Institut
Mines-Telecom

Introduction to compression

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MN907 - Multimedia Compression

Outline

The human visual system

The sound perception

Image and video representation

Compression principles

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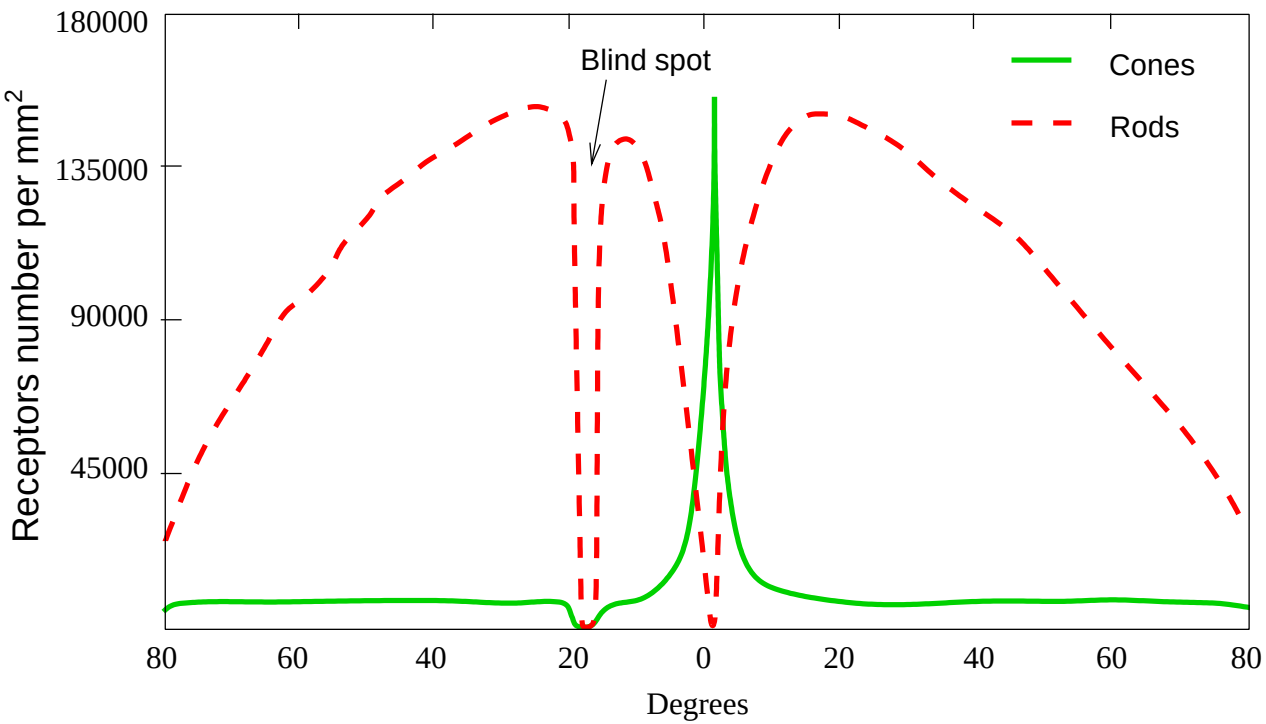
Compression principles

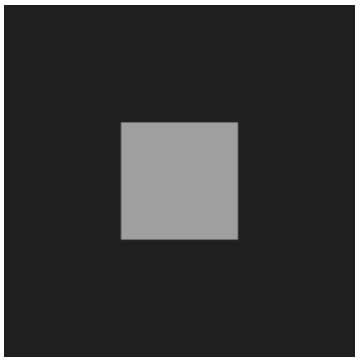
The eye

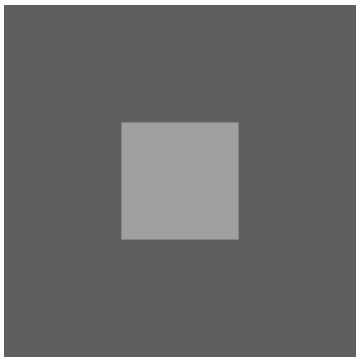
- Light is transformed into neural implusions by the retinal receptors
  - **Cones** (6÷7 millions, center of the retina) : very sensitive to cololrs, good resolutionm need high illumination
  - **Rods** (75÷150 millions) : sensitive to light intensity low resolution, very sensitive in low illumination

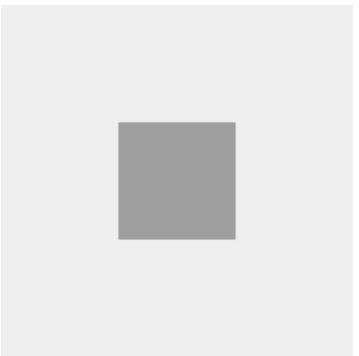


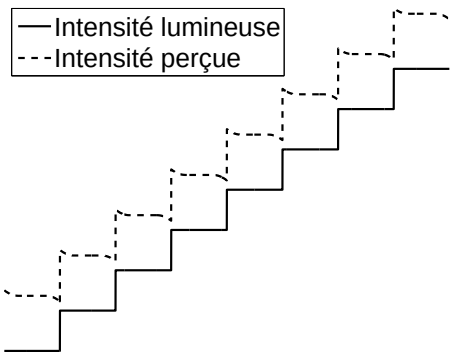
Light perception

- Perceived intensity : logarithmic function of intensity
- Intensity dynamic range: $\approx 10^{10}$ (100dB)
- The humaun visual system (HVS) cannot operate into such a large range at once
- Global lighting changesm reduced range dynamics
- Perceived light intensity:it is not just a function of light intensity

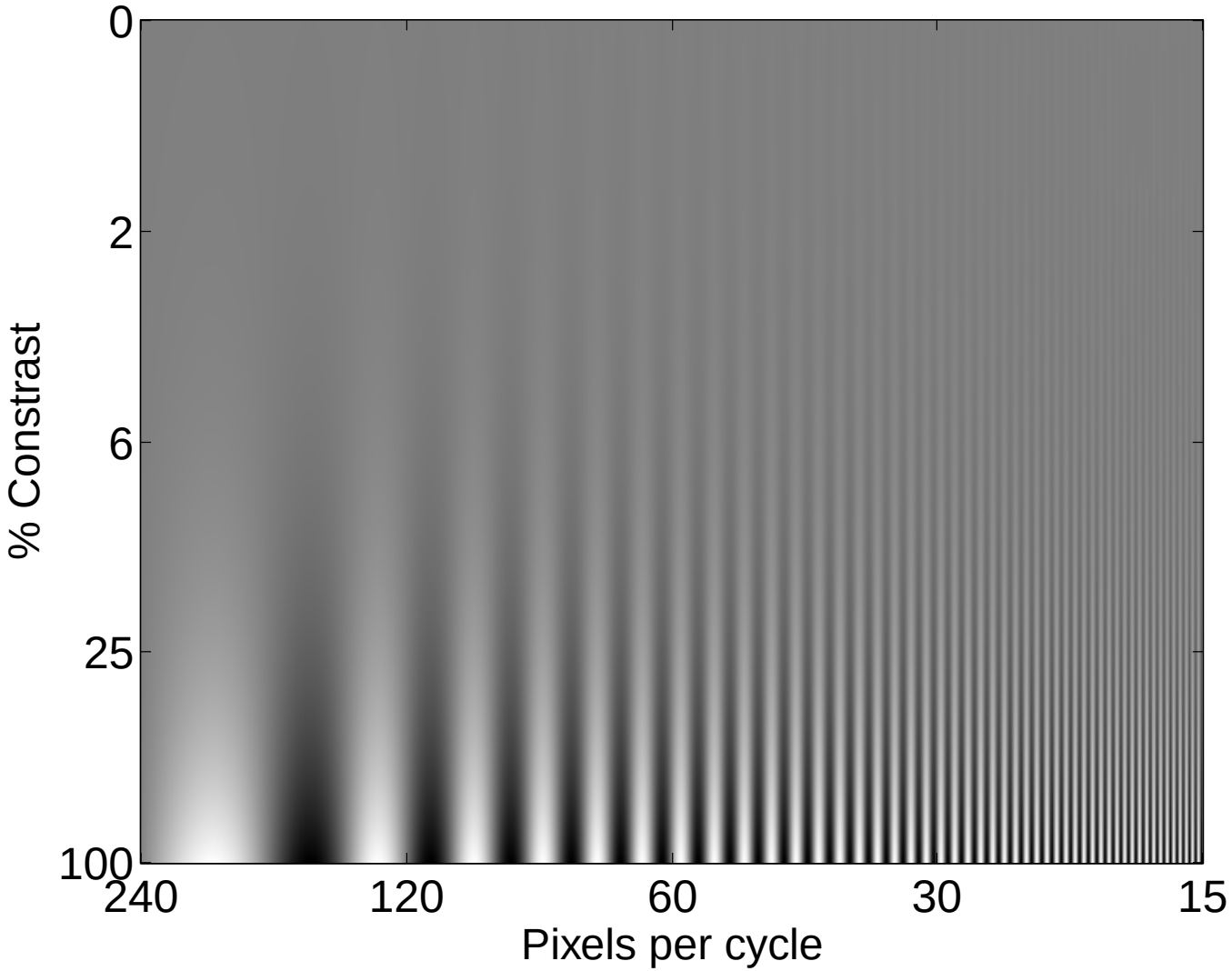








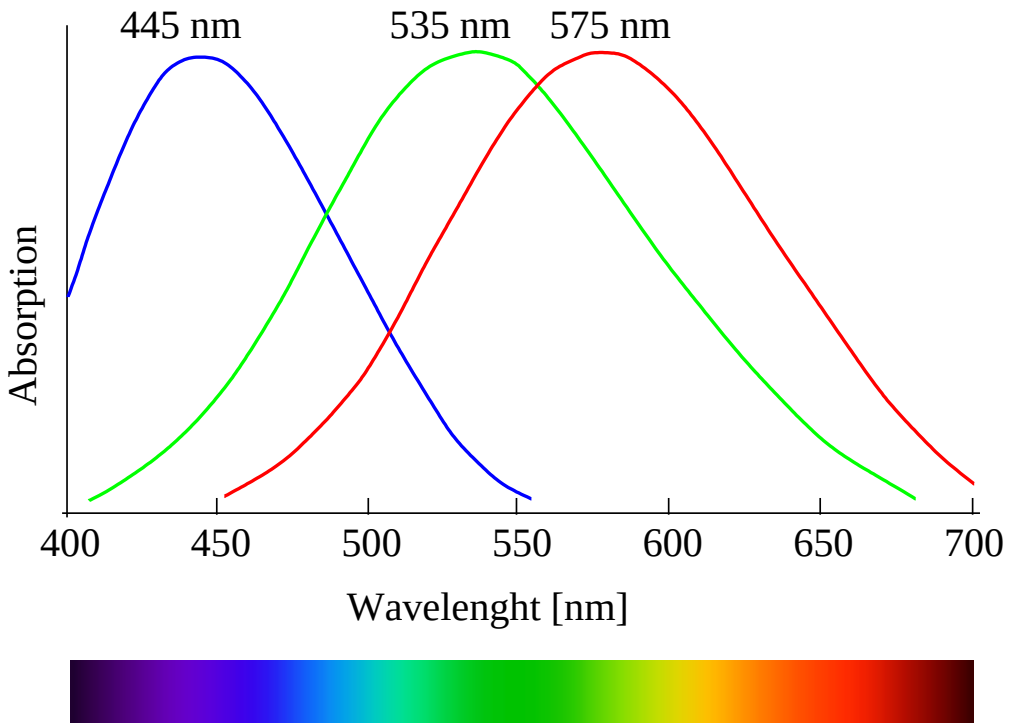
Contrast sensitivity function (CSF)



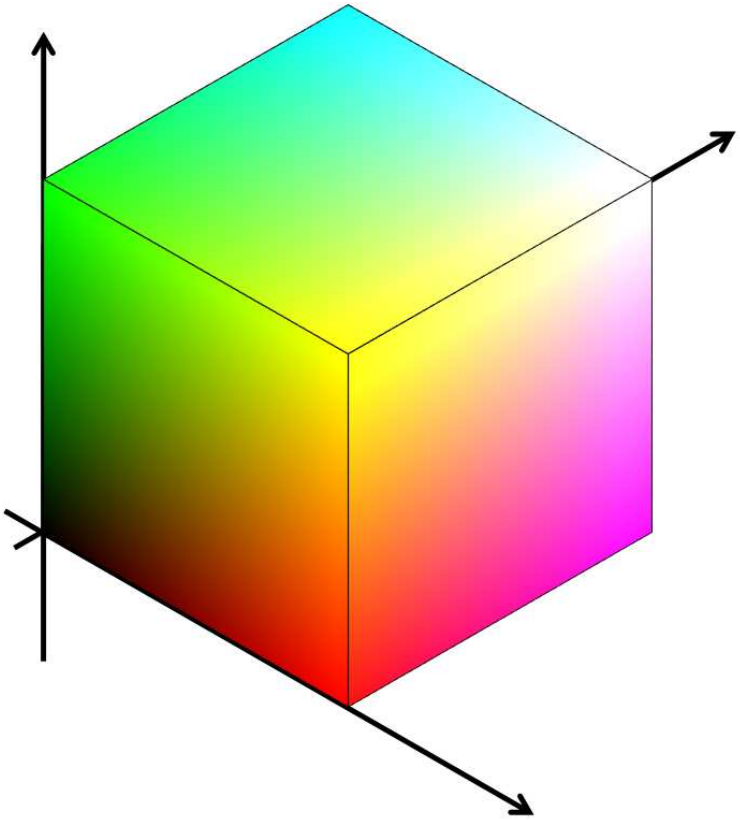
- Maximum at 2-5 cycles per degree

Color Perception

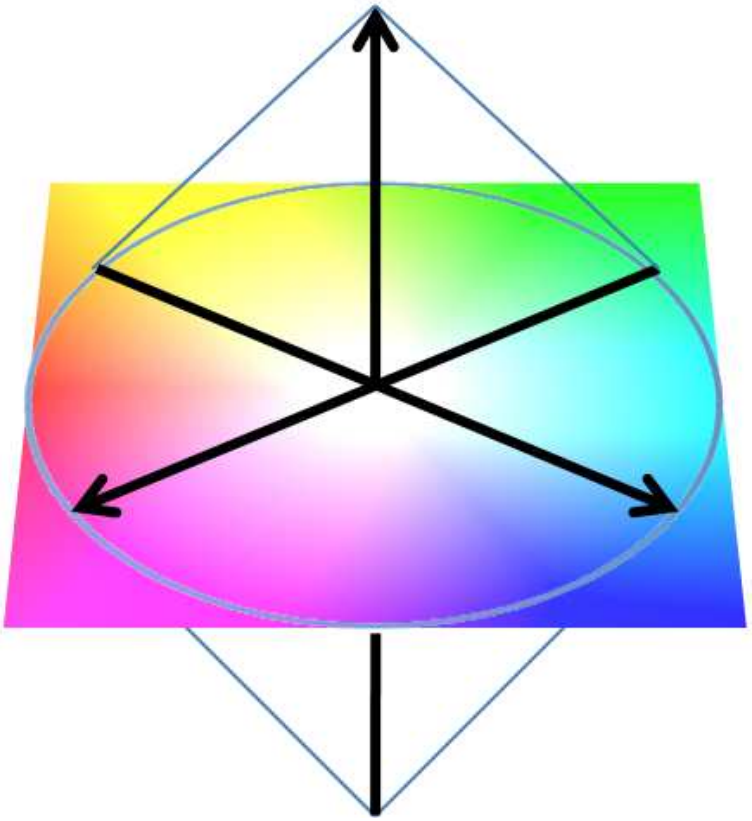
- Visible light spectrum: 400÷700 nm
- Cones sensitivity:
  - 65% sensitive to red
  - 33% sensitive to green
  - 2% sensitive to blue (but very sensitive)
- Color sensation: corresponds to the *tristimulus*
- Color is obtained as a combination of the three primary colors



Color spaces



RGB



HSV

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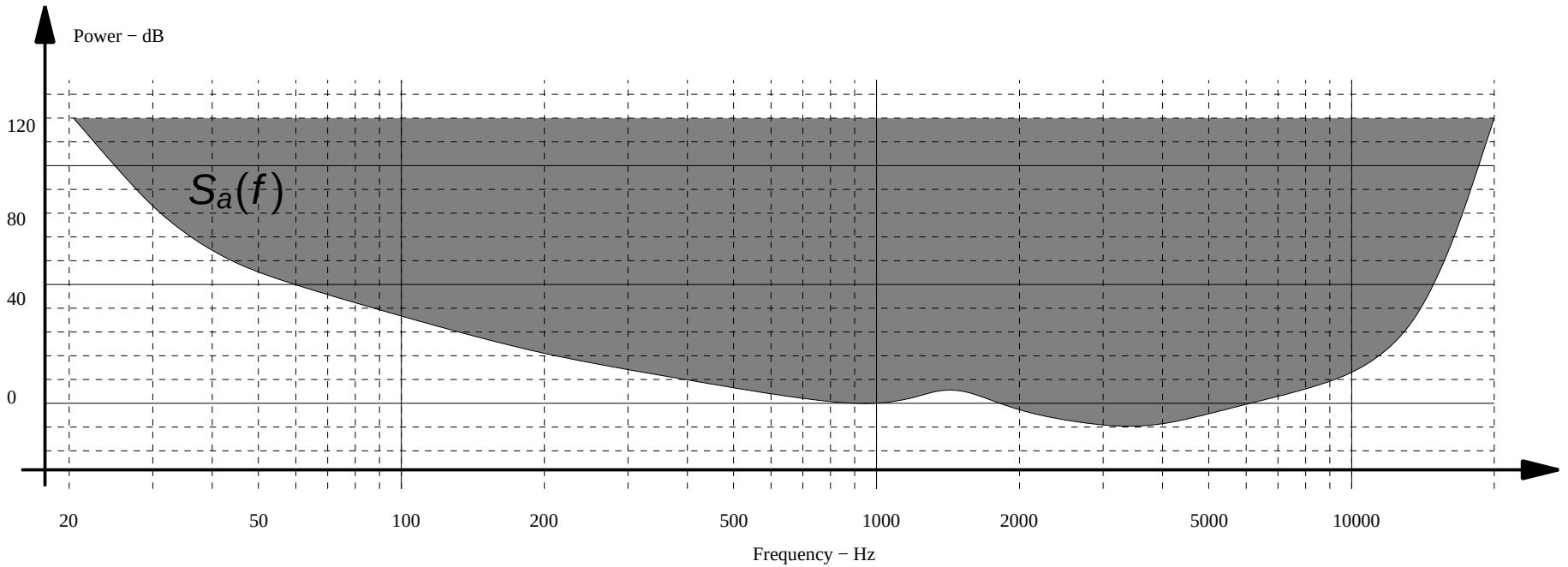
Pure tone perception

- Pure tone : $x(t) = a\sin(2\pi f_1 t)$ sinusoid with power $\sigma^2 = \frac{a^2}{2}$
- This sound excites several nerves (power spreading)
- Model : filterbank with M filters
  - The k-th filter corresponds to the k-th nervous fiber
  - Frequency response of the k-th filter: $H_k(f) = A_k(f)\exp^{j\phi_k(f)}$
  - Respons to the f_1 sinusoid:

$$y_k(t) = aA_k(f_1)\sin\left[2\pi f_1 t + \phi_k(f_1)\right]$$

- The power ratio is called spreading function: $S_E(k) = A_k^2(f_1)$

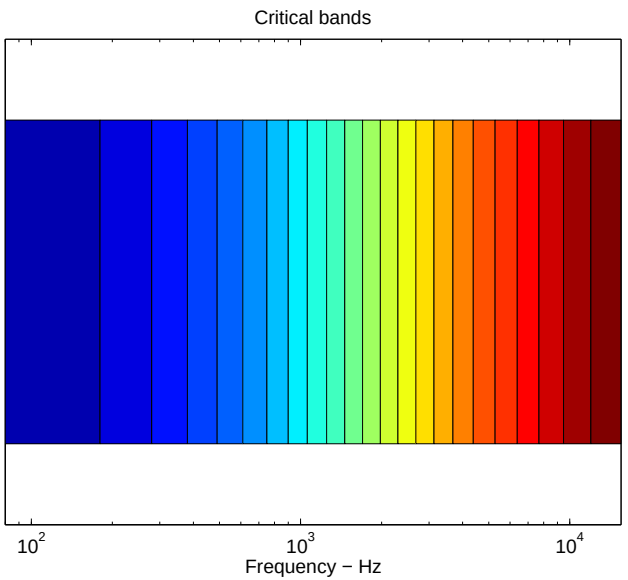
Hearing threshold



- The minimum power minimale for a tone at frequency f to be audible is $S_a(f)$
- $S_a(f)$ is a function of f and has a minimum between 1 and 4kHz (speech)

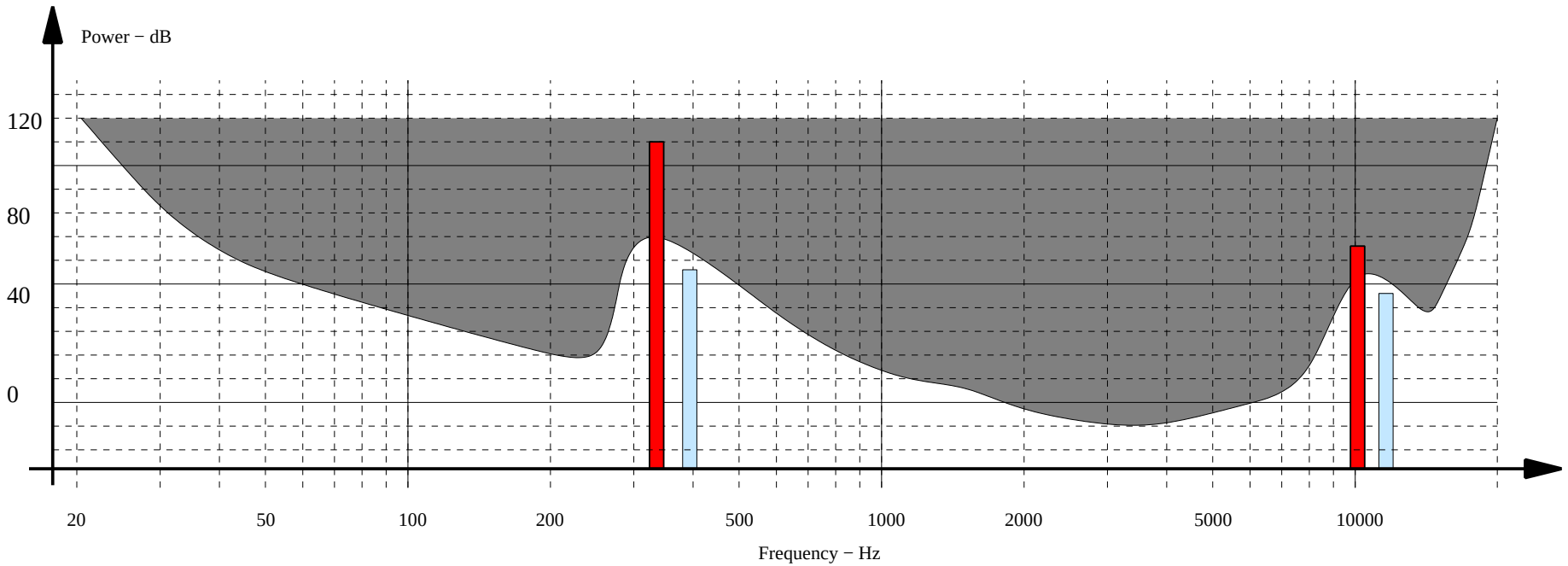
Critical band (CB)

- A pure tone at frequency f_1 must have a minimum power $\sigma_1^2 > S_a(f_1)$ to be heared
- For N sinusoids *near* f_1 we need only $\sum_i \sigma_i^2 > S_a(f_1)$
- Sinusoids are *near* if they are in the *critical band*
- CB amplitude is a function of f_1



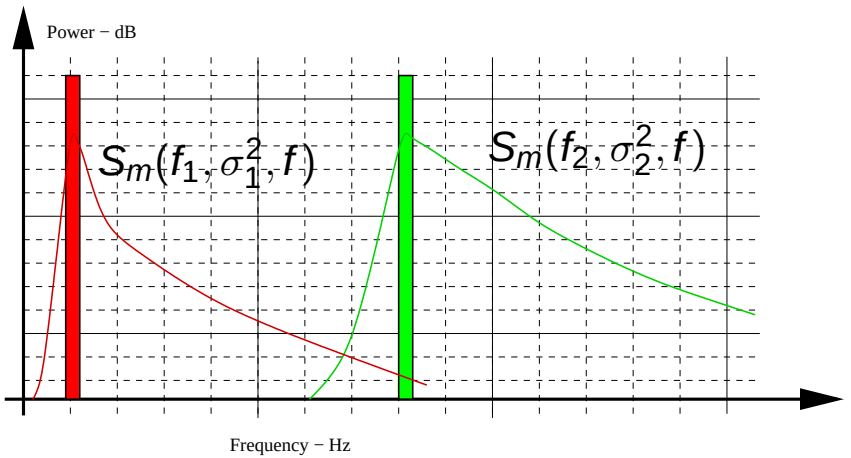
Masking curves

Frequency masking



- We define $S_m(f_0, \sigma^2, f)$ the minumum power of a pure tone at frequency f to be audible when a pure sound at frequency f_0 with power σ^2 is played, with $\sigma^2 > S_a(f_0)$
- Similar masking curve is observed for narrowband sounds

Frquency masking functions $S_m(f_0, \sigma^2, f)$

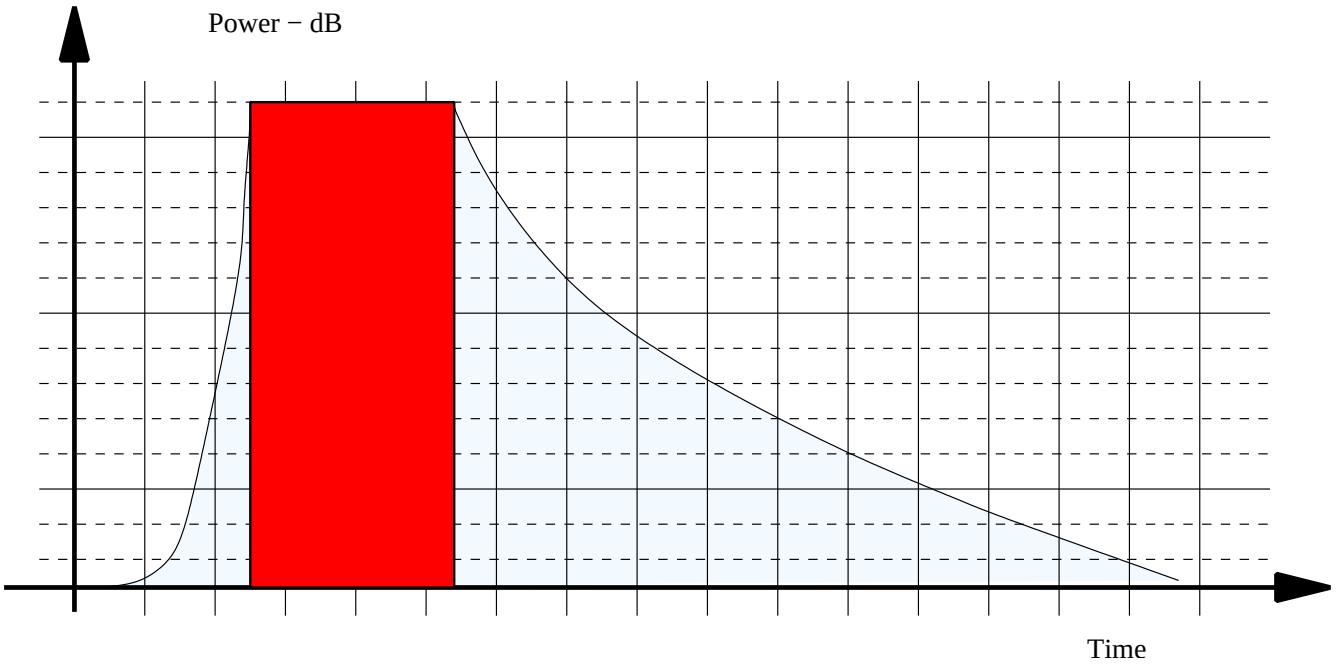


- For given f_0 adn σ^2 , $S_m(f)$ has a triangular shape
- The maximum is achieved at $f = f_0$
- Masking index: $S_m(f, \sigma^2, f) - \sigma^2$

- we observe that the second sound has not necessarily to by more powerful than the first to be heared: $S_m(f, \sigma^2, f) < \sigma^2$
- Decrease is slower for increasing f_1
- Decrease slope is proportional to CB
- Slope (toward increasing frequencies) is a decrasing function of σ^2

Masking curves

Time masking



- Pre-Masking : 2÷5 ms
- Post-Masking : 100÷200 ms

Model application

- The psychoacustical model allows to find out some non-audible parts of the signal
- We may then allow some quantization noise, as soon as it is masked by the rest of the signal
- Nevertheless, the model is not perfect:
  - Only pure tones or narrowband sounds are considered
  - We are only able to assess the influence of 3 sounds at a time
  - Real-life signals are much more complex: how do they interact?
- In practice, compression algorithms parameters are determined in an experimental way, after a large number of tests

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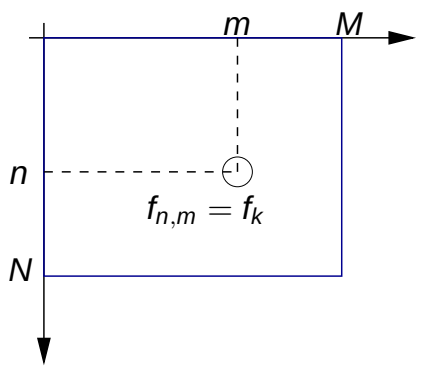
Gray level images

- Discrete grid, $N \times M$ pixels
- A given position (m, n) is scanned in raster order k
- $k = (n-1)M + m$
- $f_{n,m} = f_k$



RGB representation

Color images have three components, each represented as a gray scale image.




YUV representation

Color images: one luminance component and two chrominance components

Color Sampling

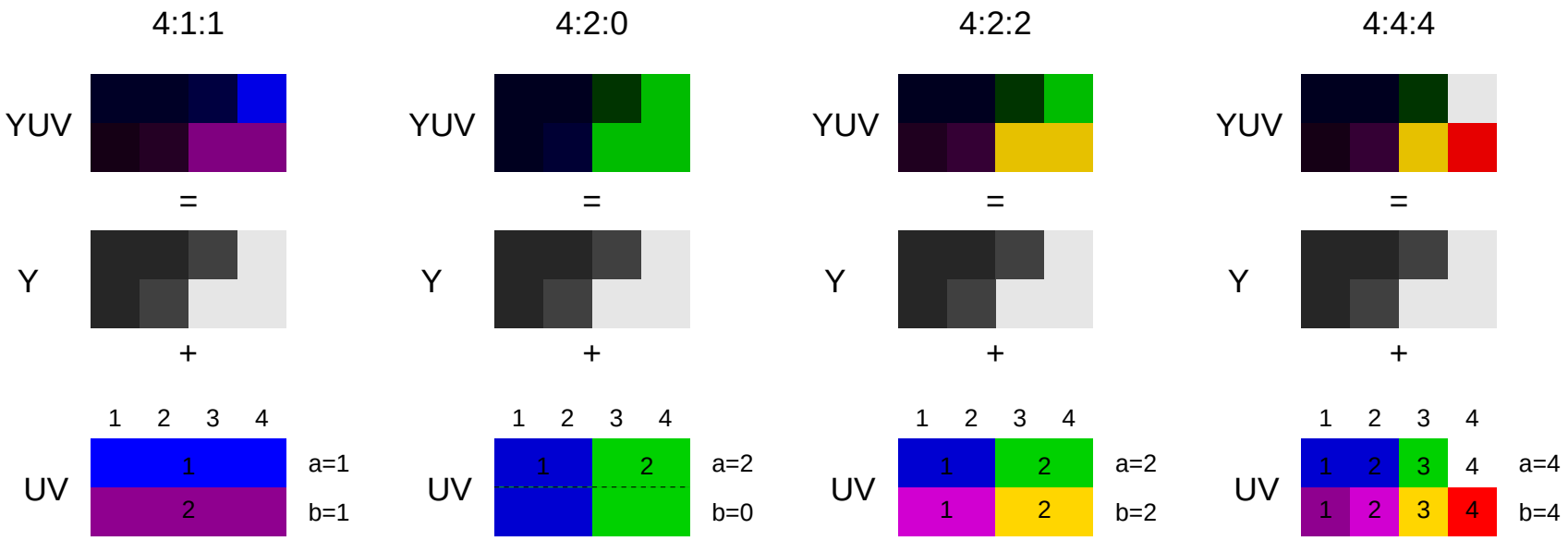
Sampling schemes

- The sampling scheme is represented with three integers

$$J : a : b$$

J Refernce horizontal size, usually equal to 4
a Number of chroma sample on the first line of the reference pattern
b Number of further sumples on the second line of the reference pattern

Color sampling



1/4 horizontal resolution
Full vertical resolution

1/2 horizontal resolution
1/2 vertical resolution

1/2 horizontal resolution
Full vertical resolution

Full horizontal resolution
Full vertical resolution

Quantization

- Samples represente on a discrete set
- Uniform quantization (rounding)
- L = number of levels
- $b = \log_2 L$ quantizer dynamics
- Typically $b = 8$ per component
  - 256 gray levels (8 bpp)
  - 16M colors (24 bpp)
- High dynamics range : 32 to 64 bits per channel

Resolution

SECAM	384×576	50 Hz
PAL	450×576	50 Hz
NTSC	323×486	60 Hz
QCIF	144×176	N/A
CIF	288×352	N/A
4CIF	576×704	N/A
SD/PAL	720×576	50 Hz
HD 720p/i	1280×720	50/100 Hz
HD 1080p/i	1920×1080	50/100 Hz
2K	2048×1556	24 Hz
4K	4096×2160	24 Hz
UHD	7680×4320	60 Hz

Representation of digital video

- Sequence of digital images
- Time dependency
- Three color components
- RGB or YUV representation
- Subsampling of color components

$$I : (n, m, T, c) \rightarrow x \in \left\{0, 1, \ldots, 2^b\right\}$$

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Compression: Motivations

- HD DVB System
  1 luminance component 1920×1080
  2 chrominance components 960×540
  8 bits quantization
  25 images per second
  $R \approx 622$ Mbps
- 2-hours movie ≈ 560 GB

Compression fundamentals

Why is it possible to compress?

- Statistical redundancy
  - images are spatially homogeneous
  - successive images are similar one to another
- Psychovisual redundancy
  - Spatial frequency sensitivity
  - Masking effects
  - Contours importance
  - Other limits of the HVS
- A compression algorithm should take into account both kinds of redundancy ot maximize its performance

Lossless and lossy algorithms

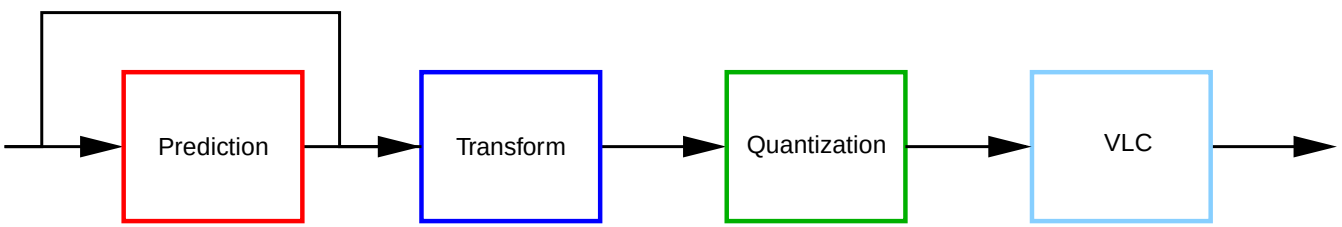
- Lossless algorithms
  - Perfect reconstruction
  - Based on statistics
  - Small compression ratio
- Lossy algorithms
  - Decoded $\neq$ original
  - Based on quantization
  - Psychovisual redundancy: “visually lossless”
  - High compression ratio

Symmetric and asymmetric algorithms (video)

- Symmetric algorithms
  - Same complexity for encoder and decoder
  - No motion estimation/compensation
  - Low compression ratio
  - Possibly real-time
- Asymmetric algorithms
  - Encoder (much) more complex than decoder
  - Motion Estimation/Compensation
  - High compression ratio
  - Typically “off line”, or hardware implementations

Basic tools for compression

- Transform
  - It concentrates information in a few coefficients
- Prediction
  - Alternative (and sometimes additional) method for information concentration
- Quantization
  - Rate reduction: rough representation of less important coefficients
- Lossless coding, or variable length coding (VLC)
  - Residual redundancy reduction



Rate

Compression ratio

- $T = \frac{B_{\text{in}}}{B_{\text{out}}} = \frac{R_{\text{in}}}{R_{\text{out}}}$

Coding rate

- Image : $R = \frac{B_{\text{out}}}{NM}$ [bpp]
- Video, audio : $R = \frac{B_{\text{out}}}{T}$ [bps]

Losslelss image coding: $T \leq 3$
Lossy image coding: $T \approx 5 \rightarrow ?$
Lossy vide ocoding: $T \approx 20 \rightarrow ?$

Quality and distortion

Criteria for image quality evaluation

- **Ojective criteria** are mathematical functions of:
  - $f_{n,m}$: original; and
  - $\widetilde{f}_{n,m}$: decoded image
- Non-perceptual objective criteria
  - Do not take into account the HVS characteristics
- Perceptual objective criteria
  - Based on perception models

Criteria for image quality evaluation

Non-perceptual objective criteria (NP-OC)

- Error image: $\mathcal{E}(f, \widetilde{f}) = f - \widetilde{f}$
- **Mean Square Error** (MSE) $\mathcal{D}$:

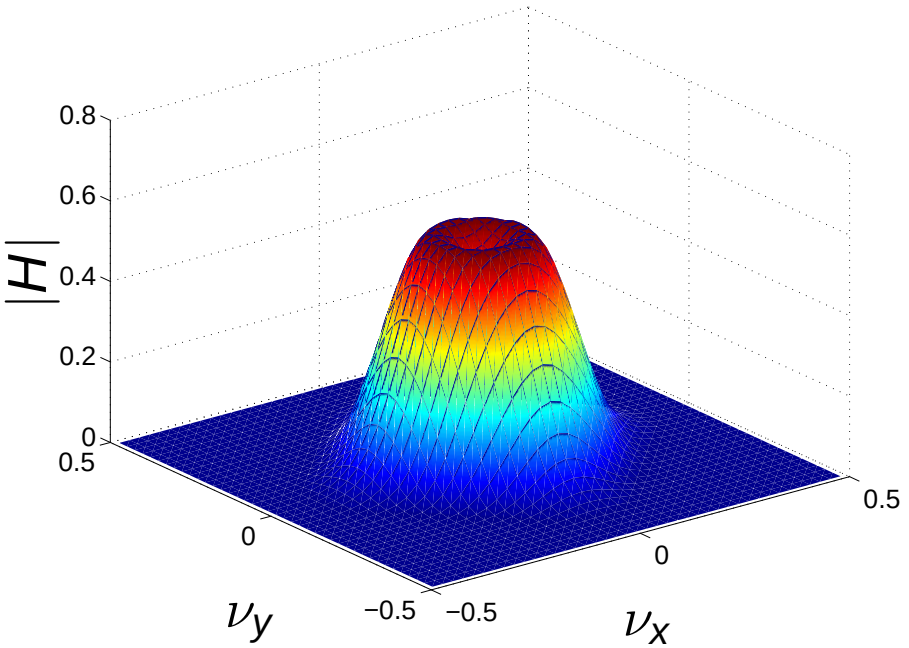
$$\mathcal{D}(f, \widetilde{f}) = \frac{1}{N\,M} \|\mathcal{E}\|^2 = \frac{1}{N\,M} \sum_{n=1}^{N} \sum_{m=1}^{M} \mathcal{E}_{n,m}^2$$

- **Peak signal-to-noise ratio** :
  $\mathrm{PSNR}(f, \widetilde{f}) = 10 \log_{10} \left(\frac{255^2}{\mathcal{D}(f, \widetilde{f})} \right)$
- Simple, derivable, linked to the $\mathcal{L}^2$ norm

Criteria for image quality evaluation

Perceptual objective criteria

Weighted PSNR : Given a frequency weighting function (filter) h :



$$\mathrm{WPSNR}(f,\widetilde{f}) = 10\ \log_{10}\left(\frac{255^2}{\mathcal{D}_{\mathrm{W}}(f,\widetilde{f})}\right) \qquad \text{où}$$

$$\mathcal{D}_{\mathrm{W}}(f,\widetilde{f}) = \frac{1}{N\,M}\,\|h * \mathcal{E}\|^2$$

Criteria for image quality evaluation

Perceptual objective criteria

Structural Similarity Index (SSIM Index) between two blocks x et y :

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

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

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

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

For thesake of simplicity, $\alpha = \beta = \gamma = 1$, $C_3 = C_2/2$

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

SSIM between images is the average of blocks' SSIM

Criteria for image quality evaluation

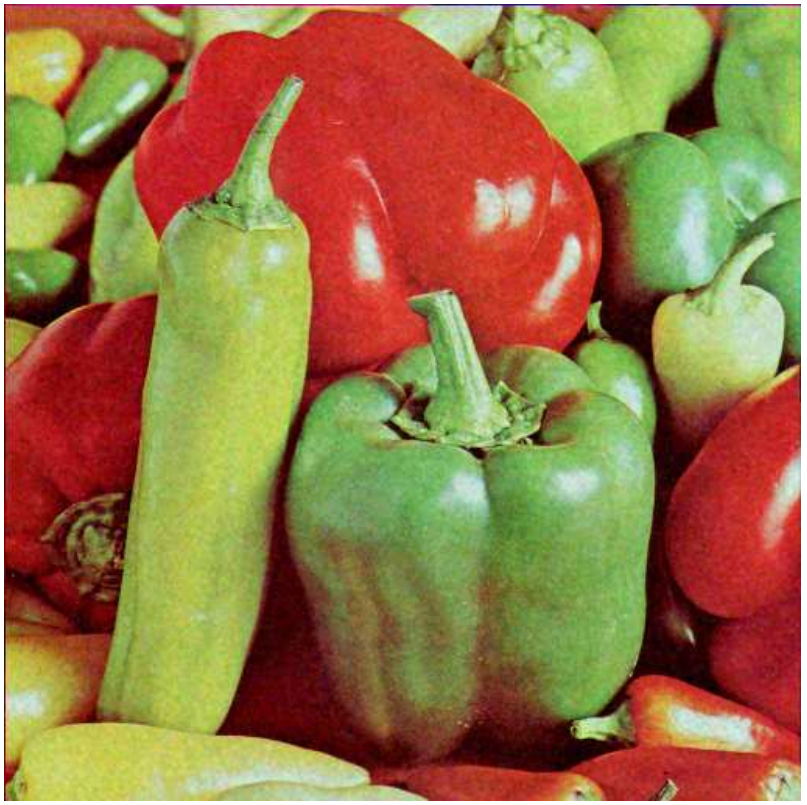
Subjective criteria (SC)

- Subjective criteria are based on the image assessment performed by human observers
  - Difficulty of HVS modelling for objective criteria
  - Statistical analysis of results
  - Long, difficult and costly evaluations
- Often NP-OC are used
  - Simplicity
  - Geometrical interpretation (norm)
  - analytical Optimisation
  - Correlation avec SC?

Error perception

Distributed error, white noise $\sigma = 4$

MSE: 16



SSIM: 0.906

Error perception

Error concentrated over 100×100 pixels

MSE: 16

SSIM: 0.972

Error perception

Error concentrated on the contours (estimation by Sobel's filter)

MSE: 16

SSIM: 0.987

Error perception

Noise on high spatial frequencies

MSE: 16

SSIM: 0.882

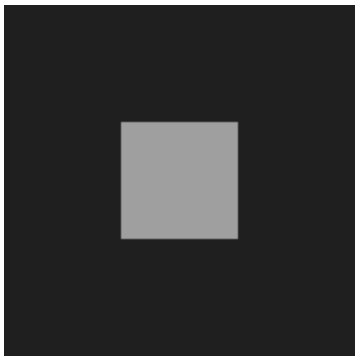
Error perception

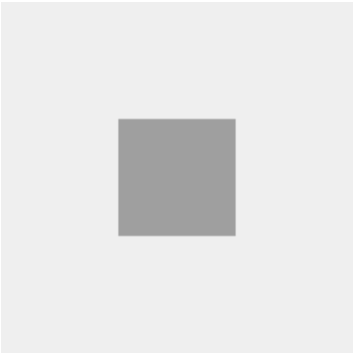
Chroma subsampling

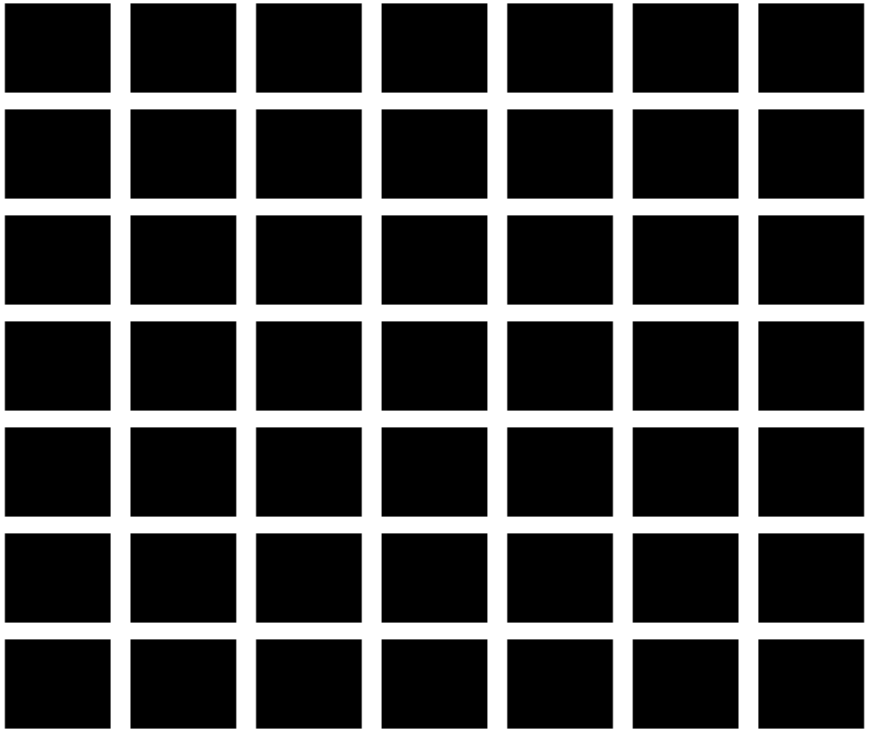
MSE: 21.27

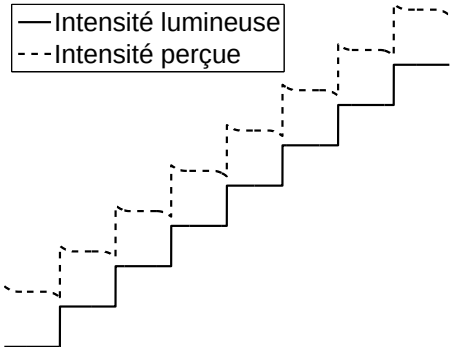
SSIM: —

Spatial effects



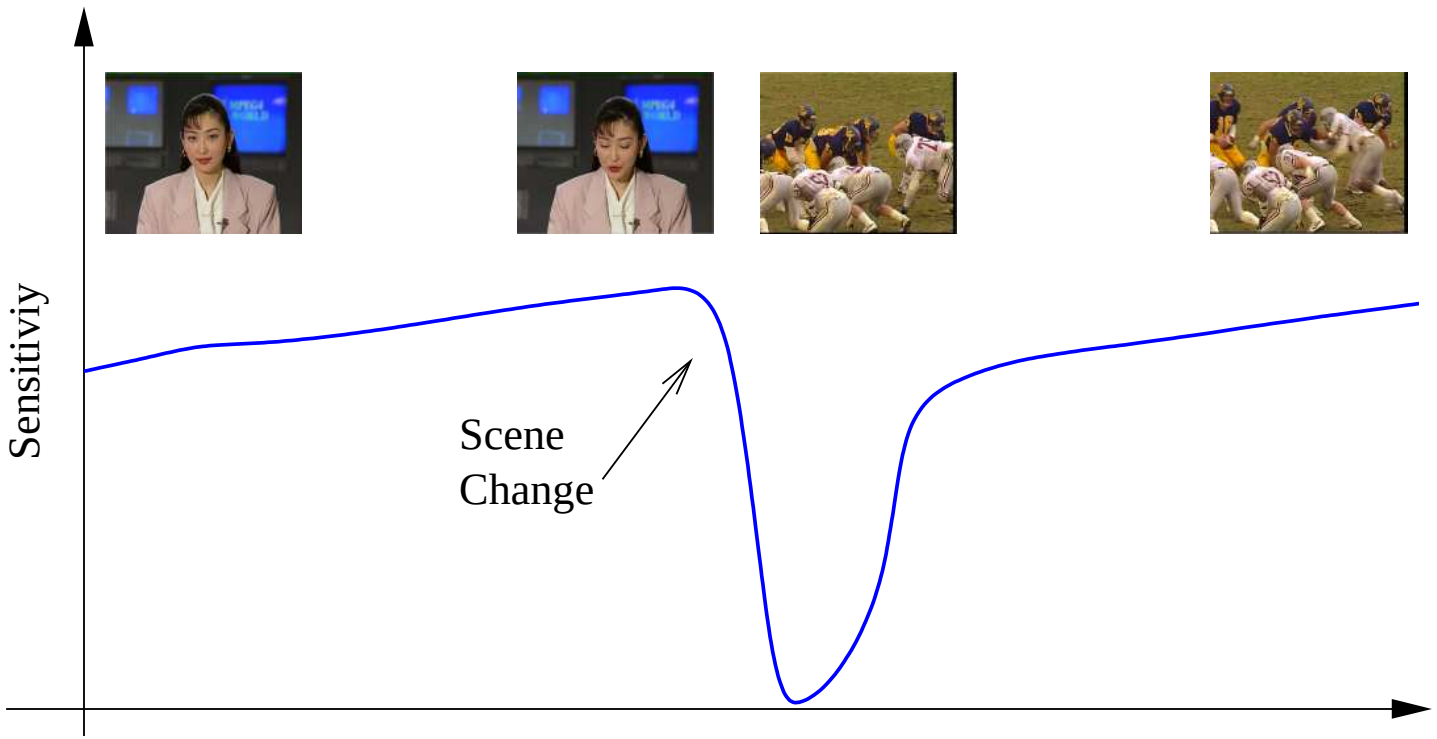






Video Perception

- Sensitivity spatio-temporal frequencies
- Spatial and time masking



Perception and quality: summary

- Perceptual models are needed in order to achieve good compression performance
- Auditive system is relatively well understood and exploited in audio coders (see later on)
- HVS less well understood
- No P-OC totally reliable
- Nevertheless, the best performance can be achieved only taking into account HVS

Complexity, delay and robustness

- The complexity of a compression algorithm may be limited by:
  - Real-time constraints
  - Hardware limitations
  - Economical cost
- Delay is usually measured at the encoder
  - It is related to complexity ...
  - ... but mainly affected by the *coding order*
- Robustness: sensitivity of the compressed stream to losses

Performance criteria: summary

Contrasting issues:

$$\begin{matrix} \Uparrow \text{Quality} \\ \Uparrow \text{Robustness} \end{matrix} \quad \begin{matrix} \Downarrow \text{Rate} \\ \Downarrow \text{Complexity} \\ \Downarrow \text{Delay} \end{matrix}$$