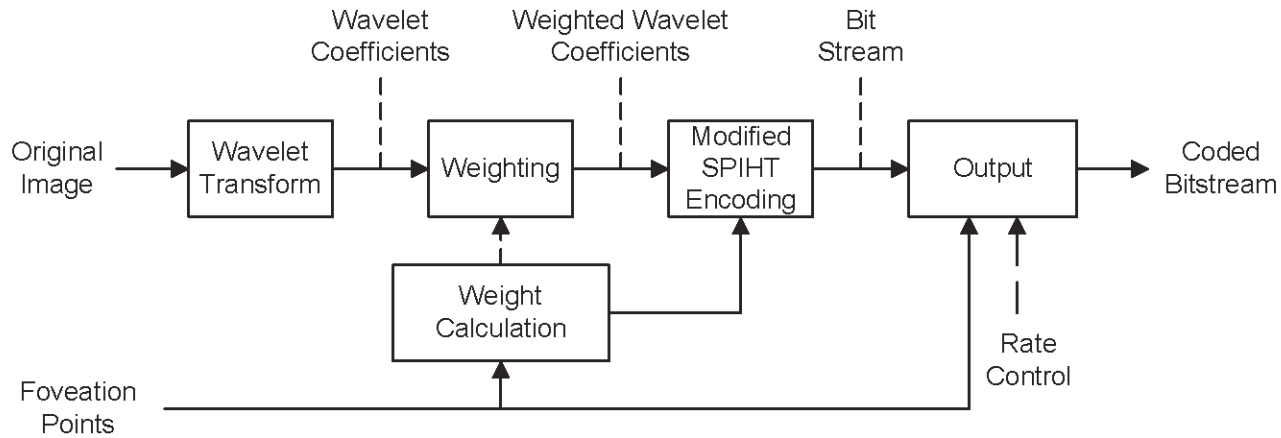
14.3.2 Embedded Foveation Image Coding (EFIC)



- EFIC components
  - Wavelet transform
  - Foveal weighting (transmitted to decoder)
  - SPHIT encoding (modified)

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Zelda Image

a) SPIHT @ 512:1
b) EFIC @ 512:1
c) SPIHT @ 128:1
d) EFIC @ 128:1
e) SPHIT @ 32:1
f) EFIC @ 32:1

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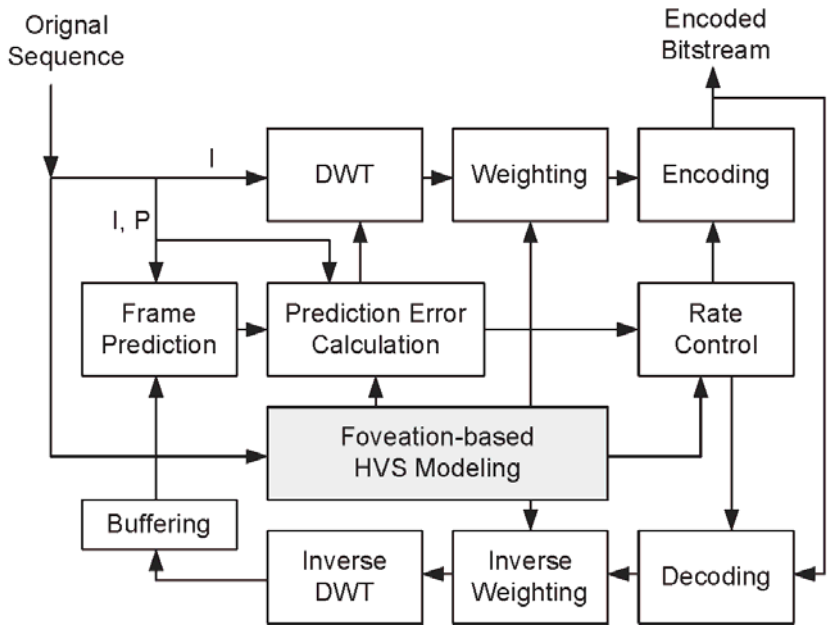
14.3.3 Foveation Scalable Video Coding (FSVC)



- Scalable coding
- I- and P-frame only
- EFIC for I-frame
- MC/DPCM for P-frame
  - Used previous original and decoded frame for prediction

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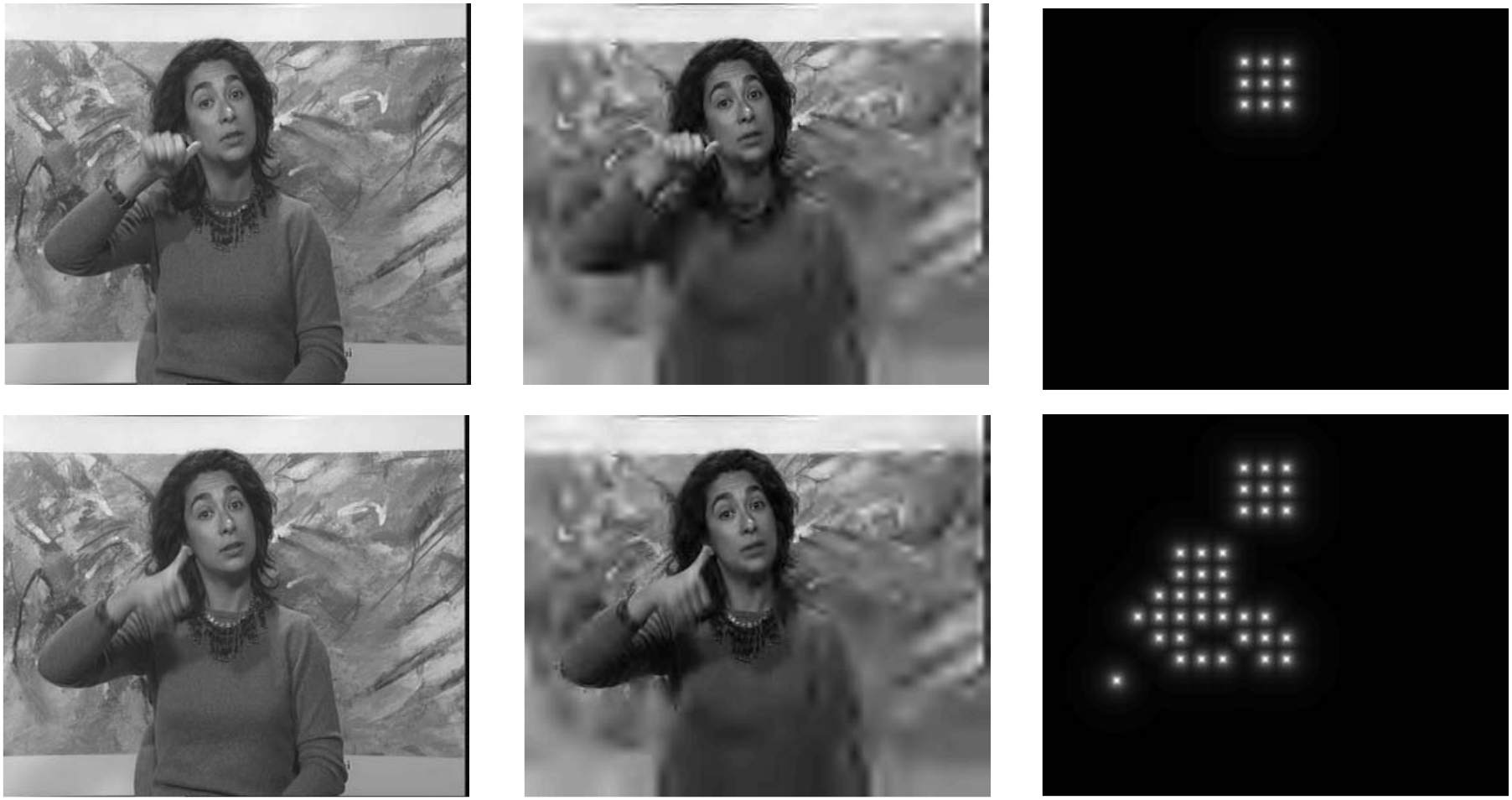
Left: Consecutive frames of *Silence* sequence. One I-frame followed by P-frames. *Middle*: FSVC @ 200kbps. *Right*: Foveation points.



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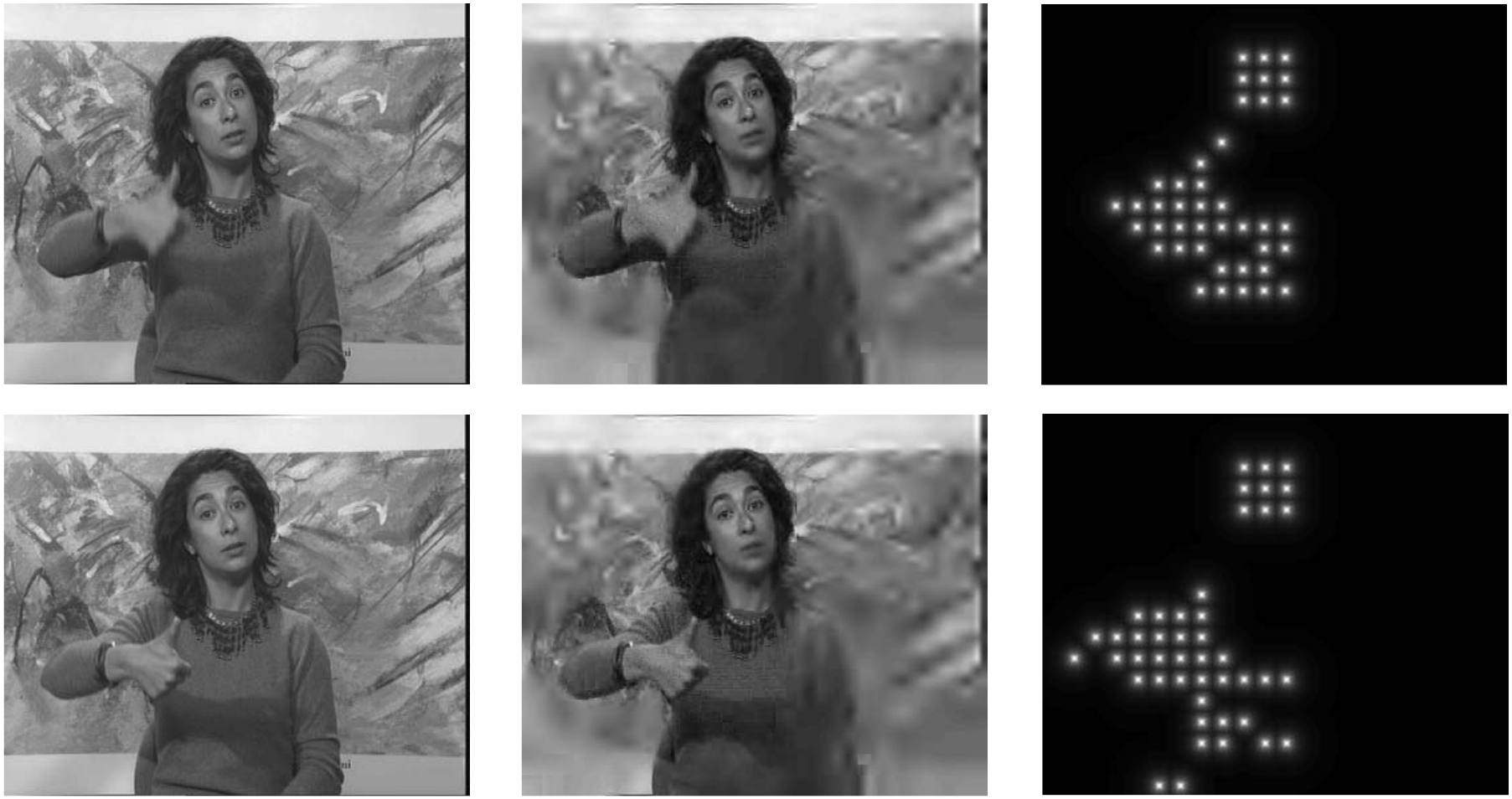

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Frame 32 of salesman sequence coded with FSVC. a) original. b) 200 kbps. c) 400 kbps. d) 800 kbps

Original

200 Kbps

800 Kbps

400 Kbps

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14.4 Discussions

- Principles of foveal operation
- Foveation methods
  - Geometric, filtering-based and mulitresolution
- Scalable foveated image/video coding
  - Foveated perceptual weighting model
  - EFIC (embedded foveation image coding)
  - FSVC (Foveation scalable video coding)

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AS00	S. Aramvith and M.T. Sun. *Handbook of Image and Video Processing (MPEG-1 and MPEG-2 video standards)*. San Diego, CA: Academic Press, May 2000
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CY97	E.C. Chang and C. Yap. A Wavelet approach to foveating images. *ACM Symposium on Computational Geometry*, 397-399, June 1997
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GB95	W.S. Geisler and M.S. Banks. *Handbook of Optics: Visual performance*. New York: McGraw-Hill, 1995
GP98	W.S. Geisler and J.S. Perry. A real-time foveated multiresolution system for low-bandwidth video communication. *Proc. SPIE: Human Vision and Electronic Imaging*, 3299(2):294-305, July 1998
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Itt00	L. Itti. *Models of bottom-up and top-down visual attention*. Ph.D. thesis, California Institute of Technology, Pasadena, CA, 2000

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KA02	A. Koz and A. Alatan. Foveated image watermarking. *IEEE ICIP*, 3:661-664, Sept. 2002
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Mal99	C.M. Privitera and L.W. Stark. Algorithms for defining visual regions-of-interest: comparison with eye fixations. *IEEE Trans. Pattern Analysis and Machine Intelligence*, 22(9):970-982, Sept. 2000
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Rud96	D.L. Ruderman. The statistics of natural images. *Network: Computation in Neural Systems*, 5:517-548, 1996
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SEB02	H.R. Sheikh, B.L. Evans and A.V. Bovik. Real-time foveation techniques for low bit rate video coding. *Real-time Imaging*, 9(1):27-40, Feb. 2003
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Wan01	Z. Wang. *Rate scalable foveated image and video communications*. Ph.D. thesis, Dept. of ECE, The University of Texas at Austin, Dec. 2001
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WYSV97	A.B. Watson, G.Y. Yang, J.A. Solomon and J. Villasenor. Visibility of wavelet quantization noise. *IEEE Trans. Image Processing*, 6(8):1164-1175, 1997
ZS93	Y.Y. Zeevi and E. Shlomot. Nonuniform sampling and anitaliasing in image representation. *IEEE Trans. Signal Processing*, 41(3):1223-1236, March 1993

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15. Artifact Reduction by Post-Processing in Image Compression

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Chapter 15 Outline

15.1 Introduction

15.2 Image Compression and Coding Artifacts

15.3 Reduction of Blocking Artifacts

15.4 Reduction of Ringing Artifacts

15.5 Summary

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15.1 Introduction

- Proliferation of applications that rely on compression systems
  - Video-conferencing, video over internet, etc
- Coding systems introduces distortions
  - Visible artifacts degrades quality of services
  - Prevalent at low bitrates
- Picture processing for distortion reduction
  - Pre-processing at encoding end
  - Post processing at decoding end

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15.2 Image Compression and Coding Artifacts

- Transform based coding
  - Employ data transformation
    - Reduces redundancies
  - Popular due to
    - Near-optimal decorrelation and energy compaction
    - Fast implementation
  - Recommended in international standards
    - DCT in JPEG, MPEG, H.26x
    - DWT in JPEG2000

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- Distortions in transform based coders
  - Appears primarily at low bitrates
  - Blocking artifact most prominent in DCT
  - Ringing and blurring artifacts for DWT
- Blocking Artifact (grid noise)
  - Discontinuities between adjacent blocks
  - Appears on block boundaries
  - Side effect of quantization operations
    - When mid and high frequency DCT coefficients are nullified

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Coded *Lena* image at 0.22 bpp. *Left*: JPEG. *Right*: JPEG2000

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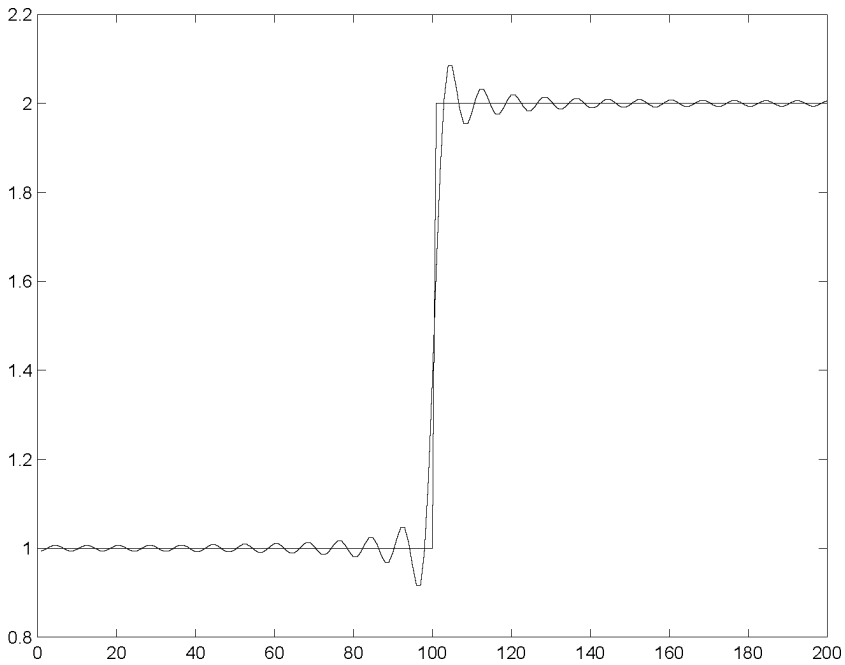

- Ringing artifacts
  - Spurious oscillation in the vicinity of major edges (at low bitrates)
  - Similar to Gibb's phenomenon

Left: example of ringing for 1-D signal

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15.3 Reduction of Blocking Artifacts

- Important part of coding system
  - Implemented in H.264/MPEG-4 AVC
- Application of de-blocking filters
  - Mostly at post-processing end
  - May also be employed at the encoding end in video coders, e.g., H.264/MPEG-4 AVC
- Simple low pass filtering in spatial domain
  - Reduces blocking, may lead to strong blurring

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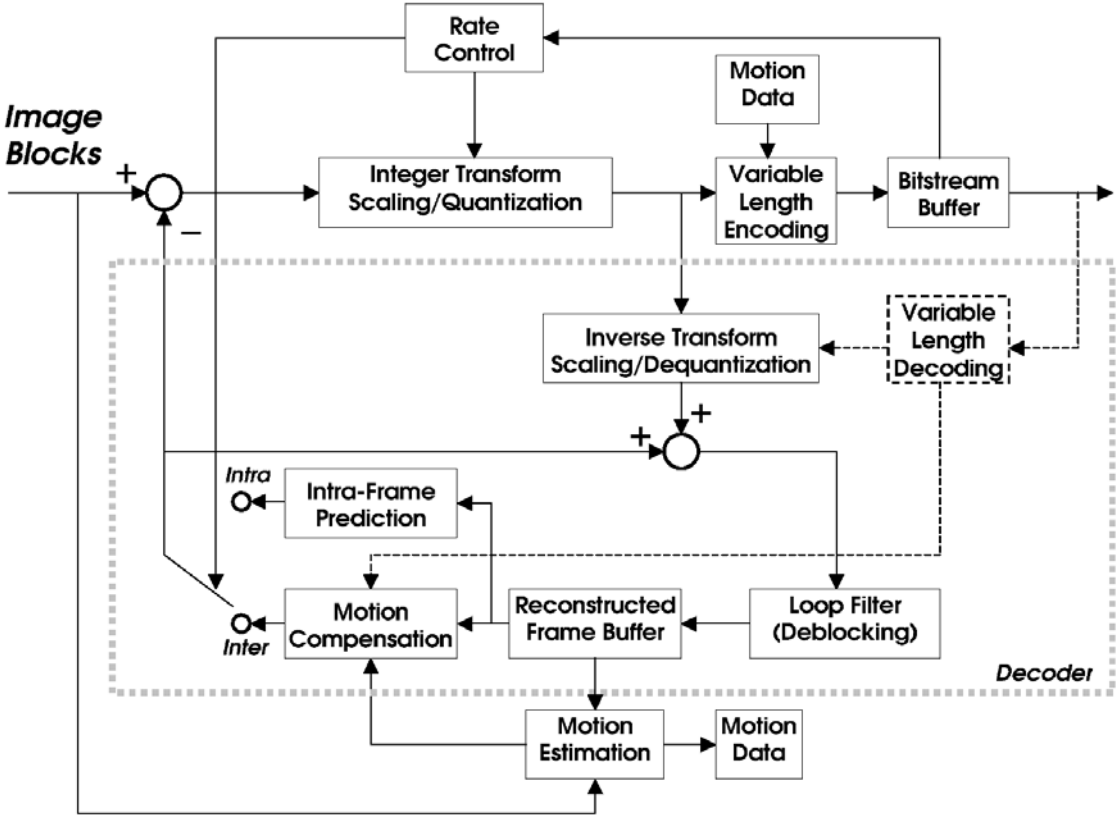
Simplified block diagram of H.264/MPEG-4 AVC



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- Projection Onto Convex Set (POCS) filter
  - Applied at the decoding end
  - Iterative filter
  - Blurs images excessively
  - Deals with pixel straddling the block boundary
    - May lead to new discontinuity between each altered pixel and adjacent pixels

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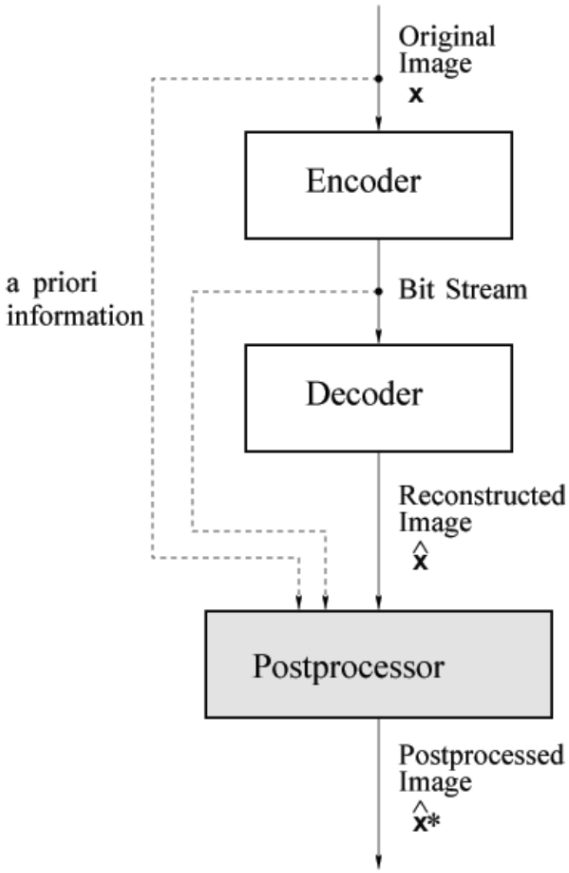
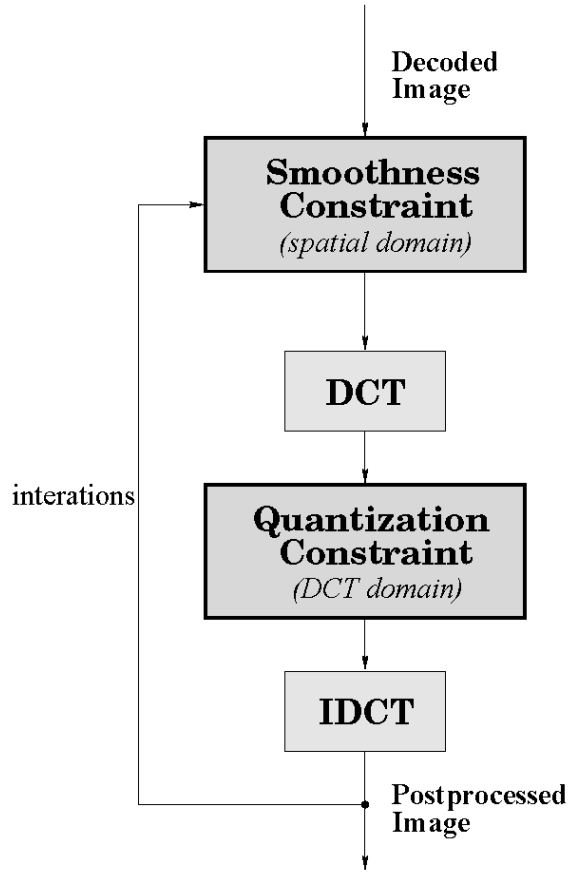
Left: General arrangement of picture coding systems. *Right*: General structure of POCS filters





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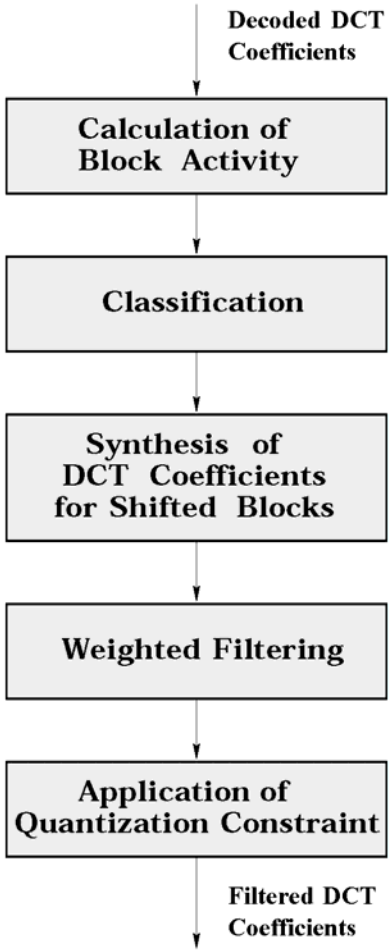
15.3.1 Adaptive Postfiltering of Transform Coefficients



Left: Illustration of the implementation of adaptive postfiltering of DCT coefficients

- HVS considered and modelled by the MTF
  - Operationally, AC coefficients weighted by MTF

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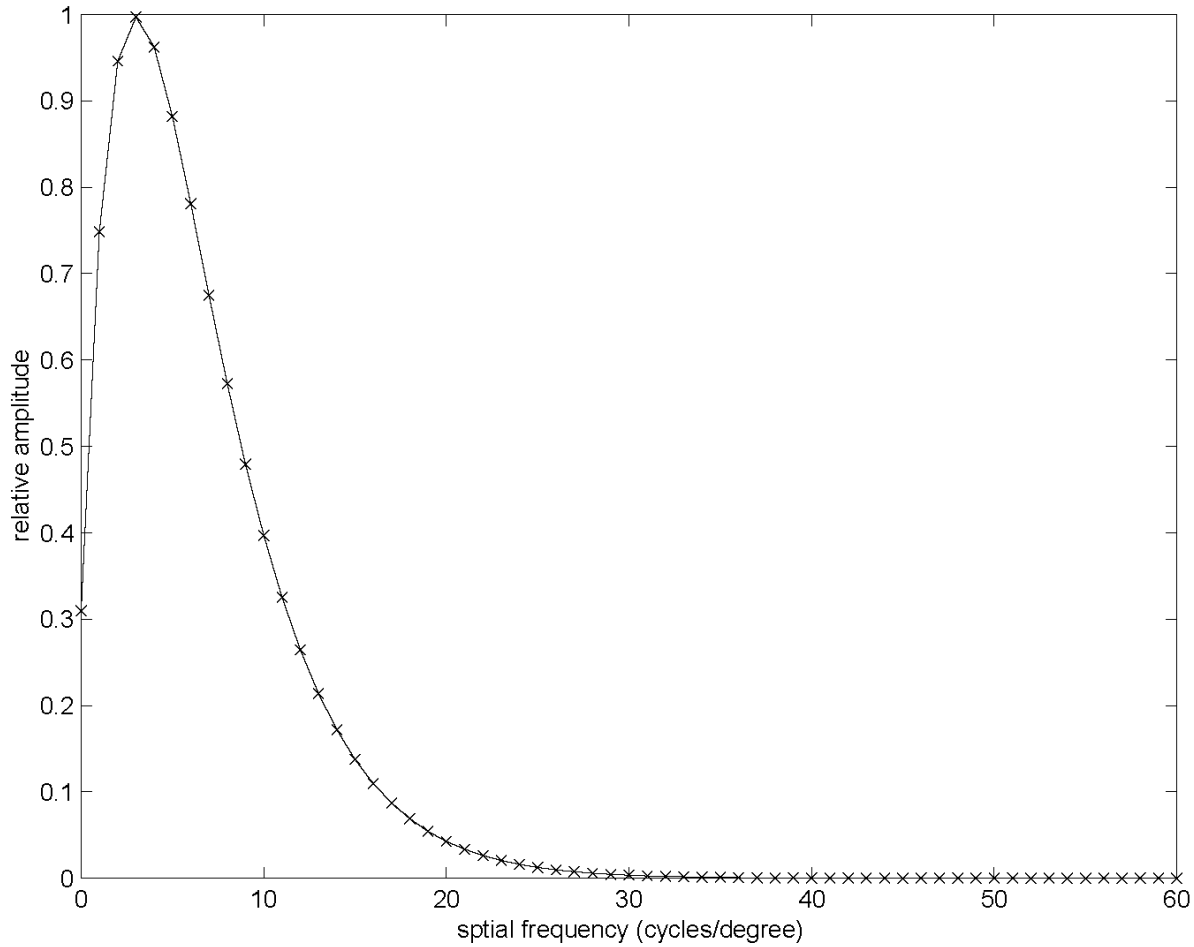
Modulation Transfer Function (MTF). Measures visual sensitivity relative to spatial frequencies



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- Calculation of Block activity
  - Sum of AC coefficients normalized by local background luminance (Weber's Law)
- Classification of blocking activity
  - Classified into low or high activity blocks
    - Based on some pre-defined threshold value
- DCT block shifting
  - Forms new stationary estimates of DCT coefficients for weighted filtering

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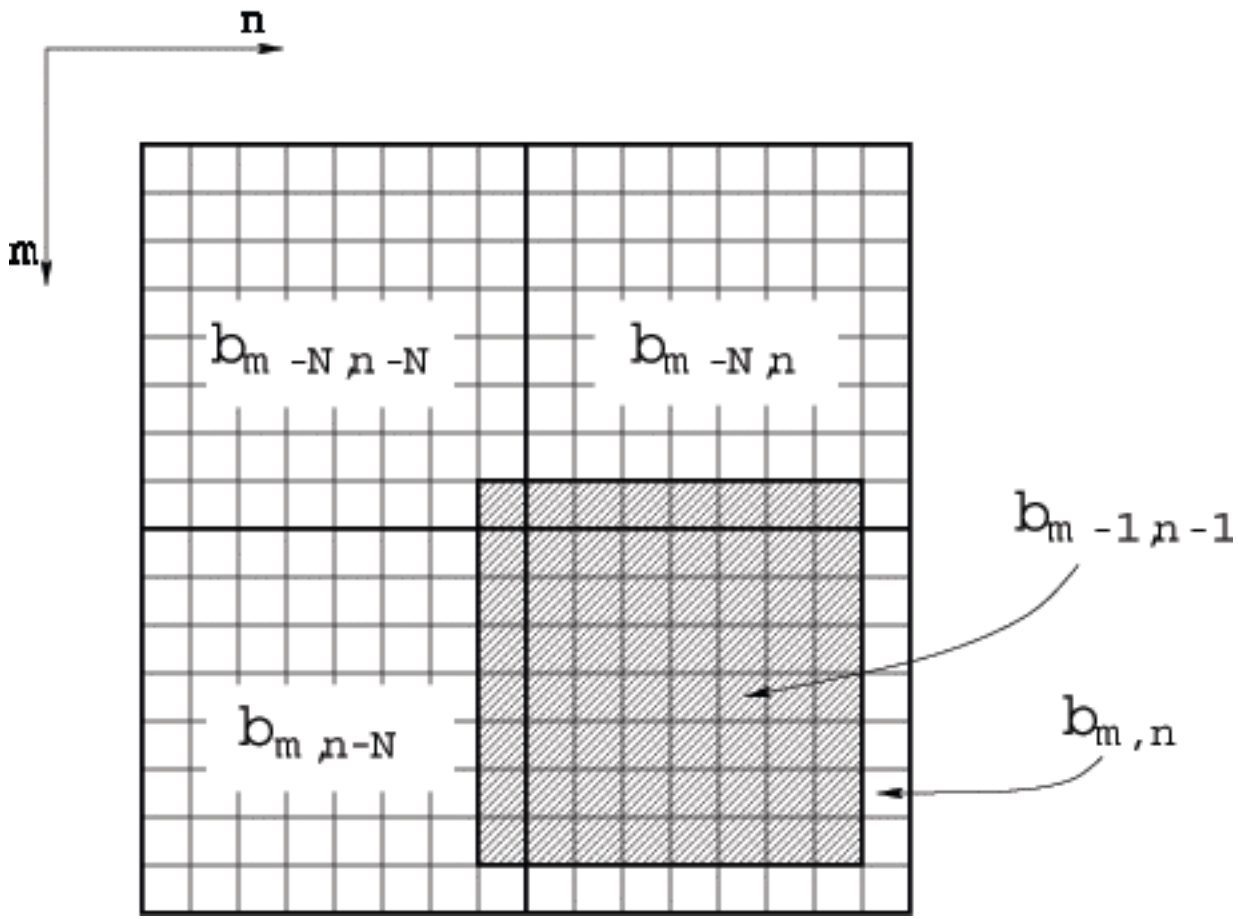
Illustration of block shifting



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- Adaptive weighted filtering
  - Weighting relative to local activity
    - Low activity
      - 5x5 filtering window
      - Uniform filter weights
    - High activity –
      - 3x3 filtering window
      - Filter weights: 3 for central coefficient and 1 for all others
      - Avoids excessive blurring of high activity block

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- Quantization constrains
  - Projects filtering to de-quantized domain
    - i.e. ensures quantizer output stays within the post-filtering boundary

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15.3.3 Simulation Results

Image	Bitrate (bpp)	PSNR (dB)						
		Decoded	H.263	MPEG4	POCS-Z	POCS-Y	POCS-P	Proposed
Airplane	0.241	28.72	29.34	29.57	27.91	29.34	29.07	29.39
Barbara	0.295	25.08	25.31	25.52	25.06	25.52	25.34	25.62
Boats	0.235	28.52	29.07	29.30	28.01	29.16	28.76	29.25
Goldhill	0.230	27.91	28.50	28.53	27.72	28.46	28.12	28.54
Lena	0.219	29.47	30.20	30.43	29.02	30.23	29.88	30.39
Peppers	0.221	29.21	30.02	30.15	28.82	29.85	29.65	29.95
Sailboat	0.286	27.00	27.51	27.68	26.46	27.57	27.26	27.66
Splash	0.178	31.23	32.00	32.29	30.61	31.77	31.75	31.89
Tiffany	0.188	29.59	30.10	30.38	29.36	30.11	29.97	30.15

- Evaluations
  - 9 images
  - Compared with 5 de-block algorithms
    - POCS and 2 POCS variations
    - H.263 and MPEG-4 standard de-block filters

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Image	M_{GBIM}							
	Original	JPEG	H.263	MPEG4	POCS-Z	POCS-Y	POCS-P	Proposed
Airplane	1.1177	4.0615	1.3917	1.4209	1.5470	1.7439	2.0292	1.2864
Barbara	1.0415	3.0789	1.7398	1.1465	1.3447	1.6753	1.7578	1.2404
Boats	1.0737	4.1674	1.9803	1.4785	1.5707	1.4402	2.1040	1.3387
Goldhill	1.0351	4.7412	1.5288	1.5091	1.5285	1.4169	2.2451	1.3979
Lena	1.1009	4.9905	1.5514	1.5931	1.5702	1.4780	2.4191	1.3777
Peppers	1.1368	5.6746	1.7197	1.7831	1.5581	1.8250	2.2613	1.3986
Sailboat	1.1414	3.8388	1.5359	1.4880	1.6358	1.4654	2.1186	1.3321
Splash	1.0435	5.7207	1.8760	1.4846	1.4191	2.3544	1.8109	1.2102
Tiffany	1.0139	6.0632	1.8979	1.5240	1.7656	2.2406	1.9322	1.3784

- Evaluation methods
  - PSNR
  - GBIM (*Generalized Block Impairment Metric*)
- Results
  - Proposed method superior to other algorithms

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Original | JPEG coded | H.263 post-filter | MPEG-4 post-filter

POCS-Z | POCS-Y | POCSP | Proposed

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15.4 Reduction of Ringing

- Problem with de-ringing
  - Blurring of image content
  - No enhancement edge sharpness
    - Due, in part, to the difficulty of distinguishing between content edges and ringing distortion
- Manifestation in DCT and DWT coders
  - More prominent on DWT coders

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Left: Lena image coded by MPEG-4 coder. *Right*: left image after de-ringing

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15.5 Summary

- Post-processing for applications in picture coding and processing
  - Reduction of coding distortions
    - Blocking for DCT
      - De-blocking filters
        - » Adaptive postfiltering of transform coefficients
    - Ringing primarily for DWT

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CM95	S.F. Chang and D.G. Messerschmitt. Manipulation and compositing of MC-DCT compressed video. *IEEE J. Selected Areas of Communication*, 13(1):1-11, Jan. 1995
CR90	B. Chitprasert and K.R. Rao. Human visual weighting progressive image transmission. *IEEE Trans.on Communications*, 38(7):1040-1044, July 1990
CWQ01	T. Chen, H.R. Wu and B. Qiu. Adaptive postfiltering of transform coefficients for the reduction of blocking artifacts. *IEEE Trans. on Circuits and System for Video Technology*, 11:594-602, May 2001
dNR96	R.L. de Queiroz, T.Q. Nguyen and K.R. Rao. GenLOT: generalized linear-phase lapped orthogonal transform. *IEEE Trans. Signal Processing*, 44:497-507, Mar. 1996
FC00	G. Fan and W.K. Cham. Model-based edge reconstruction for low bit-rate wavelet compressed images. *IEEE Trans. on Circuits and Systems for Video Technology*. 10(1):120-132, Jan. 2000

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16. Reduction of Color Bleeding in DCT Block-Coded Video

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Chapter 16 Outline

16.1 Introduction

16.2 Analysis of the Color Bleeding Phenomenon

16.3 Description of the Post-Processor

16.4 Experimental Results – Concluding Remarks

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16.1 Introduction

- Color bleeding in DCT coders
  - Appears as a smearing of color between highly contrasting chrominance
  - May lead to secondary color ringing effect
  - Visually objectionable

Left: Illustration of color bleeding

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16.2 Analysis of the Color Bleeding Phenomenon

- Manifestation of color bleeding
  - Occurs when boundaries of chroma channels overlaps inappropriately
    - Resulting in chrominance mismatch
  - Initiated by decimation and quantization of chrominance components
    - Coarse quantization of AC bands

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16.2.1 Digital Color Video Formats

- YUV colour space ($Y_dC_bC_r$ digital form)
  - Often employed in color picture coding
  - Y contains the luminance component
  - U and V the chrominance channels
  - Human vision is more sensitive to luminance than chrominance channel
    - Little or no quality with sub-sampling chroma channels

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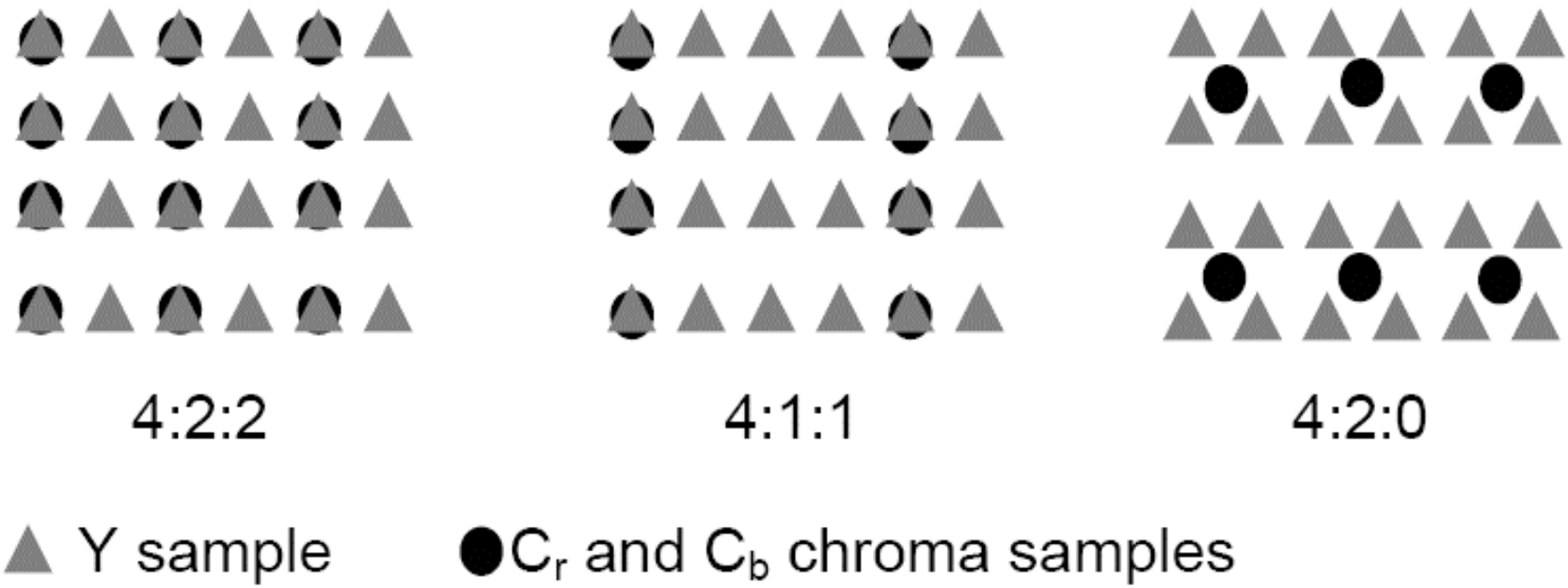
Chrominance sub-sampling strategies in $Y_dC_bC_r$ color space



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16.2.2 Color Quantization

- Quantization account for visual sensitivity
  - Sensitivity varies with spatial frequency
  - Different sensitivities for luminance and chrominance channels
    - Chroma channels less sensitive
      - Higher quantization for C_b and C_r

16	11	10	16	24	40	51	61
12	12	14	19	26	58	60	55
14	13	16	24	40	57	69	56
14	17	22	29	51	87	80	62
18	22	37	56	68	109	103	77
24	35	55	64	81	104	113	92
49	64	78	87	103	121	120	101
72	92	95	98	112	100	103	99

17	18	24	47	99	99	99	99
18	21	26	66	99	99	99	99
24	26	56	99	99	99	99	99
47	66	99	99	99	99	99	99
99	99	99	99	99	99	99	99
99	99	99	99	99	99	99	99
99	99	99	99	99	99	99	99
99	99	99	99	99	99	99	99

Luminance (*left*) and chrominance (*right*) quantization matrices

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16.2.3 Analysis of Color Bleeding Distortion

- Ringing in sub-sampled chroma channels propagates when up-sampled to full chroma resolution

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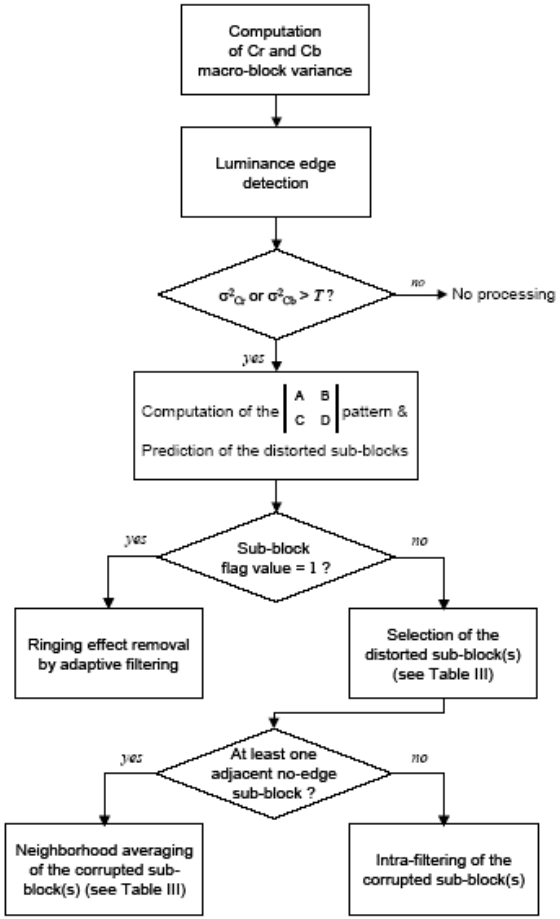
16.3 Description of the Post-Processor



- Major components
  - Detection
  - Classification
  - Filtering

Left: Illustration of post-filtering process

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- Color bleeding detection
  - Variance computation in C_b and C_r
    - 4 x 4 windowed block
    - Computes activity level in chroma block
      - For chroma edge detection
  - Luminance edge detection
    - For vertical and horizontal edges
    - Used as additional reference for chrominance edges

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- Computation of code block pattern
  - Classification of block pattern for filtering
  - Partitioning of 8 x 8 code block
    - To 4 quadrants (4x4 sub-block)
  - Binary flag for each block set if
    - Strong chrominance edge exist
    - Luminance edge detected
  - Pattern generated according to 4 flags
    - 16 possible patterns

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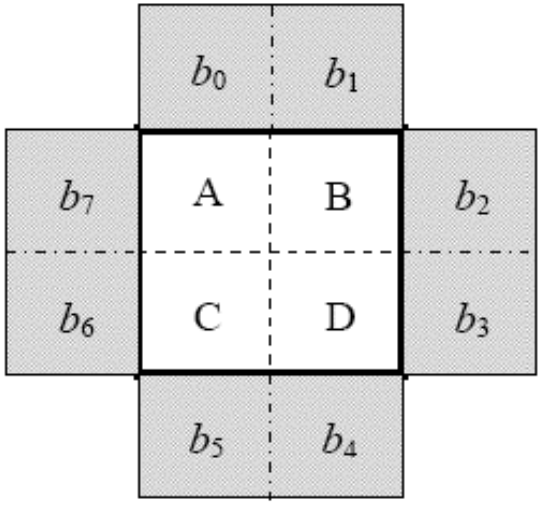
Left: 4 quadrants of 8x8 code block. *Right*: Pattern configurations for code block classification



CONFIGURATION OF THE CURRENT 8x8 CHROMINANCE BLOCK				4x4 CHROMINANCE BLOCK TO BE FILTERED	4x4 NEIGHBORING BLOCKS TO BE ACCOUNTED FOR IN THE AVERAGING PROCESS
A	B	C	D		
0	0	0	0	–	–
0	0	0	1	A	b_0, b_7
0	0	1	0	B	b_1, b_2
0	0	1	1	A and B	b_0, b_1
0	1	0	0	C	b_5, b_6
0	1	0	1	A and C	b_6, b_7
0	1	1	0	–	–
0	1	1	1	A	b_0, b_7
1	0	0	0	D	b_3, b_4
1	0	0	1	–	–
1	0	1	0	B and D	b_2, b_3
1	0	1	1	B	b_1, b_2
1	1	0	0	C and D	b_4, b_5
1	1	0	1	C	b_5, b_6
1	1	1	0	D	b_3, b_4
1	1	1	1	–	–

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- Filtering process
  - Ringing related color bleeding
    - Smoothing pixels around the target pixel (target pixel untouched)
    - Smoothing operation applied to all color channels
  - Blocking related color bleeding
    - Neighbourhood averaging (chroma channels)
    - Intra-filtering
      - Averaging of corrupted pixels identified by pattern configuration

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16.4 Experimental Results – Concluding Remarks

- Noticeable improvement with post-processing
  - Visual reduction of color bleeding
  - supported by PSNR results

Sequence (frame)	Δ PSNR (dB)	
	C_r component	C_b component
Table tennis (#001)	+0.32	+0.10
Foreman (#225)	+0.41	+0.43

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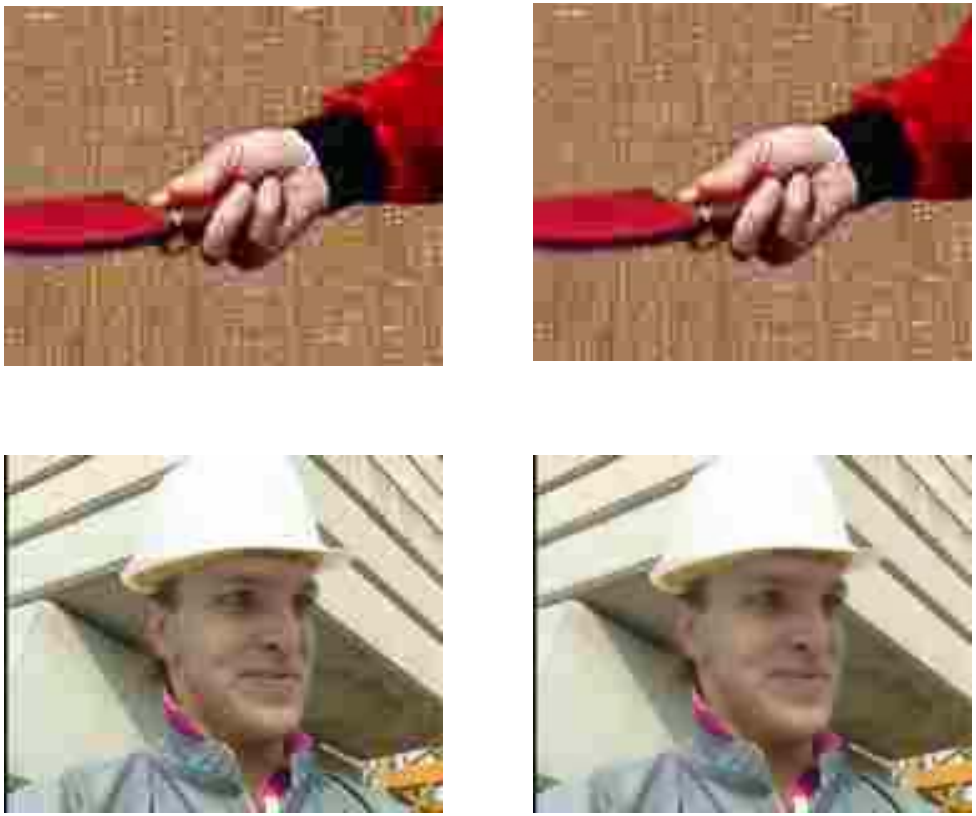
Left: decode picture frames.
Right: post-filtered frames



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17. Error Resilience for Video Coding Service

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Chapter 17 Outline

17.1 Introduction to Error Resilient Coding Technique

17.2 Error Resilient Coding Methods Compatible with MPEG-2

17.3 Methods for Concealment of Cell Loss

17.4 Experimental Procedure

17.5 Experimental Results

17.6 Conclusions

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17.1 Introduction to Error Resilient Coding Technique

- Network transmission errors
  - Due network congestion, mis-routing and channel noise
    - Results in packet corruption and/or packet loss
  - Has severe impact on picture quality of video stream
  - Minimize transmission errors with error resilient coding

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- Error resilient coding
  - Error detection
    - Know when and where errors occurs
  - Resynchronization
    - when video streams lose synchronization due to errors
  - Data recovery and error concealment
    - Estimate lost data
    - Minimize estimation errors

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17.2 Error Resilient Coding Methods Compatible with MPEG-2

- Temporal localization
  - Minimizes propagation errors
- Spatial localization
  - Minimizes the effects of errors within picture frames
- Concealment processes
  - Minimizes effects of errors within picture frames

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17.2.1 Temporal Localization

- Stop propagation error with early re-synchronization pictures
  - Cyclic intra-coded pictures
    - Replace damaged P or B frames with I frames
    - High cost in bitrate
  - Cyclic intra-coded slices
    - Intra-frame split into a number of row slices
    - Slices are embedded into a number of P-frames
      - One slice per P-frame
    - This approach leads to “window screen wipe”

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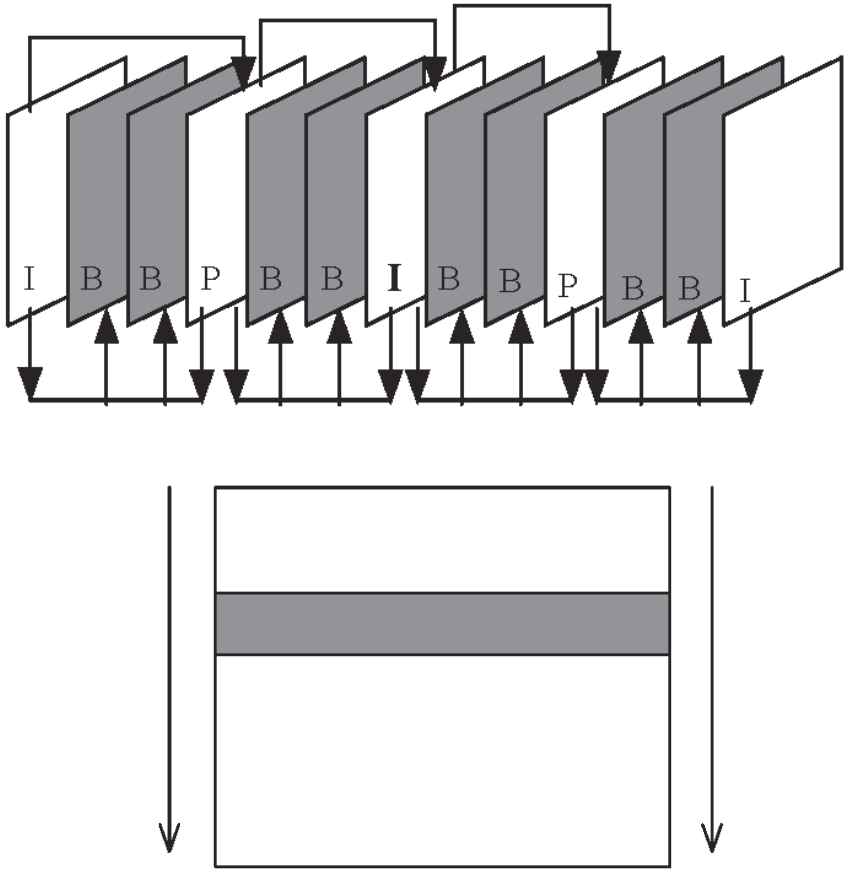
Top: Cyclic intra-coded picture. *Bottom*: Cyclic intra-coded slices



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17.2.2 Spatial Localization

- Re-synchronization for differential coded macroblock (MB)
  - Small slice method
    - Minimize errors due to cell lost by
      - Reducing slice to cell ratio, i.e., having few cells per slice
  - Adaptive slice scheme
    - Slice size changes according to spacing of cells

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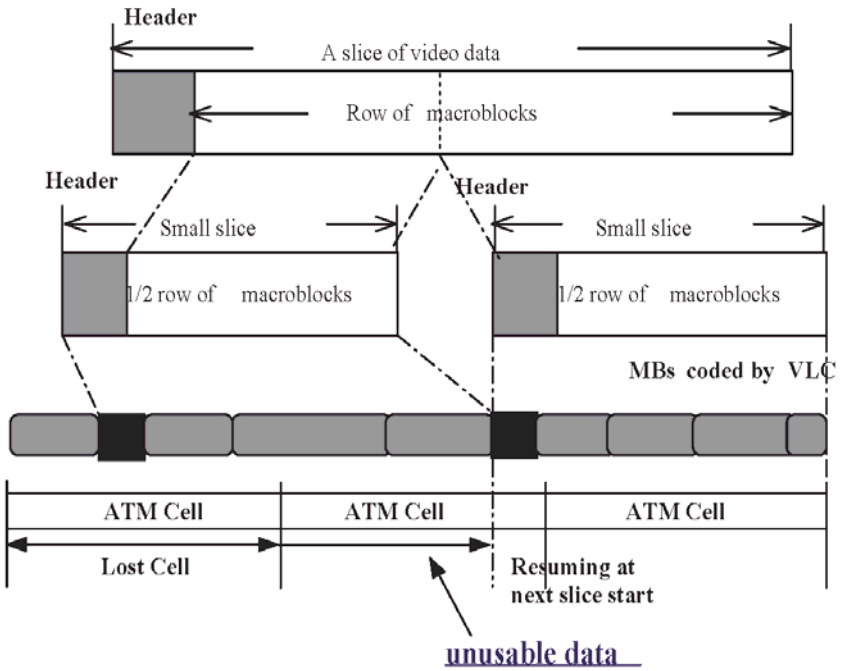
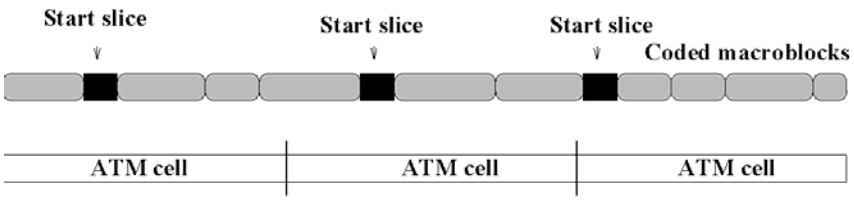
Illustration of small slice (*left*) and adaptive slice (*right*) approaches





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17.2.3 Concealment

- Methods for error concealment
  - Temporal Predictive Concealment
    - Block replacement from previous frame
  - Spatial Interpolation
    - Estimate missing MB with adjacent MBs
  - Motion Compensated Temporal Concealment
    - Motion compensated block replacement

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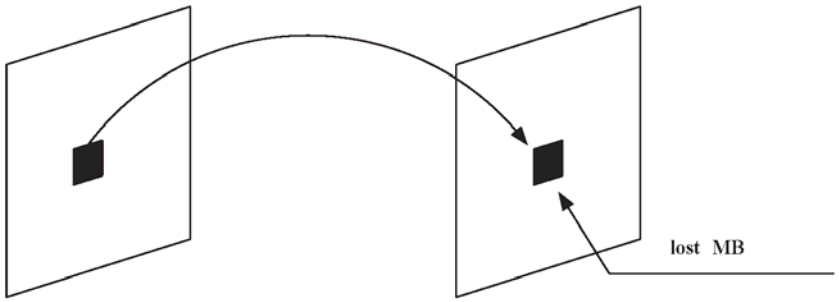
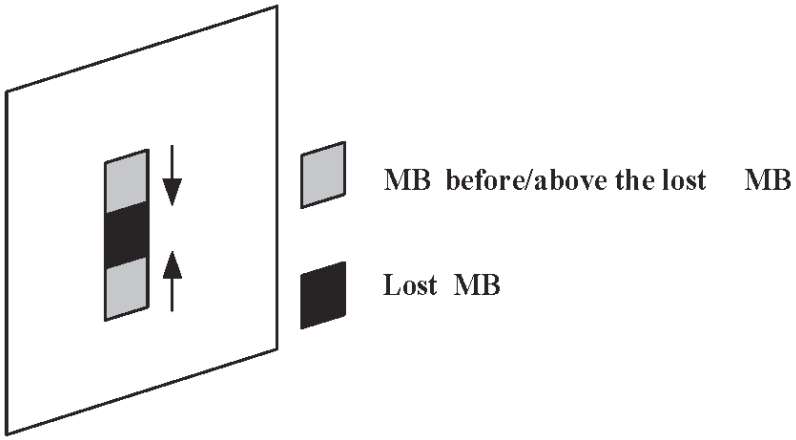
Concealment methods

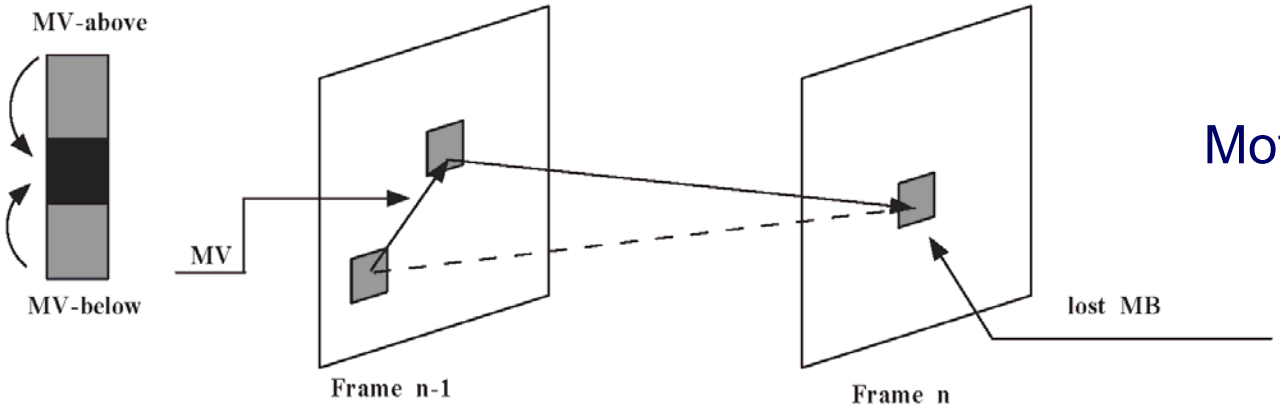
Temporal Predictive



Spatial Interpolation



Motion Compensated Concealment



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Macro-block replacement (*right*) of the *Bus* sequence with cell loss (left)

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Spatial interpolation error concealment (*right*) of the *Flower Garden* sequence with cell loss (left)

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17.2.4 Scalability

- Multiple layers of information
  - Base layer has the most important information
  - Other layers carry additional information
- Applicable for ATM networks
  - Cells loss from congestion can be controlled
    - Network management can decide what cell to drop
- Ineffective for wireless networks
  - Cells loss uncontrollable
    - When cause by signal propagation

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Scalability method

- Data partitioning
  - Split data into layers relative to importance
    - e.g. motion vectors, DC coefficient, AC coefficient
  - May have motion drift
    - When only base layer is available
      - Missing enhancement layers needed for MC
- SNR Scalability
  - Split into multiple quality layers
  - Motion compensation based on all layers
    - Motion drift occurs in the lower layer

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Scalability method

- Spatial Scalability
  - Motion compensation with separate picture store for each layer
    - Resolves the low layer motion drift
- Spatial Scalability without Temporal Prediction
  - Prediction in upper layers derived from base layer
    - Eliminates drift in upper layers

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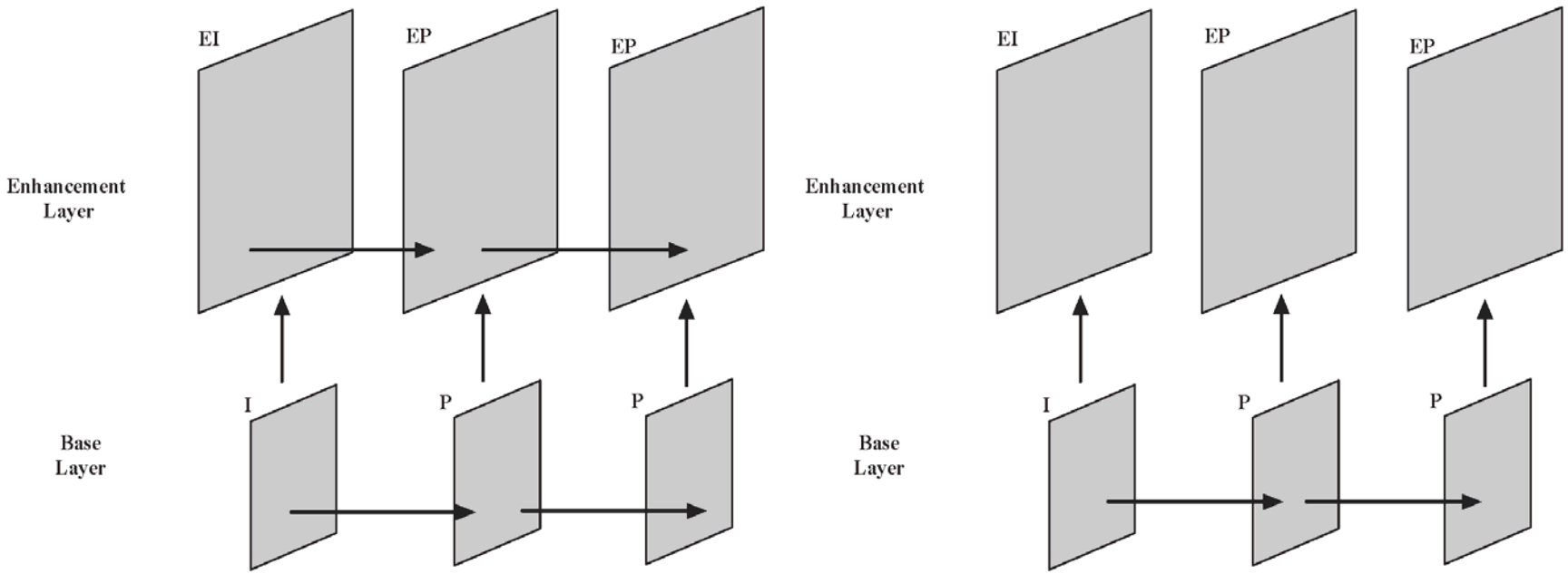
Illustration of spatial scalability with (*left*) and without (right) temporal prediction



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17.3 Methods for Concealment of Cell Loss

- *Boundary Matching Algorithm* (BMA)
  - Replacement block from previous frame is selected based on the best boundary match of current frame
  - 3 boundaries used for matching calculation
    - Top, left and bottom (of the lost block)
  - May employ full search or fast search
    - Fast searches relative to
      - Motion vector (MV) of same MB in previous frame
      - MV of a neighbouring MB
      - Average or median MV of neighbouring MBs

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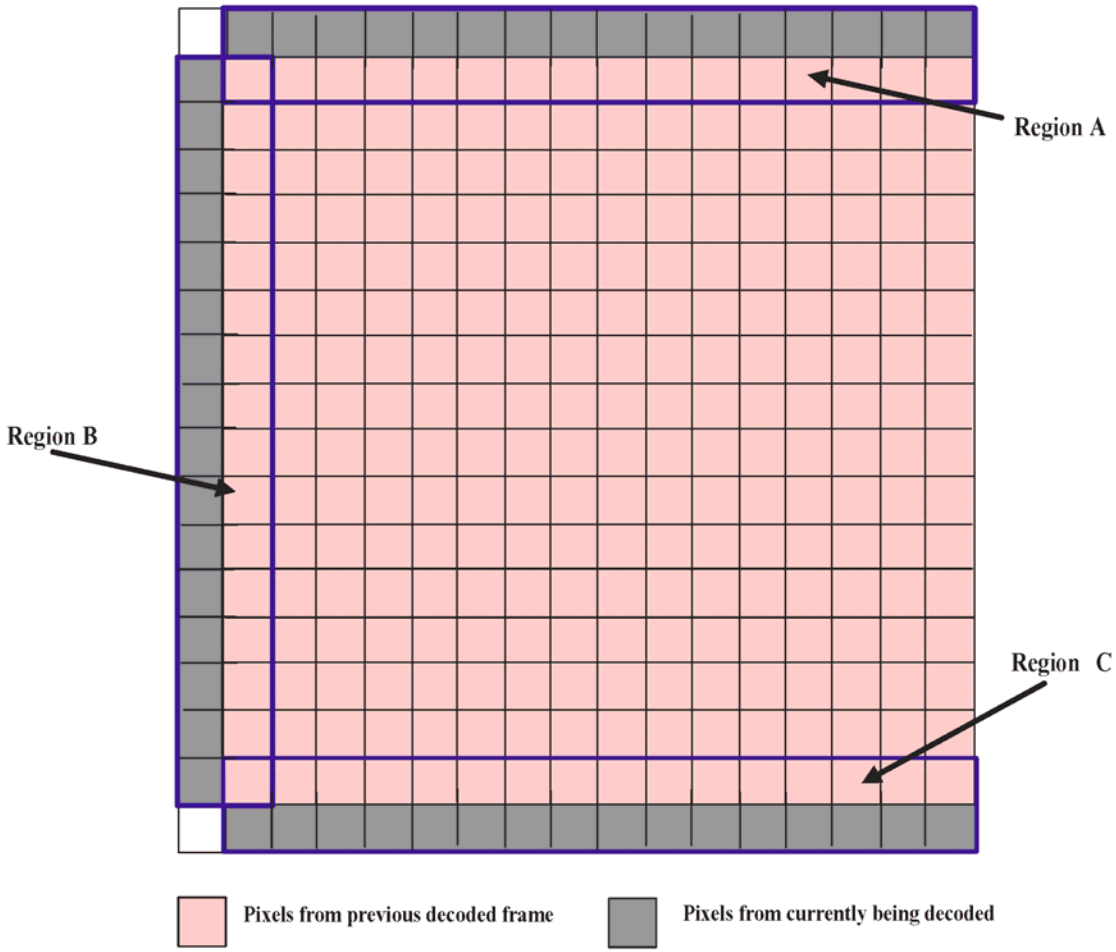
Illustration of boundary matching of BMA



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- *Decoder Motion Vector Estimation* (DMVE)
  - An improvement of the BMA
  - Uses additional boundaries for matching calculation
    - top right and bottom left
  - Performs full search for boundary matching

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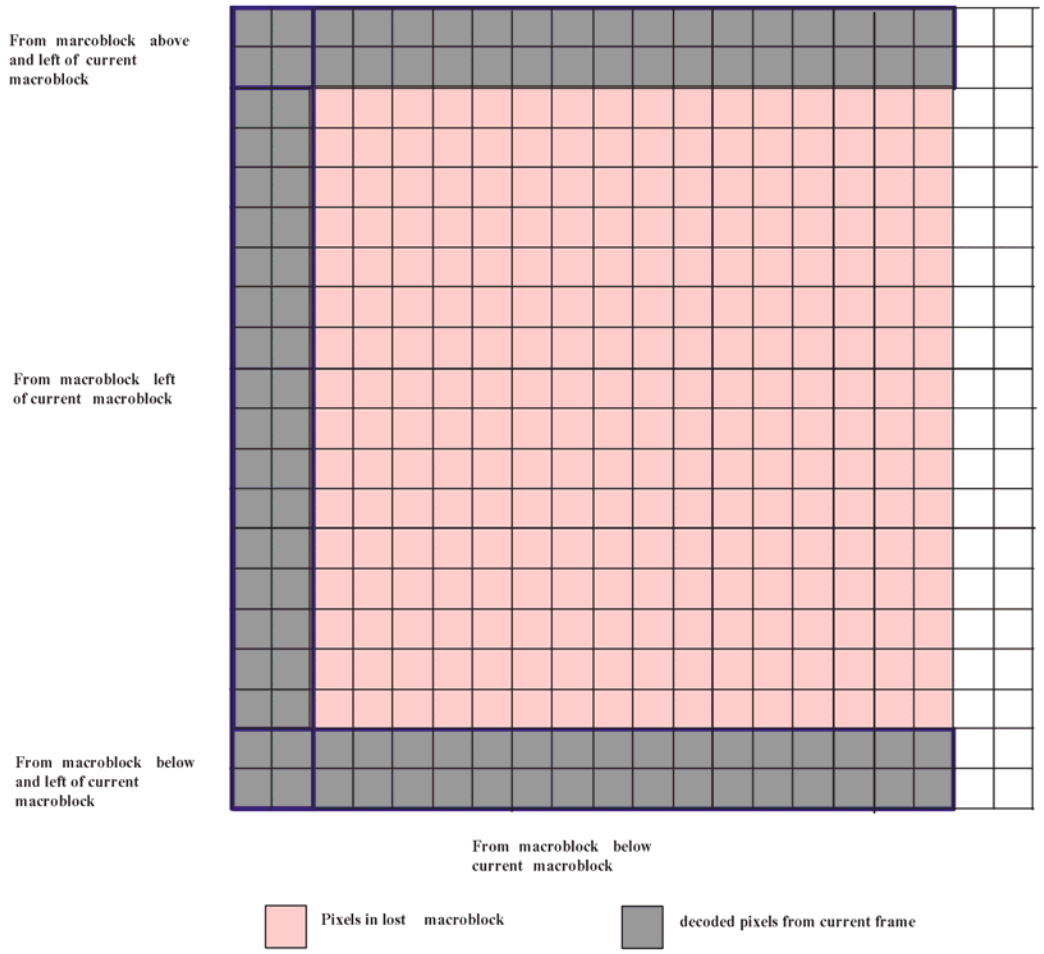
DMVE boundary matching



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- Extension of DMVE
  - Utilize fast search as in BMA
    - *Optional Candidate Search* (OCS)
      - Based on MV of previous frame MB and neighbouring MB
  - Bi-directional frames prediction
    - If loss MB comes from B-frame
  - Two Line Search
    - Use only 2 lines surrounding lost MB for search
      - Reduces computation

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17.4 Experimental Procedure

- 2 MPEG-2 coded sequences @ 4 Mbps used for test
  - *Flower Garden* and *Bus*
- Cell loss probabilities set at 10^{-4}, 10^{-3}, 10^{-2} and 0.5
- 7 error concealment techniques compared

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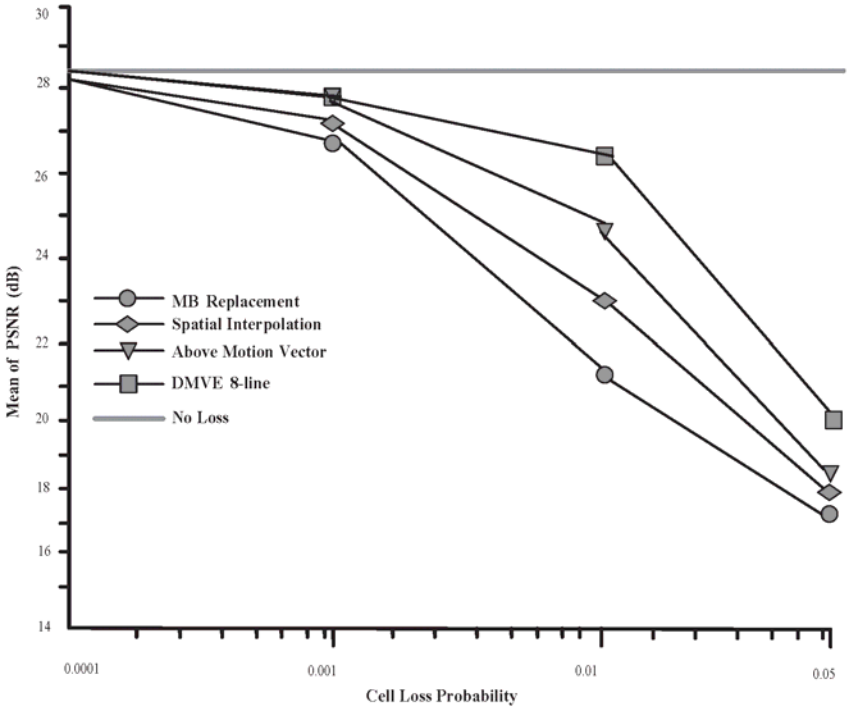
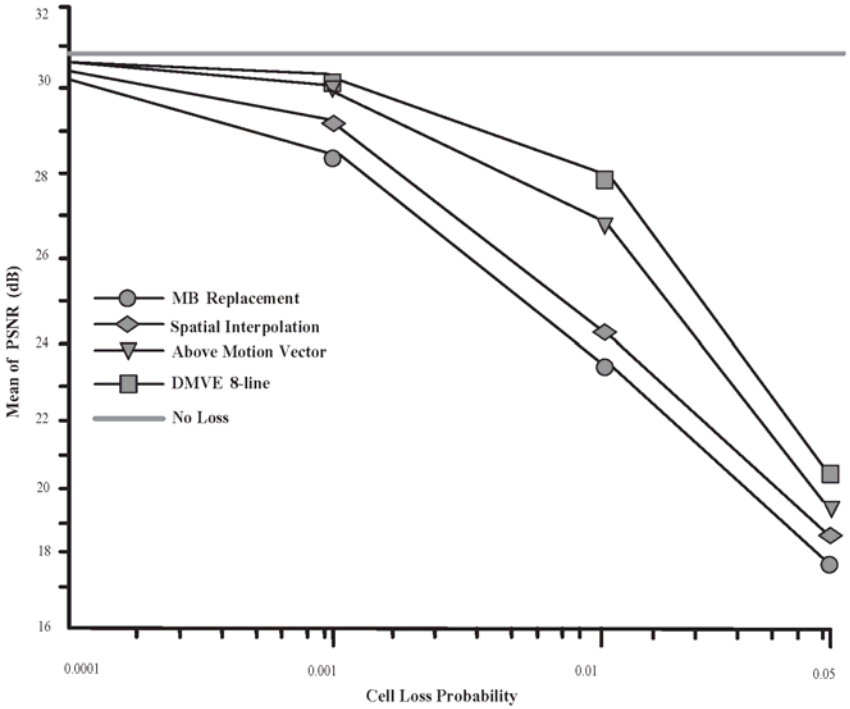
17.5 Experimental Results

PSNR vs Cell Loss



Flower Garden



Bus

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- PSNR Observations
  - Low cell loss (10^{-4})
    - Little difference between various methods
  - Medium cell loss (10^{-3})
    - DMVE and Above Motion Vector noticeably better
  - High cell loss (10^{-2})
    - DMVE clearly the superior method
      - 6-7dB better than MB replacement
  - Very high cell loss (0.5)
    - Performance dropped substantially for all

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Experimental results with cell loss of 10^{-4} (*left*) and 10^{-3} (*right*)

Measurements for *Flower Garden* sequence					
Mean of total damaged MBs = 92, PSNR with no loss = 28.38 dB					
Technique	Single Slice Header per Row				
	Mean	Max	Min	Std. Dev	CPU Time
MB Replacement	28.16	28.30	27.88	0.13	1.0
Above Motion Vector	28.34	28.36	28.31	0.01	1.0
BMA	28.32	28.35	28.26	0.03	1.0
DMVE-OCS (8 line)	28.34	28.36	28.32	0.01	1.0
DMVE (2 line)	28.34	28.36	28.31	0.01	1.0
DMVE (8 line)	28.34	28.36	28.32	0.01	1.0
DMVE-Bi-Dir (8 line)	28.35	28.36	28.32	0.01	1.0

Measurements for Bus sequence					
Mean of total damaged MBs = 106, PSNR with no loss = 30.71 dB					
Technique	Single Slice Header per Row				
	Mean	Max	Min	Std. Dev	CPU Time
MB Replacement	30.49	30.70	29.93	0.22	1.0
Above Motion Vector	30.67	30.71	30.57	0.04	1.0
BMA	30.64	30.70	30.51	0.06	1.0
DMVE-OCS (8 line)	30.68	30.71	30.60	0.03	1.0
DMVE (2 line)	30.67	30.70	30.57	0.04	1.0
DMVE (8 line)	30.68	30.71	30.61	0.03	1.0
DMVE-Bi-Dir (8 line)	30.69	30.71	30.61	0.03	1.0

Measurements for *Flower Garden* sequence					
Mean of total damaged MBs = 864, PSNR with no loss = 28.38 dB					
Technique	Single Slice Header per Row				
	Mean	Max	Min	Std. Dev	CPU Time
MB Replacement	26.90	27.59	26.25	0.39	1.0
Above Motion Vector	28.11	28.26	27.77	0.13	1.0
BMA	28.03	28.21	27.69	0.13	1.0
DMVE-OCS (8 line)	28.13	28.25	27.96	0.09	1.0
DMVE (2 line)	28.16	28.26	27.91	0.10	1.0
DMVE (8 line)	28.17	28.26	27.98	0.08	1.0
DMVE-Bi-Dir (8 line)	28.18	28.27	27.99	0.07	1.0

Measurements for Bus sequence					
Mean of total damaged MBs = 865, PSNR with no loss = 30.71 dB					
Technique	Single Slice Header per Row				
	Mean	Max	Min	Std. Dev	CPU Time
MB Replacement	29.24	29.72	28.80	0.32	1.0
Above Motion Vector	30.37	30.52	30.18	0.11	1.0
BMA	30.21	30.43	30.00	0.15	1.0
DMVE-OCS (8 line)	30.42	30.55	30.25	0.10	1.0
DMVE (2 line)	30.43	30.54	30.15	0.11	1.0
DMVE (8 line)	30.44	30.55	30.25	0.09	1.0
DMVE-Bi-Dir (8 line)	30.46	30.56	30.26	0.09	1.0

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Experimental results with cell loss of 10^{-2} (*left*) and 0.5 (*right*)

Measurements for *Flower Garden* sequence					
Mean of total damaged MBs = 864, PSNR with no loss = 28.38 dB					
Technique	Single Slice Header per Row				
	Mean	Max	Min	Std. Dev	CPU Time
MB Replacement	26.90	27.59	26.25	0.39	1.0
Above Motion Vector	28.11	28.26	27.77	0.13	1.0
BMA	28.03	28.21	27.69	0.13	1.0
DMVE-OCS (8 line)	28.13	28.25	27.96	0.09	1.0
DMVE (2 line)	28.16	28.26	27.91	0.10	1.0
DMVE (8 line)	28.17	28.26	27.98	0.08	1.0
DMVE-Bi-Dir (8 line)	28.18	28.27	27.99	0.07	1.0

Measurements for Bus sequence					
Mean of total damaged MBs = 865, PSNR with no loss = 30.71 dB					
Technique	Single Slice Header per Row				
	Mean	Max	Min	Std. Dev	CPU Time
MB Replacement	29.24	29.72	28.80	0.32	1.0
Above Motion Vector	30.37	30.52	30.18	0.11	1.0
BMA	30.21	30.43	30.00	0.15	1.0
DMVE-OCS (8 line)	30.42	30.55	30.25	0.10	1.0
DMVE (2 line)	30.43	30.54	30.15	0.11	1.0
DMVE (8 line)	30.44	30.55	30.25	0.09	1.0
DMVE-Bi-Dir (8 line)	30.46	30.56	30.26	0.09	1.0

Measurements for *Flower Garden* Sequence					
Mean of total damaged MBs = 36374, PSNR with no loss = 28.38 dB					
Technique	Single Slice Header per Row				
	Mean	Max	Min	Std. Dev	CPU Time
MB Replacement	17.45	17.55	17.36	0.05	1.0
Above Motion Vector	18.59	18.81	18.46	0.11	1.0
BMA	18.84	18.97	18.61	0.09	1.5
DMVE-OCS (8 line)	19.23	19.40	19.04	0.10	1.6
DMVE (2 line)	19.68	19.95	19.38	0.16	3.9
DMVE (8 line)	20.13	20.55	19.71	0.27	14.1
DMVE-Bi-Dir (8 line)	20.21	20.60	19.84	0.22	17.8

Measurements for Bus Sequence					
Mean of total damaged MBs = 38100, PSNR with no loss = 30.71 dB					
Technique	Single Slice Header per Row				
	Mean	Max	Min	Std. Dev	CPU Time
MB Replacement	17.75	17.95	17.59	0.11	1.0
Above Motion Vector	19.45	19.61	19.28	0.12	1.0
BMA	19.59	19.89	19.36	0.15	1.6
DMVE-OCS (8 line)	20.12	20.53	19.70	0.24	1.7
DMVE (2 line)	20.04	20.73	19.32	0.39	4.3
DMVE (8 line)	20.30	20.84	19.72	0.34	15.0
DMVE-Bi-Dir (8 line)	20.38	20.89	19.75	0.40	18.8

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17.6 Conclusions

- Error resilient coding
  - Important for combating cell loss in networks
  - Several approaches
    - Spatial localization, MB resynchronization, concealment
  - Error concealment method
    - DVME demonstrates excellent performance at various cell loss probabilities
      - Further improvements if this method is combined with spatial localization and resynchronization methods

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Ad-96	Ad-hic group on core experiments on error resilience aspect in MPEG 4 video. Description of Error Resilient Core Experiments. *ISO/IEC JTC1/SC29/WG11 MPEG-96*, Aug. 1996
ISO93	ISO/IEC JTC1/SC29/ WG11. MPEG 2 Test Model 4. *ISO/IEC*, 1993
ISO95	ISO/IEC JTC1/SC29/ WG11. Generic coding of moving pictures and associated audio information: Video. *ISO/IEC International Standard 13818-2*, 1995
J. 97	J. Zhang, M.R. Frater, J.F. Arnold and T.M. Percival. MPEG-2 Video Service for Wireless ATM Networks. *IEEE Journal on Selected Areas in Communications*, 15(1):119-128, Jan. 1997
J. 99	J. Zhang. *Error Resilience for Video Coding Services over Packer-based Networks*. Ph.D. thesis, University of New South Wales, 1999
M. 93a	M.. Ghanbari. Standard codecs: Image Compression to Advanced Video Coding. *IEE UK*, 1993
M. 93b	M. Ghanbari and V. Seferidis. Cell-loss concealment in ATM Video Codecs, *IEEE Trans. on Circuits and Systems for Video Technology*, 3:238-248, 1993

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M. 96	M.D. Prycker. *Asynchronous Transfer Mode Solution for Broadband ISDN*. Upper Saddle River, NJ: Prentice-Hall, 3rd ed., 1996
R. 96	R. Aravind, M.R. Civanlar and A.R Reibman. Packet Loss Resilience of MPEG-2 Scalable Video Coding Algorithms. *IEEE Trans. on Circuits & Systems for Video Technology*, 6:426-435, Oct. 1996
Rec90	Recommendations and Report of the CCIR Recommendation of 601. Encoding Parameters of Digital Television of Studios: Broadcasting Service (television) Rec. 601-2. *CCIR*, 1990
W. 93	W.M. Lam, A.R. Reibman and B. Liu. Recovery of lost or erroneously received motion vectors. *Proc. ICASSP*, 5:417-420, 1993

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18. Critical Issues and Challenges

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Chapter 18 Outline

18.1 Picture Coding Structures

18.2 Vision Modelling Issues

18.3 Spatio-Temporal Masking in Video Coding

18.4 Picture Quality Assessment

18.5 Challenges in Perceptual Coder Design

18.6 Codec System Design Optimization

18.7 Summary

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18.1 Picture Coding Structures

- Picture coding structures
  - Not just a mathematical framework for reducing statistical redundancies
  - Need to consider human vision in the coding framework
    - To reduce visual redundancies
    - and help push the compression boundary further

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- Coding systems often driven by applications
  - In turn driven by some practical limitations
    - Bitrate constrain is often the driving point in the development efforts for practical coding systems
    - Insufficient consideration given to picture quality in the development of coding systems
      - e.g. limited progress in addressing certain distortions in high definition digital TV
        - » Granular noise
        - » Stationary area temporal fluctuation
        - » Jerky motion

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- Four directions for picture coding
  - Push boundaries of existing waveform and entropy coding techniques
  - Incorporating various HVS aspects into waveform coding techniques
  - Pursuing mathematical alternatives for waveform coding
  - Derive new coding framework and structures propelled by vision science and research

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18.1.1 Performance Criteria

- Framework of coding systems
  - Determined by a set of performance criteria
  - Different criteria for different components of a coder, e.g.
    - Selection of transform is dependent on decorrelation and energy packing efficiency
    - Coding performance has traditionally been measured by MSE/PSNR for a given coding rate
  - Criterions are tailored towards reduction of statistical errors or redundancies

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- Consequently, coding frameworks are determined
  - According to their mathematical properties
  - Performance in statistical redundancy reduction
- Choices of coding framework
  - Affects compression performance
  - Exhibit specific type of distortions
    - e.g. Blocking for DCT coders or ringing/edge rippling for DWT coders

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- An assumption for lossy coding
  - Primarily removes statistical redundancy
  - Leads to a coding structure that reflects assumption
  - Strict definition of statistical redundancy
    - The removal of redundant data not the removal of information
  - Lossy coding removes both redundant data and information
- So assumption not longer holds!

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- Paradigm shift may be necessary
  - From pure statistical model to a combination of statistical and psychovisual models
  - Such an approach could address more effectively issues concerning
    - Various types of picture impairments
    - Overall picture quality

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18.1.2 Complete vs. Over-Complete Transform

- Complete transform (common DWT)
  - Perfect reconstruction (reversible)
  - Good energy packing
  - Short filter support (FIR implementation)
  - Low complexity
  - Critically sample
    - Number of inputs = number of outputs
  - Lacks shift invariance
  - Limited directional selectivity

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- Over-complete transform (CWT)
  - Good orientation selectivity
    - Relative to filter kernel
  - Over sampled
    - Number of Outputs > number of inputs
  - Shift invariant
  - More complex than complete transform

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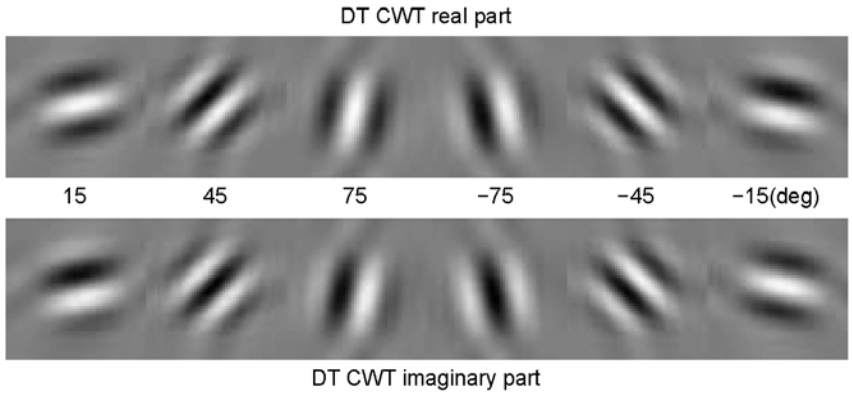
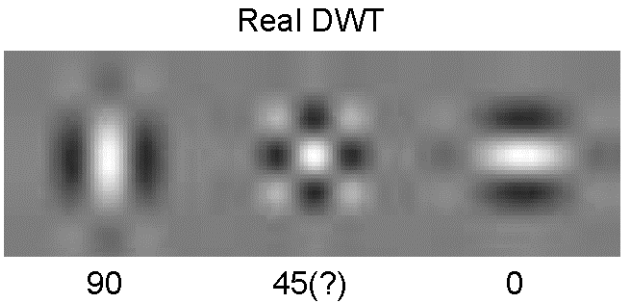
Basis function CWT and 2-D real DWT



2-D Q-shift Complex Wavelet Transform (CWT)



2-D real Discrete Wavelet Transform (DWT)

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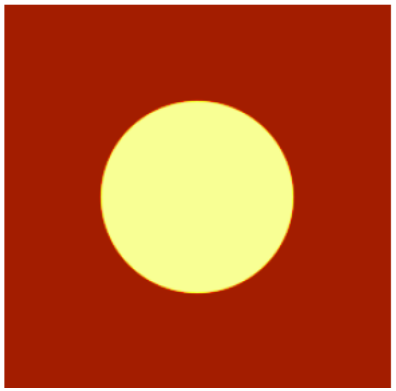
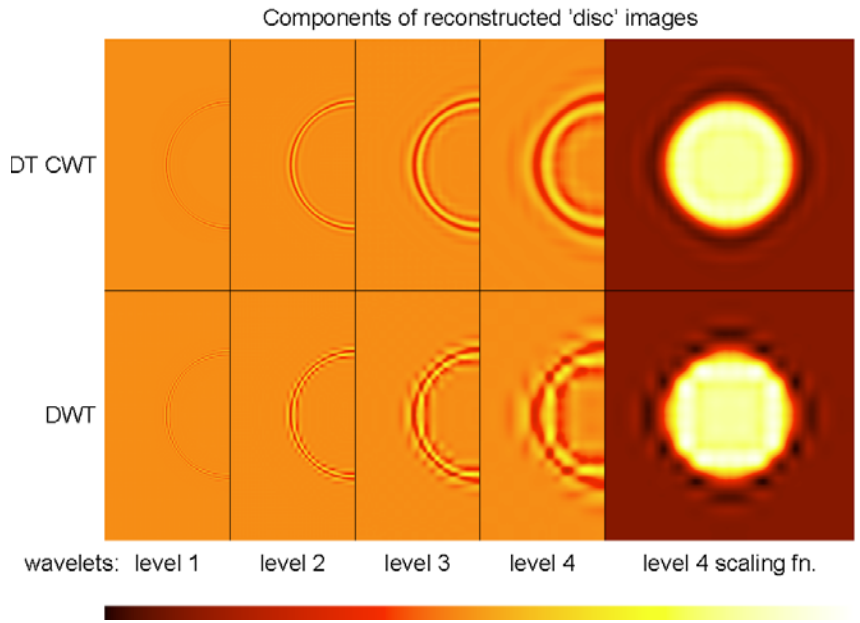
Illustration of wavelet and scaling functions component for CWT and DWT. Aliasing is visible in the DWT domain

Input (256 x 256)



Disc Image



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- Aliasing in DWT domain
  - Due to shift invariance
    - Resulting from decimation of DWT coefficients
- In compression terms
  - CWT has demonstrated performance gains over DWT
    - ≈ 1dB PSNR gain and better visual quality
- What is the criteria for selecting coder transform?

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DWT (*left*) and CWT (*right*) coded images

0.1994 bpp (PSNR: 33.47 dB)

0.1992 bpp (PSNR: 34.12 dB)

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18.1.3 Decisions Decisions

- Each approach has it strengths and weaknesses
- How to quantify overall strengths over weaknesses?
  - Possibly joint performance criteria
    - Multiple criterions
    - Evaluate coding components individually and jointly
  - New criterions? Perhaps HVS based?

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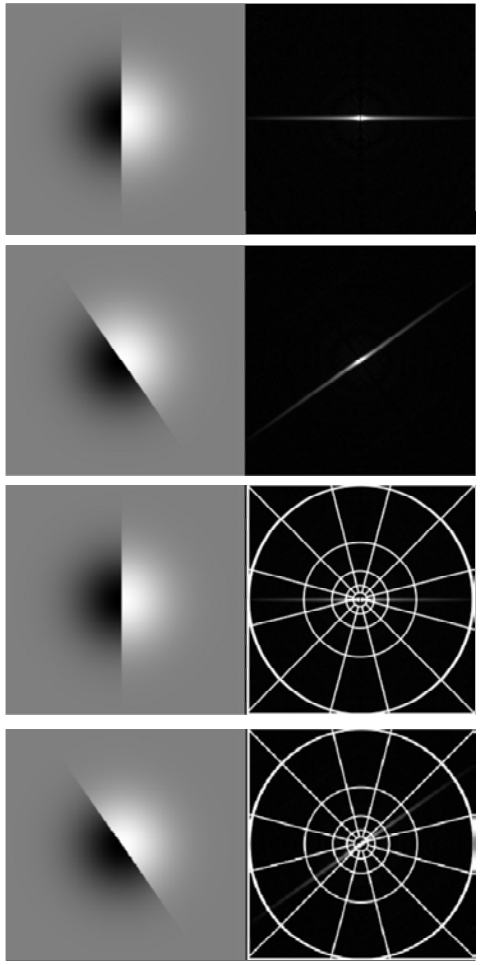
Example of 2-D aliasing and blurring tradeoffs

Original vertical disembodied edge

Original edge at 25° from vertical axis

Original vertical edge

Original edge at 45° from vertical axis



2-D Fourier spectrum of vertical edge

2-D Fourier spectrum of 25° edge

2-D Fourier spectrum of vertical edge showing Cortex channels

2-D Fourier spectrum of 25° edge showing Cortex channels

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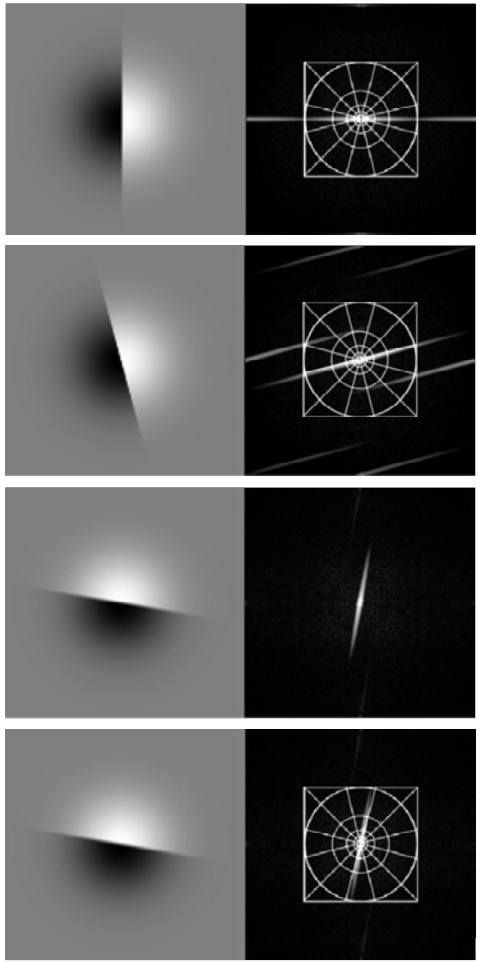
Example of 2-D aliasing and blurring tradeoffs

Sub-sampled vertical edge without anti-aliasing filtering



2-D Fourier spectrum edge showing Cortex channels

Sub-sampled edge at non-orthogonal orientation without anti-aliasing filter

2-D Fourier spectrum of edge

2-D Fourier spectrum edge showing Cortex channels

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18.2 Vision Modelling Issues

- Limited understanding of overall human vision
  - Need to build up knowledge to model more complex higher level vision
- Better modelling of supra-threshold vision
  - Since considerable number of coding applications operate above the threshold level
- Optimizing vision models for applications
  - Devise more robust/comprehensive methods?

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18.3 Spatio-Temporal Masking in Video Coding

- Transient and sustain channels in human vision
  - Segregates temporal information into low pass (sustain) and band pass (transient) bands
- Current standards have yet to employ temporal masking
  - To address temporal artifacts
    - e.g. Temporal granular noise and fluctuation

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18.4 Picture Quality Assessment

- Picture quality metrics design approaches
  - MSE and PSNR insufficient for qualify visible picture impairments and picture quality
  - HVS based metric more suitable
    - But has a number of challenges
      - Computation and model complexity issue
      - Model accuracy
      - Optimization of models
      - Initial VQEG study indicated little gain for HVS based metric over PSNR

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- Alternative assessment methods and issues
  - Measure impairments and quality
    - Can it measure enhancement as well?
  - FR, NR and RR objective metrics
    - Application specific
      - NR and RR have restricted range of applications
  - Subjective assessment
    - Impractical for many applications

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- More challenges in picture quality assessment
  - Improvement needed for current picture assessment techniques to meet new applications, e.g., 3-D video/TV
  - Factors for consideration in assessment
    - e.g. picture accompanied by audio

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18.5 Challenges in Perceptual Coder Design

- Pre- and post-processing
  - For removal of distortions
  - Enhancement of image details and overall visual quality
- Error detection and concealment
  - Embedded into coders for improve resilience from network induced noise

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- Incorporating HVS into existing coders
  - Pre- and post-filtering
  - Quantization
  - Distortion metric for R-D optimized coders
    - EBCOT with self-masking function (Taubman)
    - PLC: EBCOT with PIDM
- Qualifying the lower bound for perceptually lossless picture coding
  - Perceptually lossless coding

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18.6 Codec System Design Optimization

- Considerations for future generation picture coding framework
  - Pre- and/or post-filtering
  - Overall encoding and decoding system should be optimization
    - To better address existing coding issues
    - To improve compression performance and picture quality

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18.7 Summary

- Goal of picture compression
  - Rate-Distortion minimization
    - Equivalently Rate-Quality optimization
- Most picture coders are rate driven
- Quality driven coders are rarities
- However, this may can if the lower bound for perceptually lossless coding is determined

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Lena image coded at 0.125 bpp

Original

JPEG2000
MSE

JPEG2000
CVIS
(self-masking)

JPEG2000
PIDM

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ABMD92	M. Antonini, M. Barlaud, P. Mathieu and I. Daubechies. Image Coding Using Wavelet Transform. *IEEE Trans. on Image Processing*, 1(2):205-220, April 1992
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