Advanced Image Processing

Part I:

Human Visual System

S. Voloshynovskiy

Recommended books

- B.A. Wandell, Foundations of Vision, Sinauer Associates, Inc., 1995.
- A. K. Jain, Fundamentals of Digital Image Processing, Prentice-Hall, 1989.

Roadmap:

1. Introduction
2. Perceived information attributes (light, luminance, brightness, contrast)
3. Optical properties of the Human Visual System (HVS):

   Point Spread Function and Modulation Transfer Function

3. Masking data hiding compression
4. Image quality (fidelity) criteria
5. Conclusions

Introduction

Why is it important to know the features of the Human Visual System (HVS)?

1. To develop measures of image fidelity and quality.
2. To design the algorithms matched with these measures.
3. To exploit the knowledge of the HVS for efficient compression, denoising, restoration and watermarking.

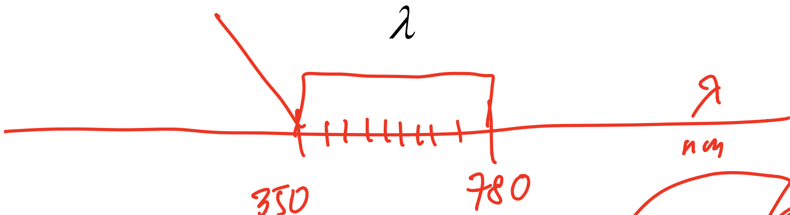
Perceived information attributes

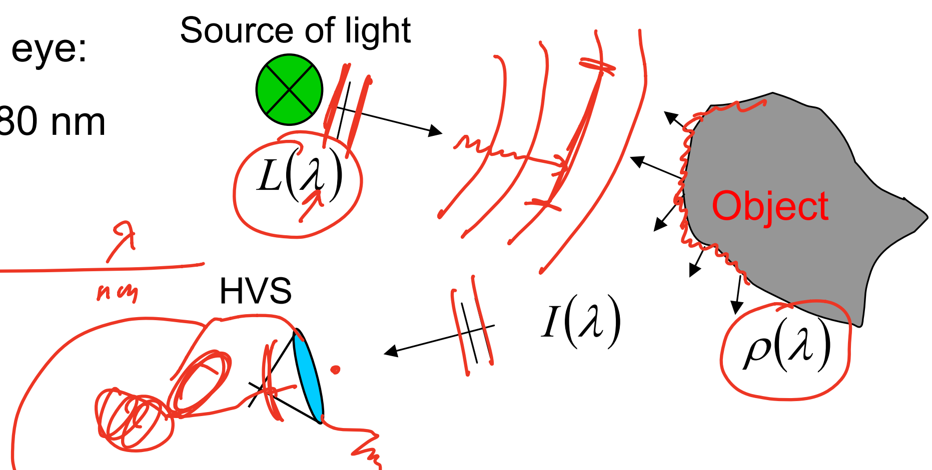
Light is the electromagnetic radiation that stimulates our visual response.

Visible range of human eye:

350 nm < wavelength > 780 nm

λ





Light received from the object:

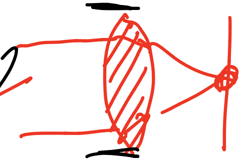
$$\boxed{I(\lambda) = \rho(\lambda)L(\lambda)}$$

Reflectivity   Incident light

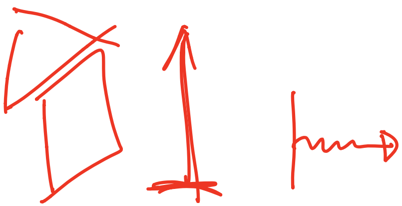
0... 1

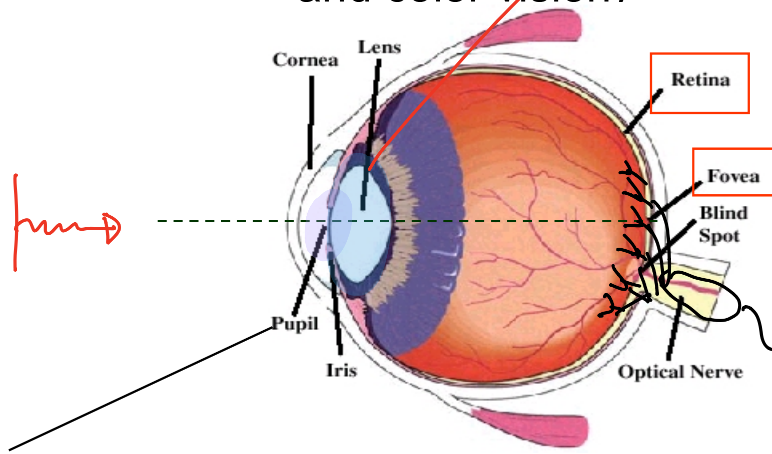
The Human Eye

Retina contains two types of photoreceptors : B&W



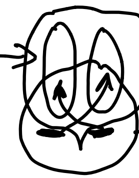
- 100 millions of *rods* (dark environment)
- 6.5 millions of *cones* (well-lighted environment, high resolution and color vision)





Cones are packed in Fovea.

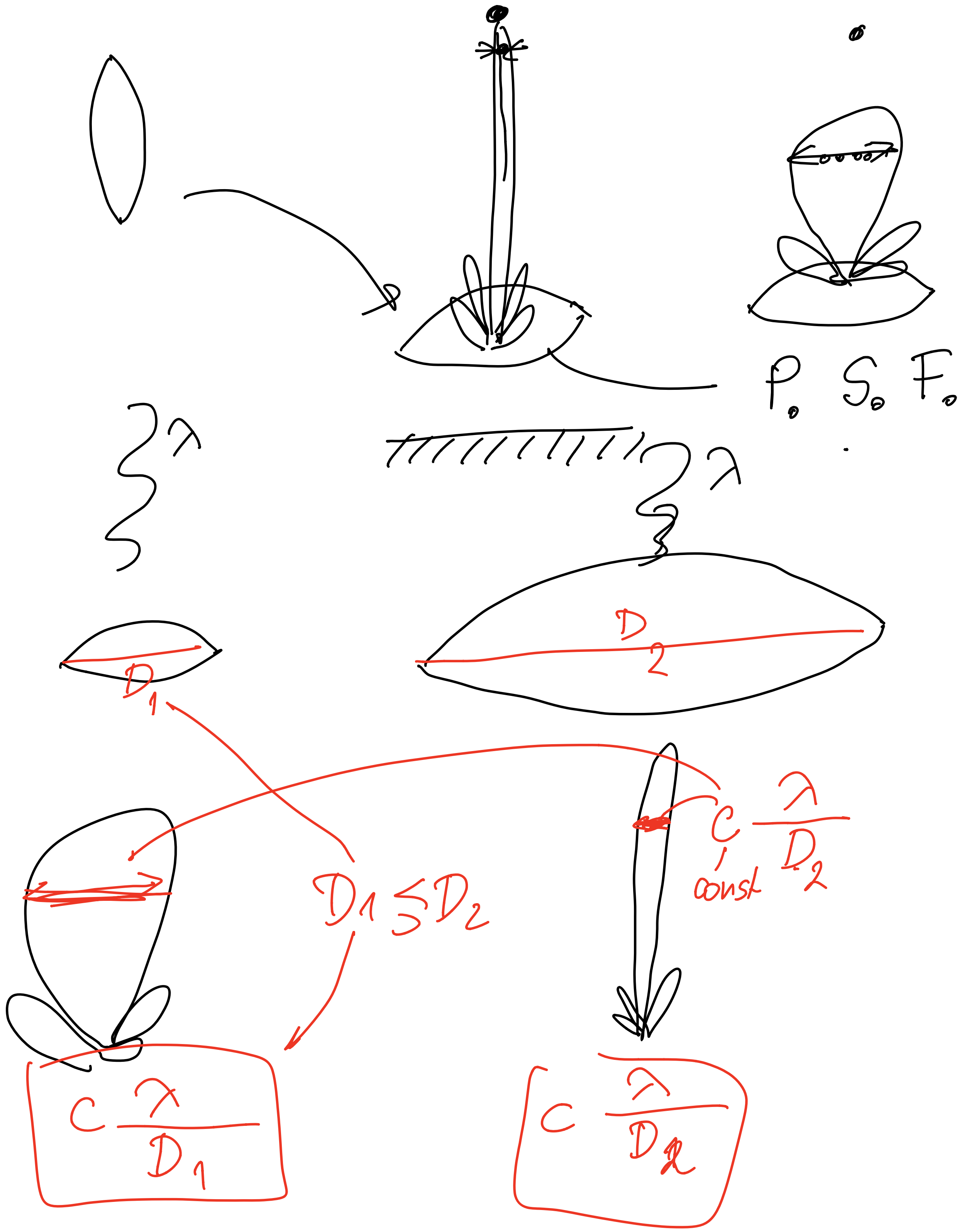
Rods are distributed over all Retina.

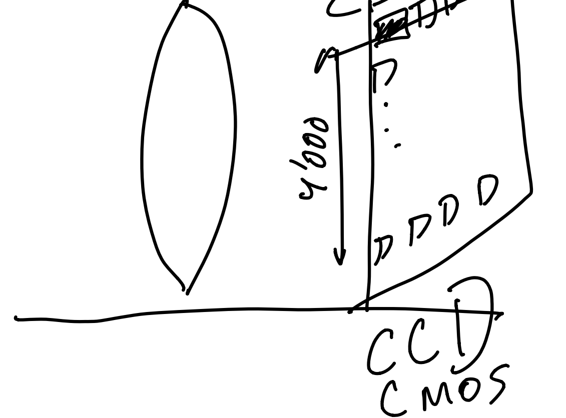


Visual Vortex

Pupil acts as small imaging aperture (size is varying from 2 to 8 mm).

Lens determines the aperture focusing. Iris is the muscle that controls the pupil size.

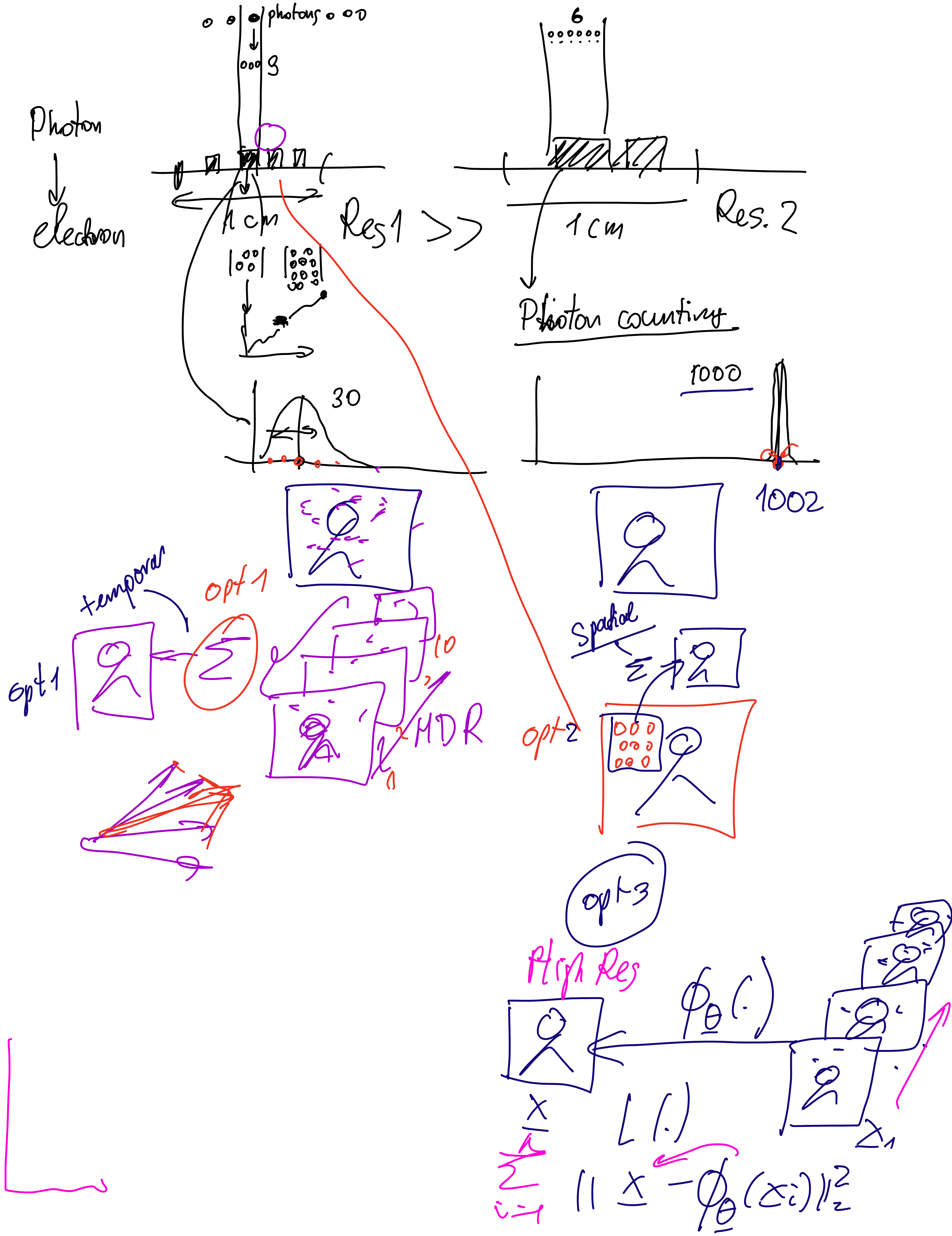




$3'000 \times 4'000 = 12\ Mp$

$\equiv \underline{1'000 CHF}$

?

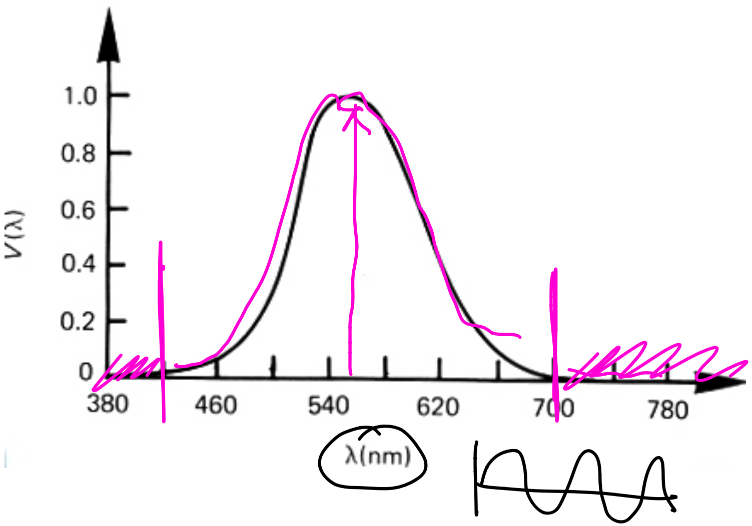

photons
3
6
Photon
electron
1 cm
Res1 >>
1 cm
Res. 2
Photon counting
30
1000
1002
temporal
opt 1
opt1
10
HDR
Spatial
opt 2
opt 3
High Res
$\phi_\theta(.)$
x
$L(.)$
x_1
$\sum_{i=1} \| x - \phi_\theta(x_i) \|_2^2$

Perceived information: Luminance and Brightness

Luminance (or intensity) : $$f(i,j)=\int_0^{\infty} I(i,j,\lambda)V(\lambda)d\lambda$$

Spatial object light distribution.

relative luminous efficiency function of the HVS (describes the sensitivity of the HVS to different wavelength)

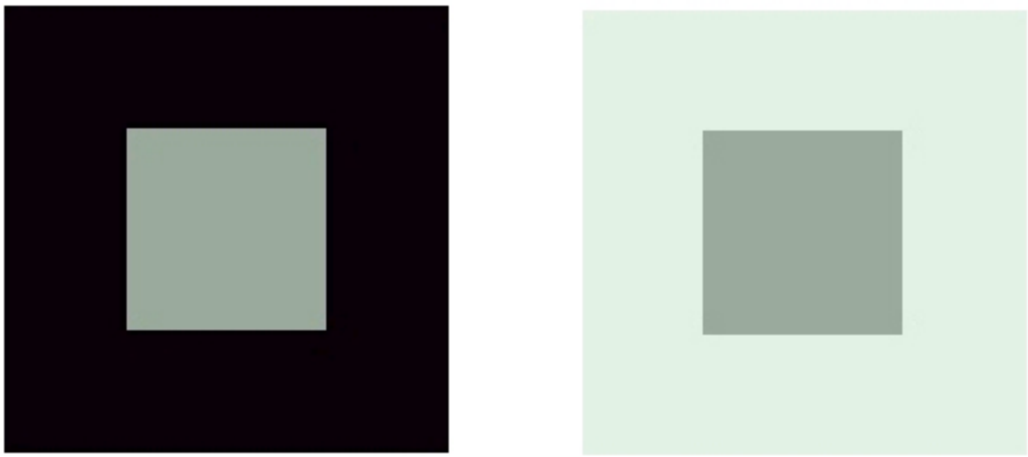


The luminance of the object is independent of the luminance of the surrounding objects.

The brightness of an object is the perceived luminance and depends on the luminance of the surround.

Perceived information attributes

Brightness is the perceived luminance. It depends on luminance of the surround:

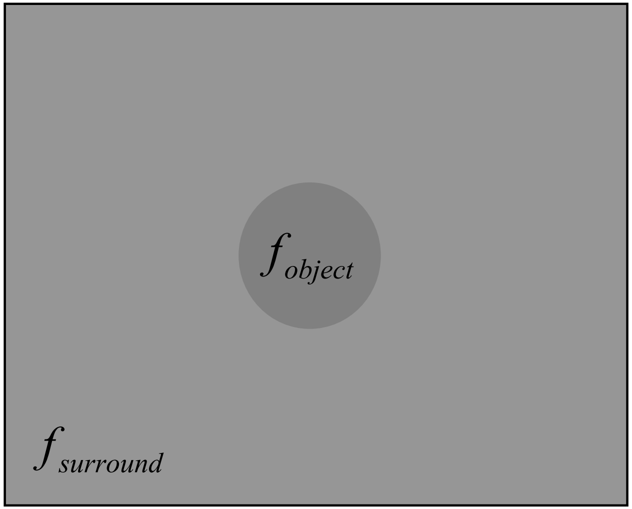


Small squares in the middle have equal luminances but do not appear equally bright.

The human perception is sensitive to luminance contrast rather than the absolute luminance values themselves.

Visibility Threshold: Weber law

Can you see the circle?



- The HVS can perceive the small difference in luminance.
- However, the minimum difference that can be perceived depends on the surround luminance.
- This dependence is known as contrast sensitivity.

Weber's law: $$\frac{\left|f_{surround} - f_{object}\right|}{f_{object}} = constant$$

If the luminance of an object is just noticeable difference from the luminance of its surround, then their ratio is constant.

Perceived information attributes

- Let: $f_{object} = f$ and $f_{surround} = f + \Delta f$ Just noticeable difference

$$\boxed{\frac{\Delta f}{f} \cong d(\log f) = \Delta c \qquad (constant) \approx 0.02}$$

Luminance-to-Contrast (c) **models**:

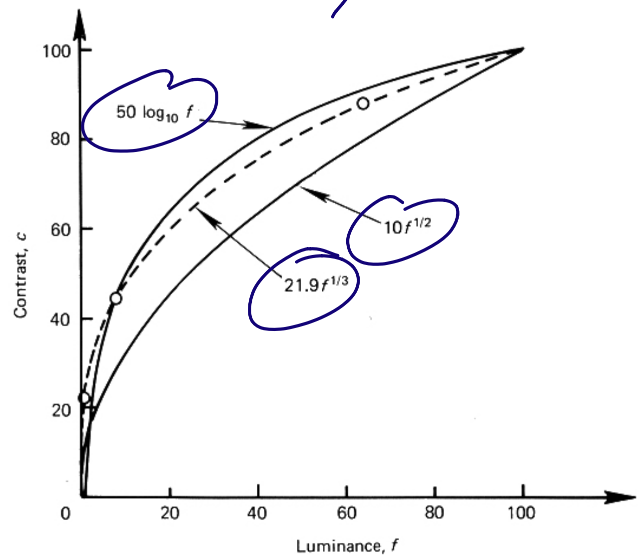
- Logarithmic law: $c = 50 \log_{10} f, \quad 1 \le f \le 100$

- Power law: $c = \alpha_n f^{1/n}, \quad n = 2,3,\ldots$

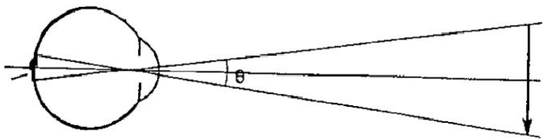
  $\alpha_2 = 10, \qquad \alpha_3 = 21.9$

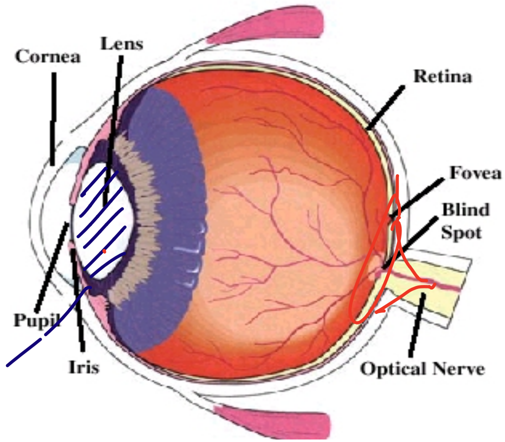
- Background ratio: $c = \dfrac{f(f_b + 100)}{f_b + f}$

  f_b – *background luminance*

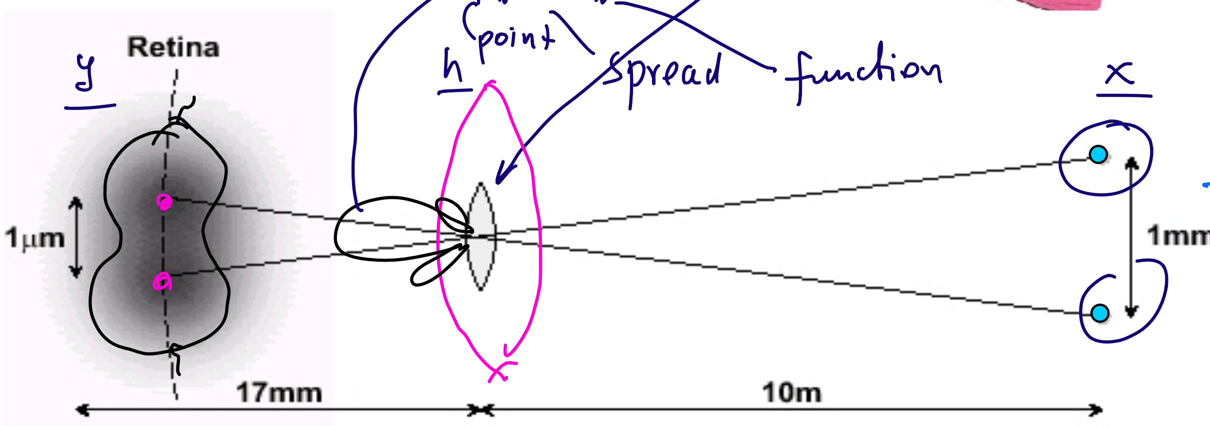


Optical properties of the HVS



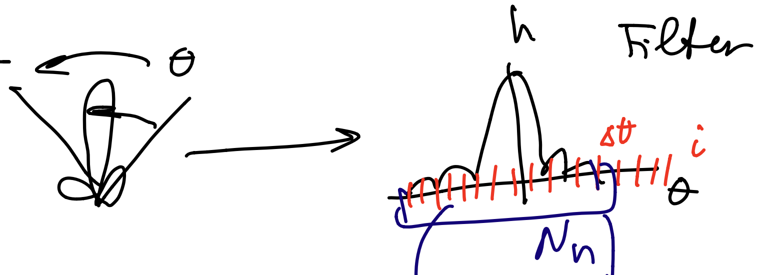


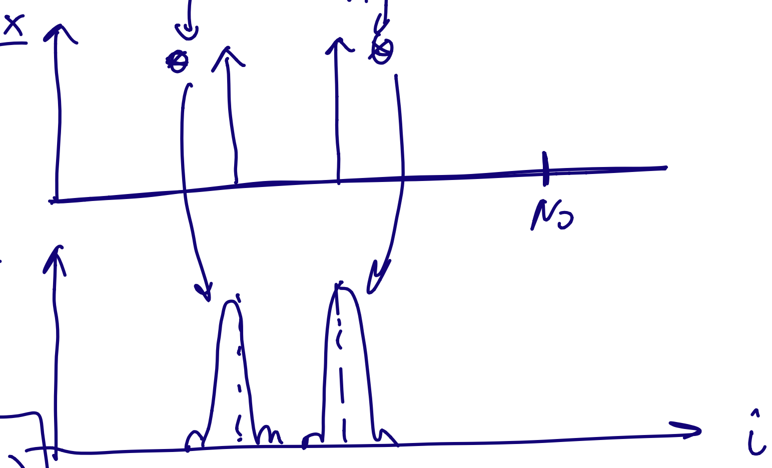
P. S. F.
(point spread function



Ex 4.

Convolution

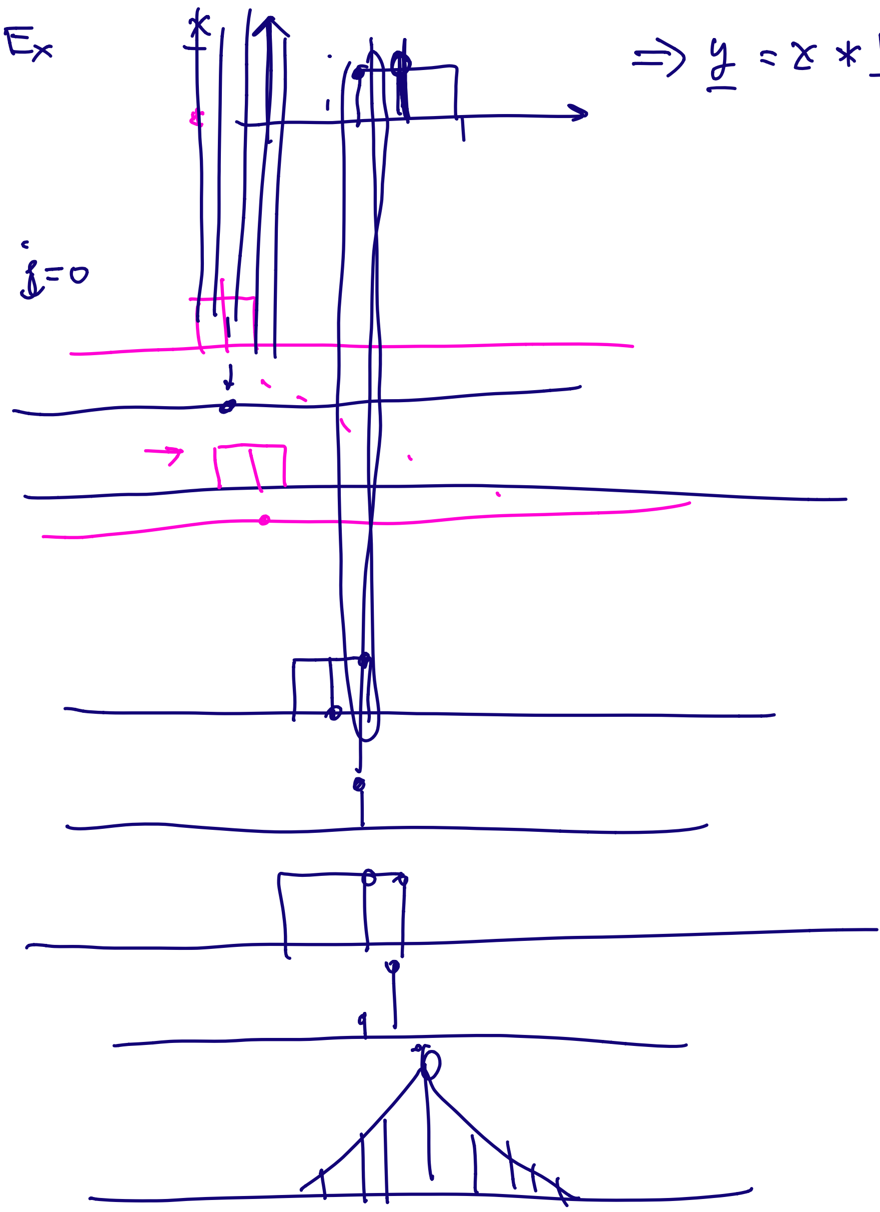




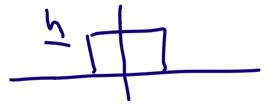
$\underline{y} = \underline{x} * \underline{h}$

$$\boxed{y(i) = \sum_{j=1}^{N_0+N_h-1} x(j)\, h(i-j)}$$

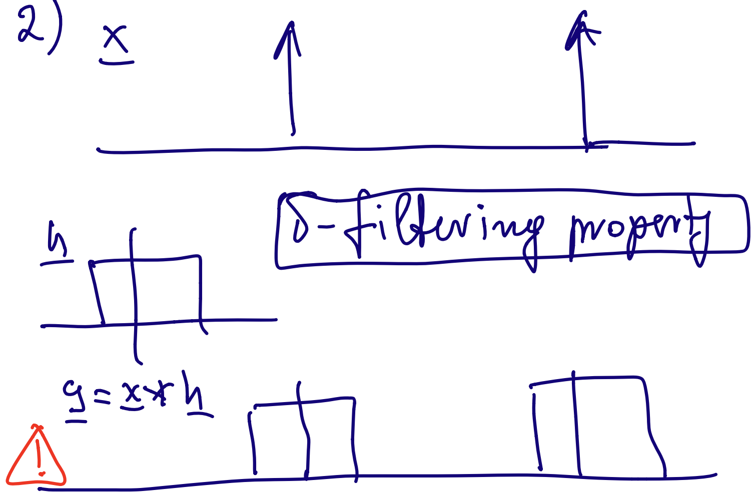
Ex



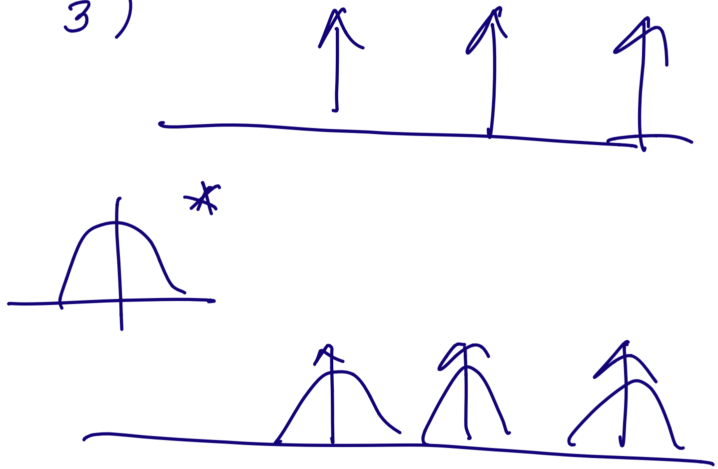
$\Rightarrow \underline{y} = x * \underline{h}$ (to do at home)



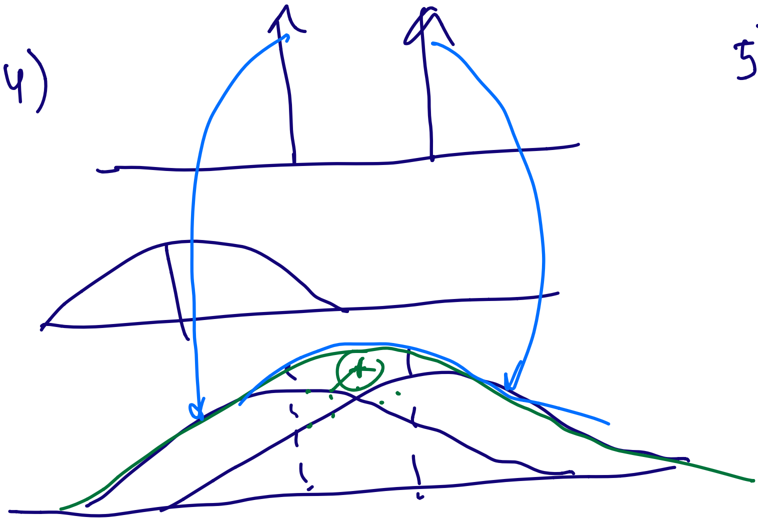
2)



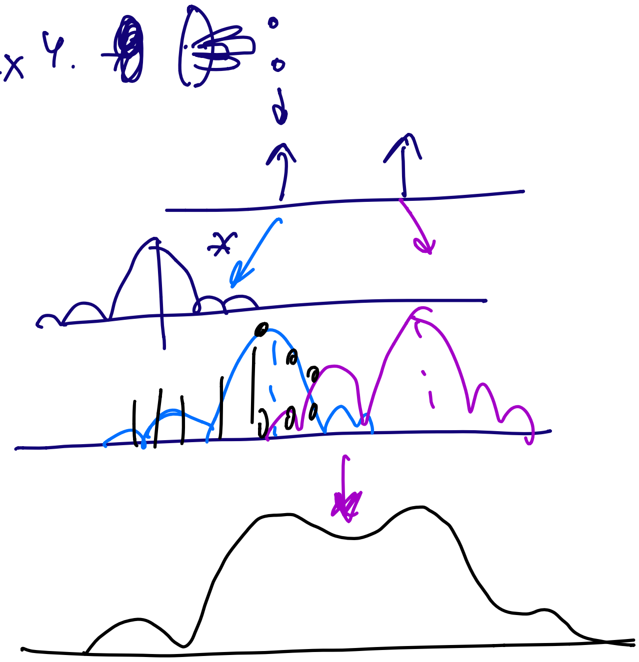
3)



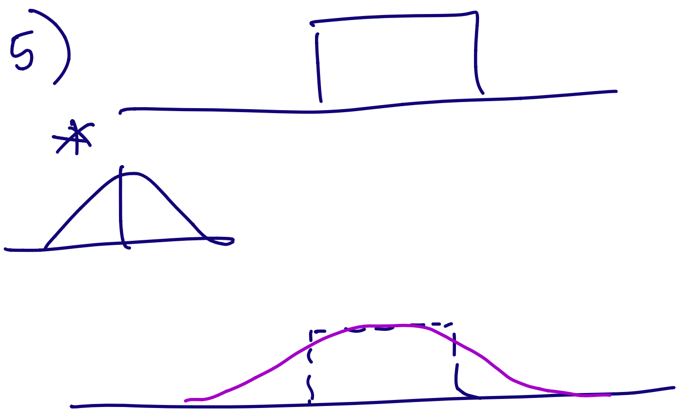
4)



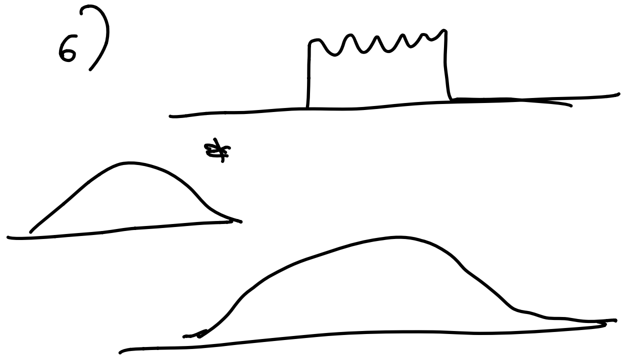
5) Ex 4.



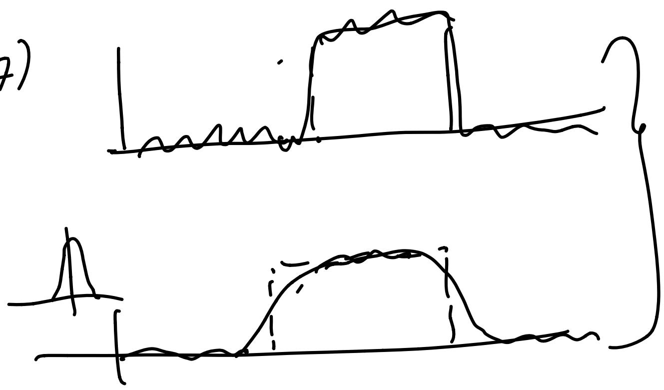
5)



6)



7)



noise removal

[wiki]

$$* \xrightarrow{\mathcal{F}} \odot$$

point-wise multiplication

fast methods $n \log n$

$$\odot \xrightarrow{\mathcal{F}} *$$

???

complexity

1) $\underset{n}{h} \xrightarrow[n \cdot \log n]{\mathcal{F}} \underset{n}{\mathring{H}}$

$*$

2) $\underset{n}{x} \xrightarrow[n \log n]{\mathcal{F}} \underset{n}{\mathring{X}}$

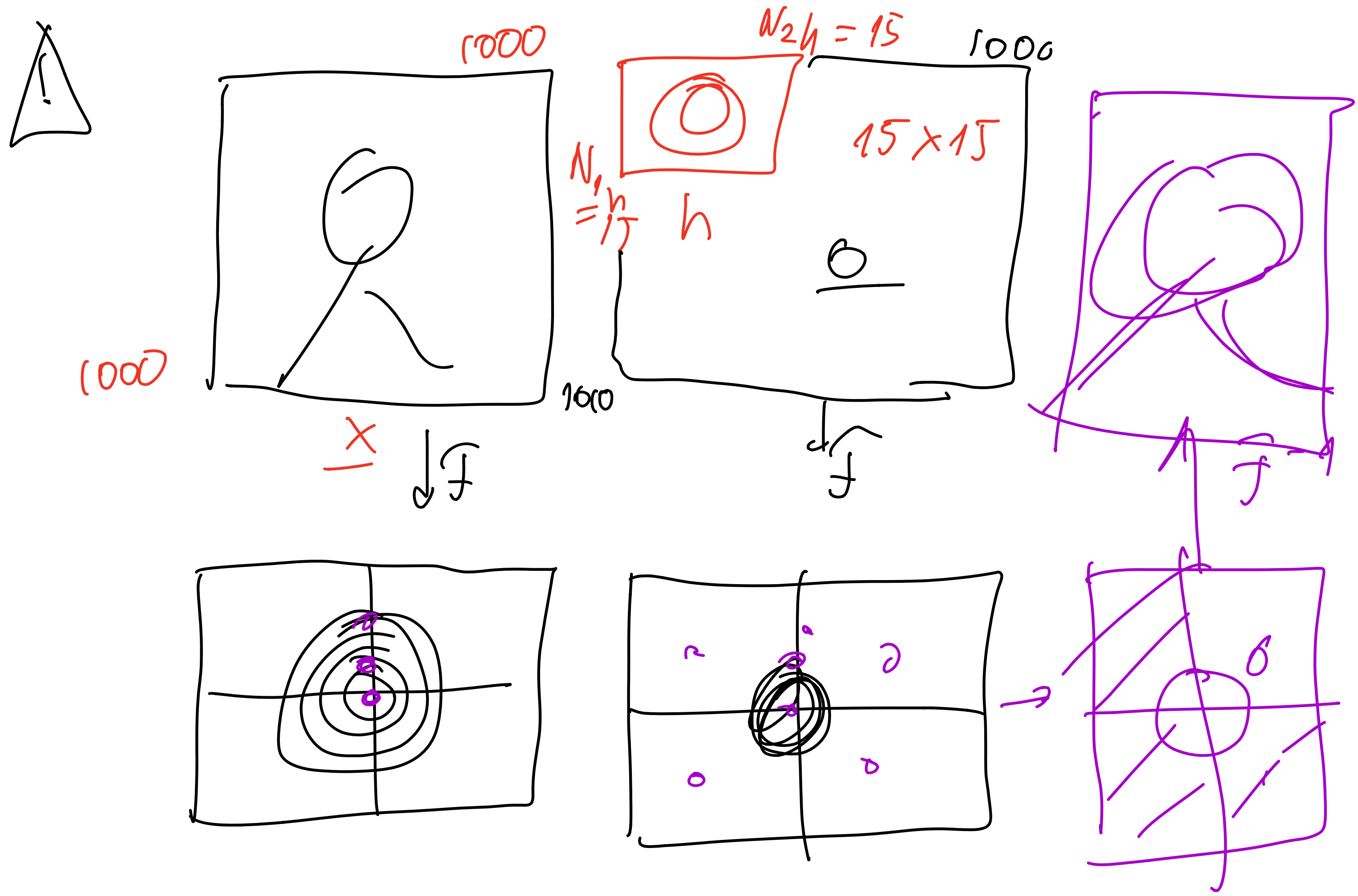
$2 n \log n$

$\mathcal{F}^{-1}$

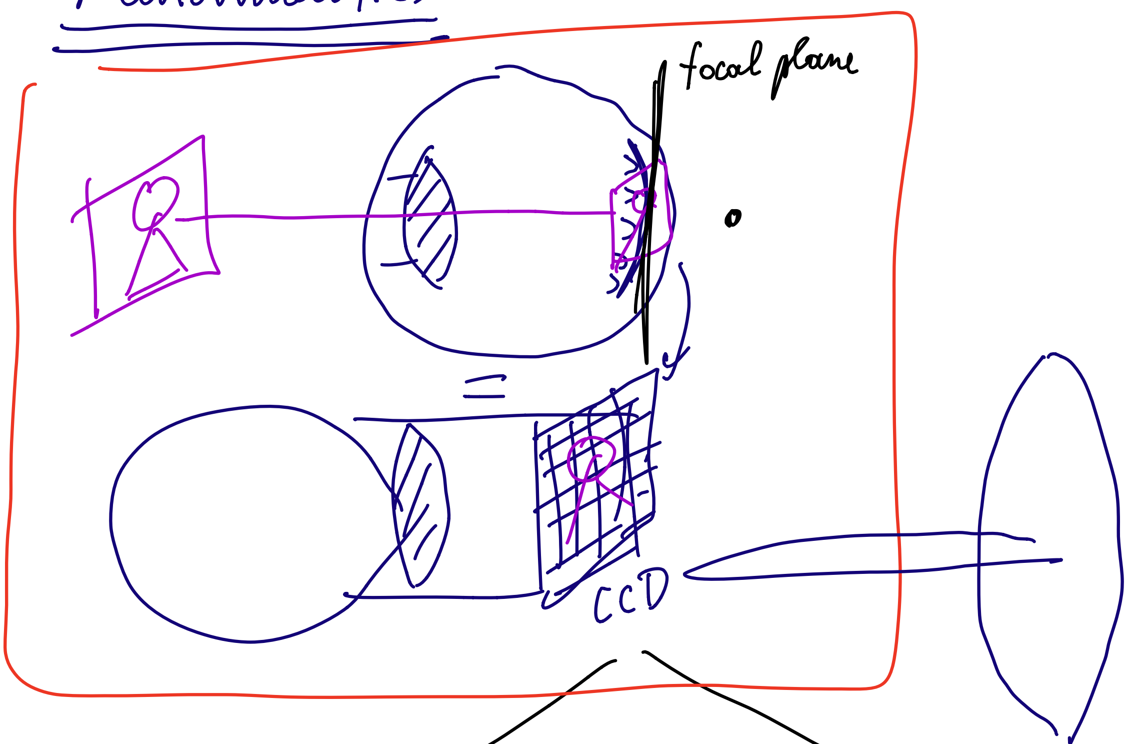
$n \log n$.

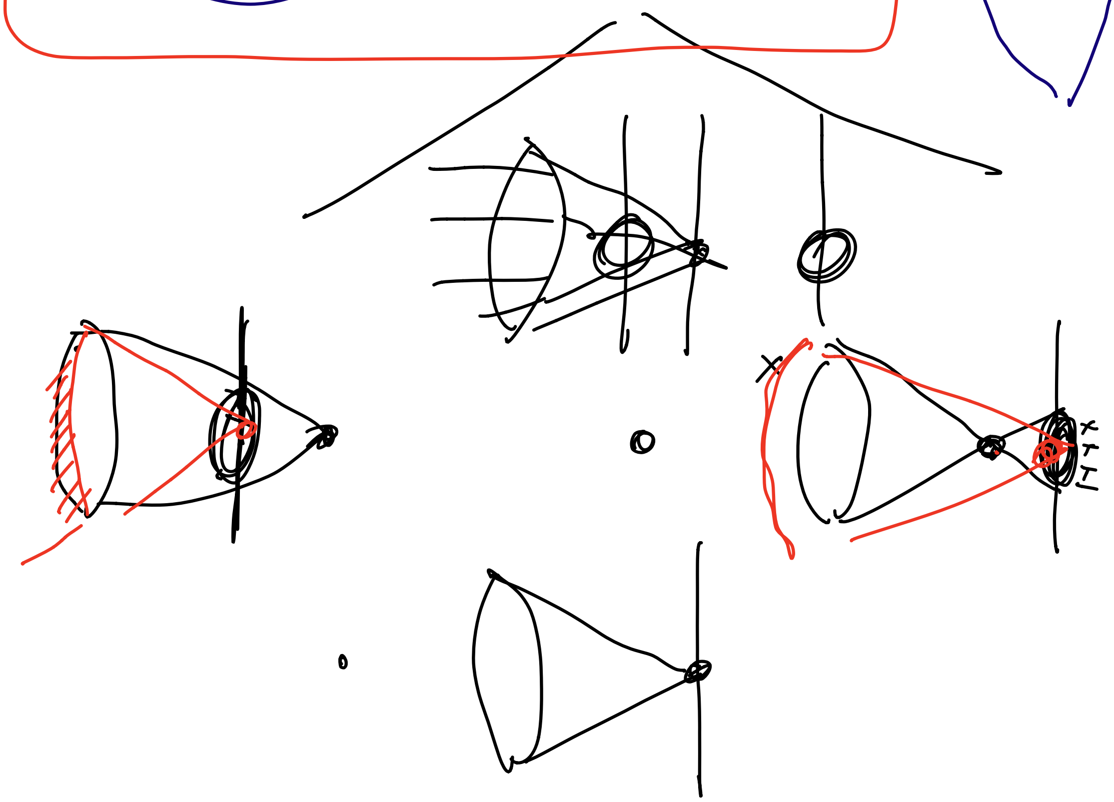
$3 \cdot n \log n$

(N^2)



Adnormalities

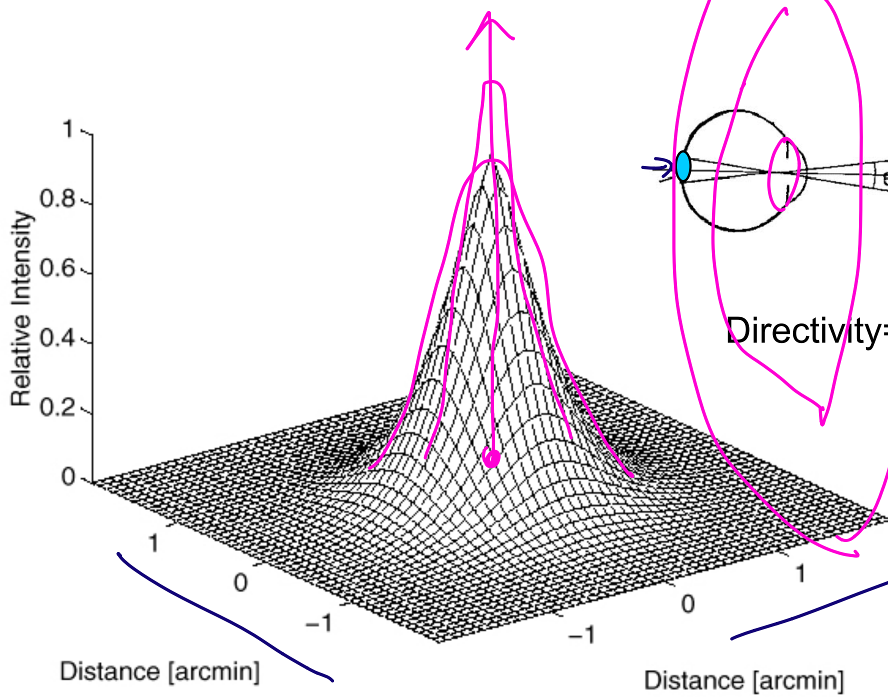


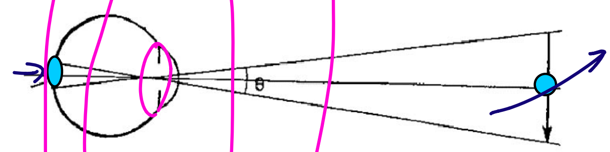


Optical properties of the human eye

- Deviations from ideal perspective projection due to
  - Aperture of the eye
  - Focus errors (spherical aberration)
  - Chromatic aberration
  - Dispersion
- Effects can be summarized by a 2D convolution with the optical point-spread function (PSF).
- Instead of a PSF, an optical line-spread function (LSF) is often given, which can be measured more easily.

Optical properties of the human eye: the PSF





Directivity=Wavelength/Diameter

"CLEAN"
↳ deblurring
↳ restoration

Because the cornea is not perfectly symmetric the optical properties of the eye are not shift invariant.

Optical properties of the human eye: the PSF

Additionally, it is difficult to focus the eye for all wavelengths simultaneously (it is known as chromatic abberation).

Therefore, the PSF changes with wavelength.

PSF → Fourier Transform → MTF (Modulation Transfer Function)

① h

PSF $\xrightarrow{\mathcal{F}}$ MTF

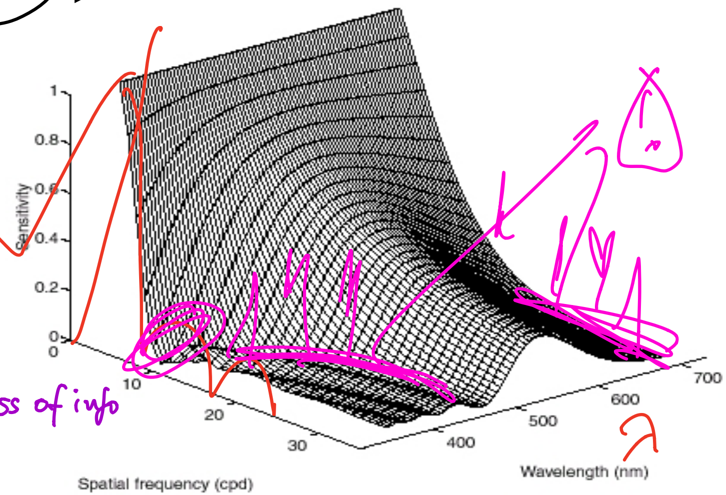
x t ω

[wiki]: basic properties of Fourier transform

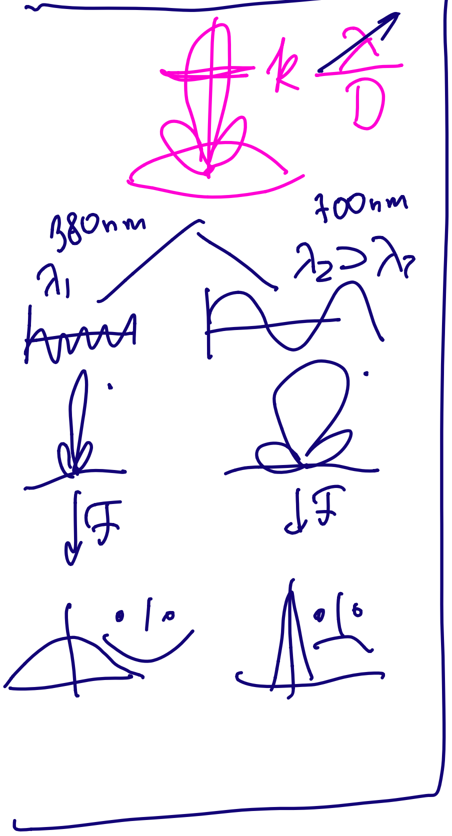
h PSF $\xrightarrow{\mathcal{F}}$ const = 1

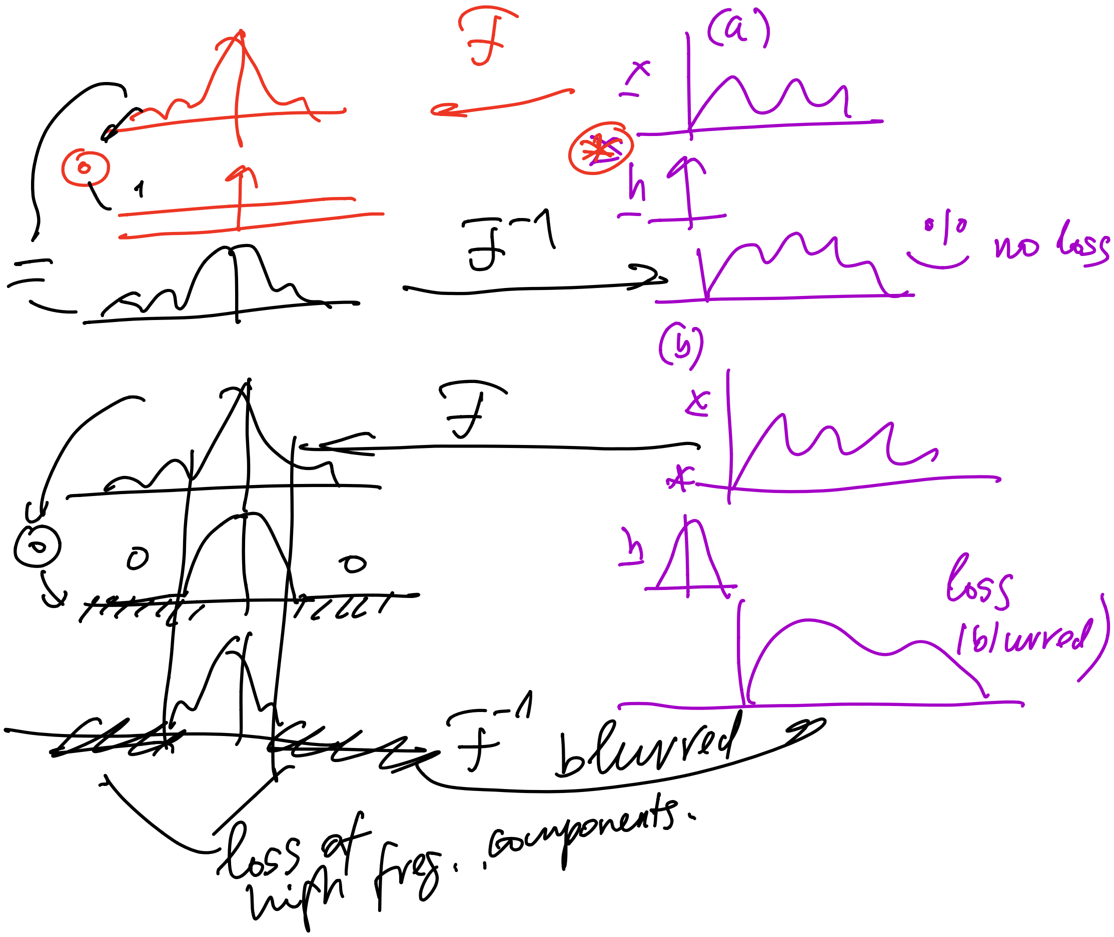
no loss of info

② h(x)

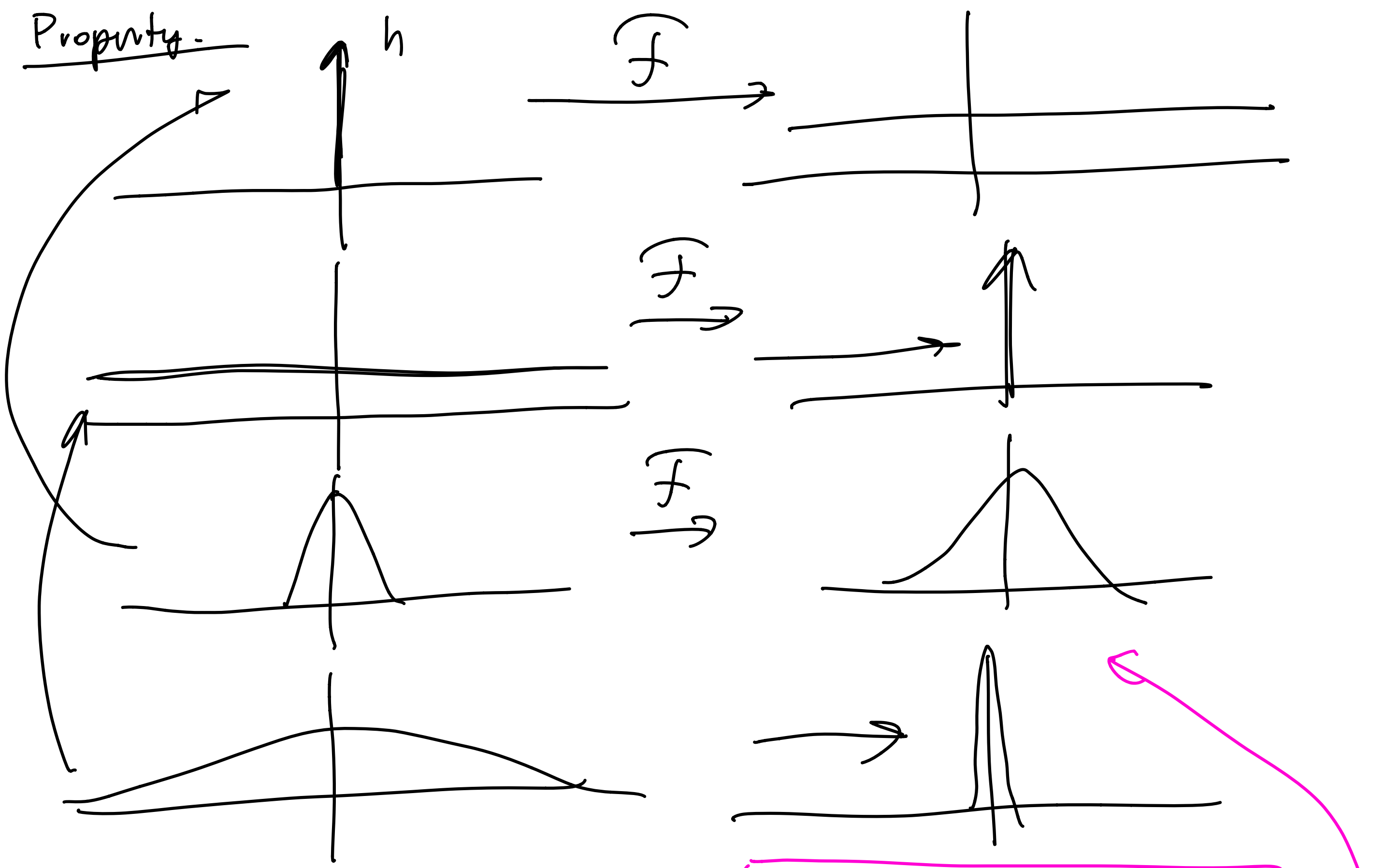


MTF of human eye





Property.



Matlab : $\boxed{\text{x\_fft = fft(x);}}$ $\boxed{\text{x = [0 1 5 . . . .]}}$

plot (x_fft);

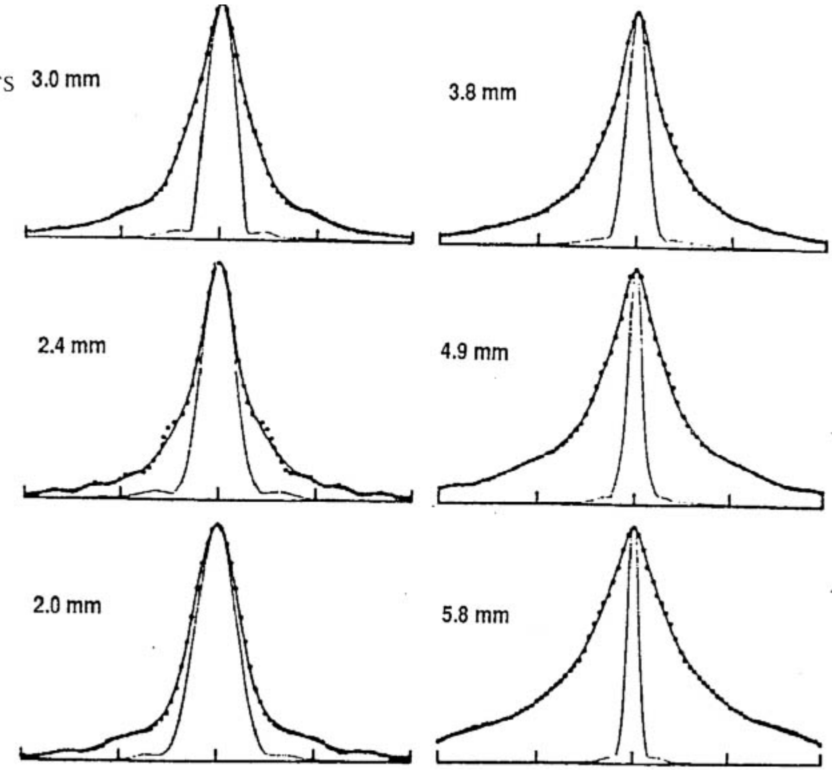
M & φ

x_fft_mag = abs(x_fft)

Optical LSF of the human eye

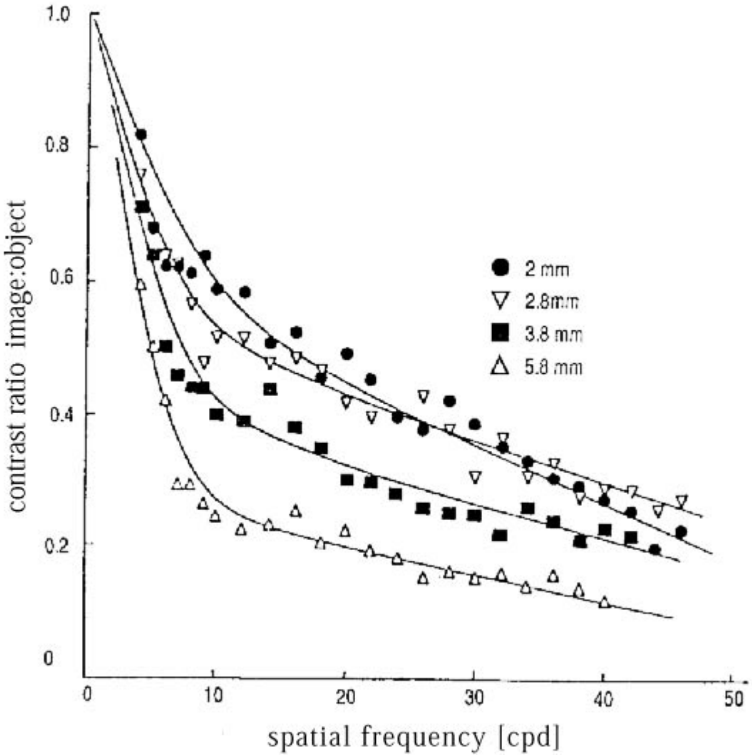
LSF measured for different pupil diameters (Campbell+Gubisch)

LSF calculated from eye aperture (due to diffraction)



Optical Modulation Transfer Function (MTF) of human eye

- MTF is measured directly with sinewave gratings.
- The optical modulation transfer function (MTF) can be interpreted as Fourier transform of the optical LSF.



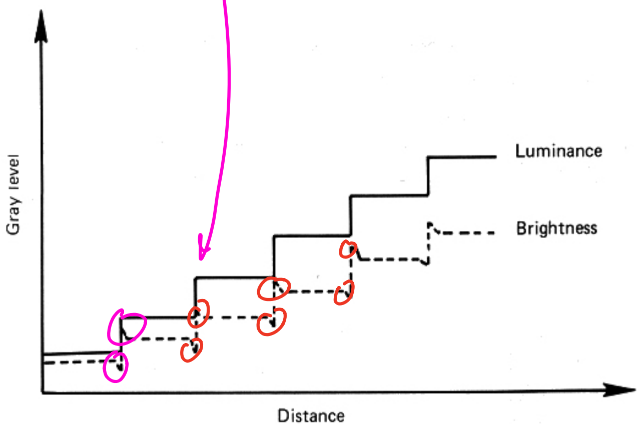
Practical Estimation of the MTF

The MTF (or the impulse response of the HVS) can be estimated:

- directly in the spatial domain using a Mach band effect;
- using spatial sinusoidal grating of varying contrast and spatial frequencies.

Mach Bands

Mach bands – the measure of visual system in spatial domain.

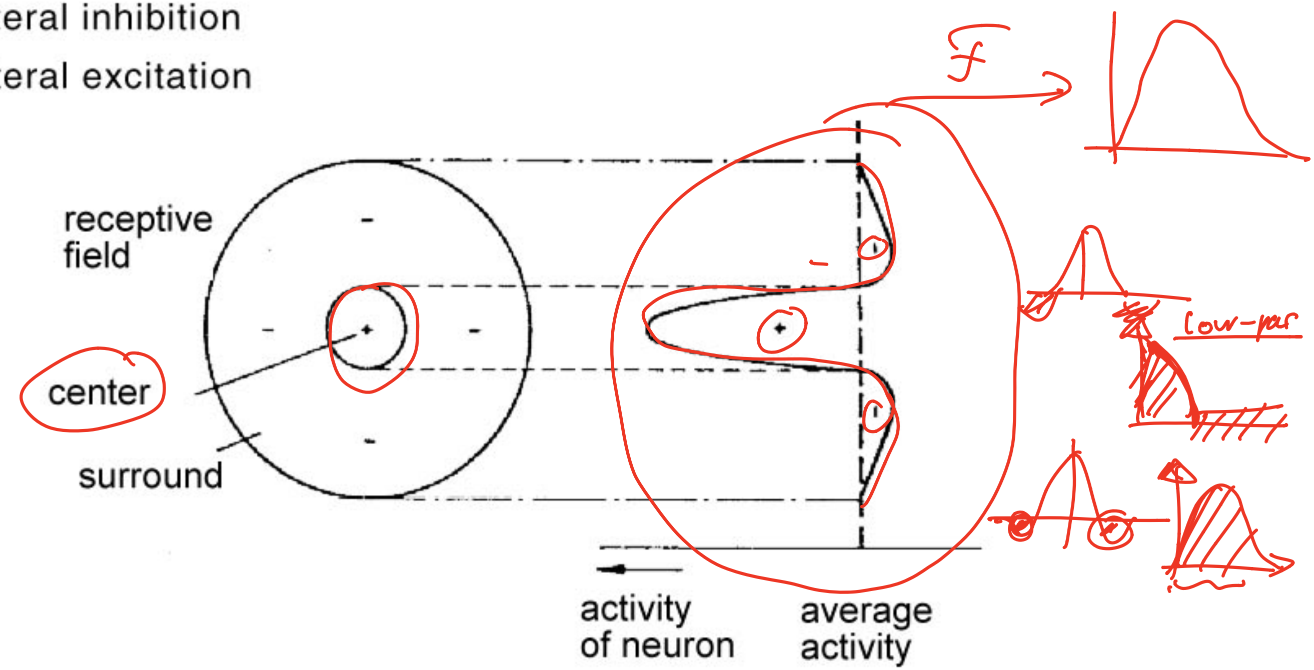


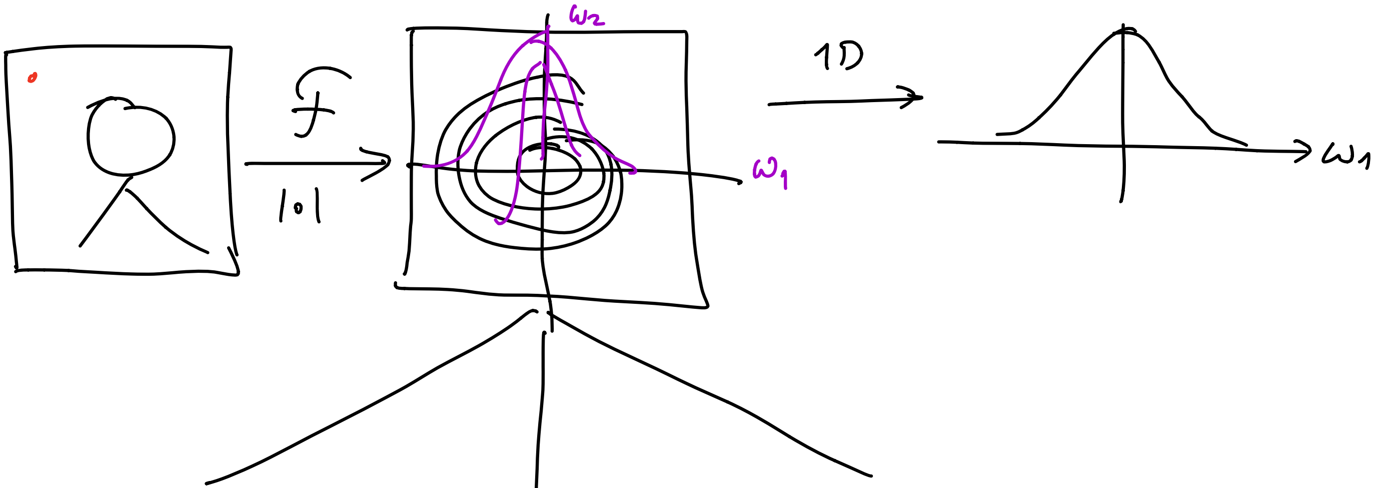
The bars have constant luminance.

However, the apparent brightness is not uniform along the width of the bar.

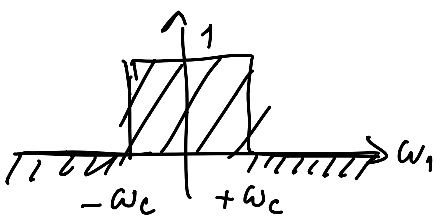
Inhibition of excitation in the retina

- Receptive field of a ganglion cell (=fiber of the optic nerve) shows „center-surround response“ with both
  - Lateral inhibition
  - Lateral excitation

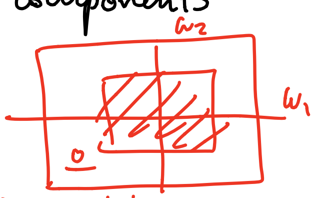




Low-pass

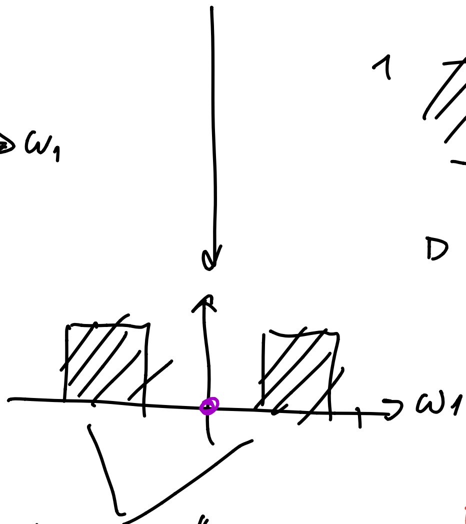


▷ keep only low-pass components



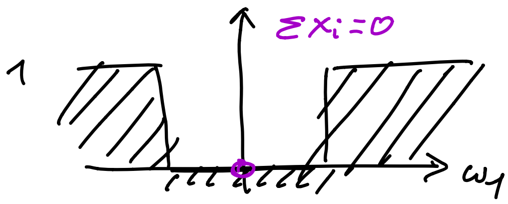
▷ Effect: blurred

Band-pass

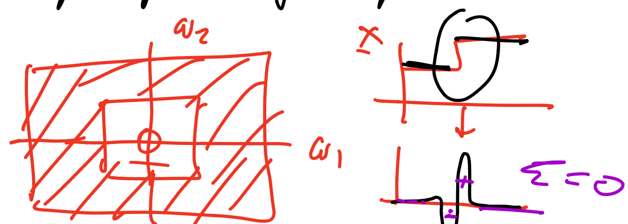


'Band'

High-pass

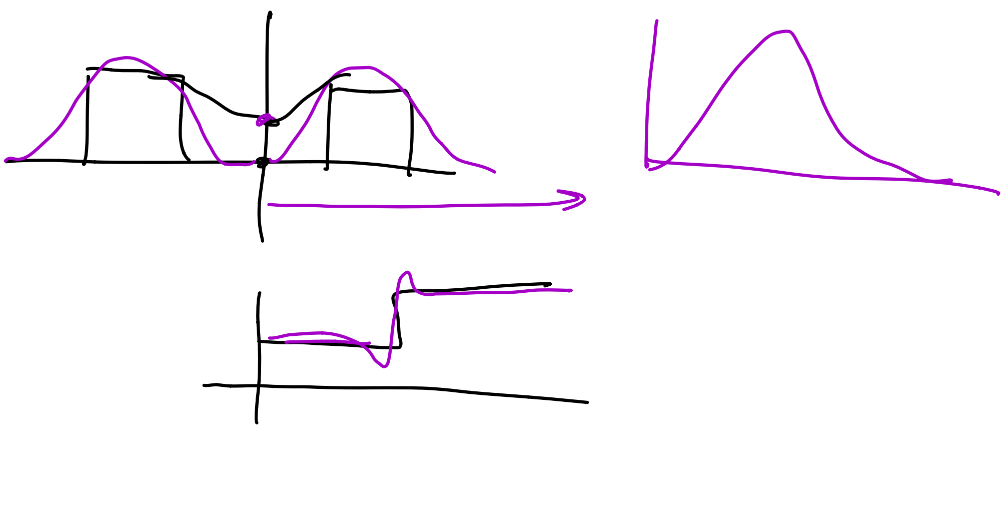


▷ keep high freq. components.



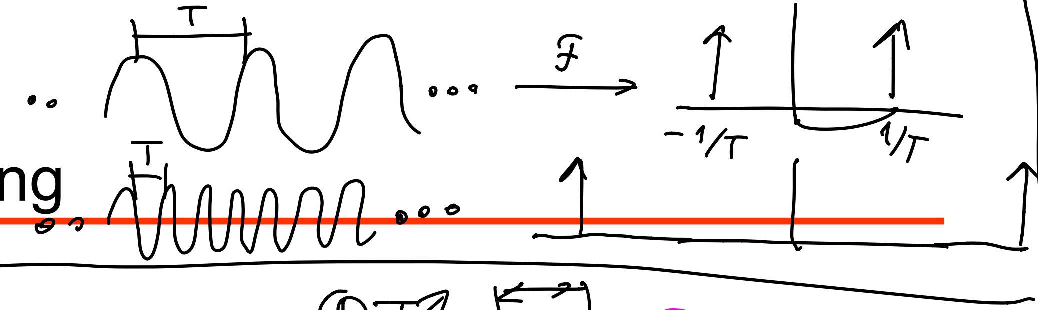
▷ Effect: edge detection

HUS

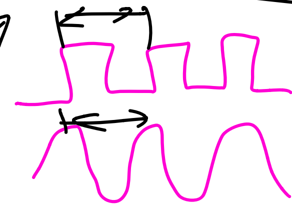


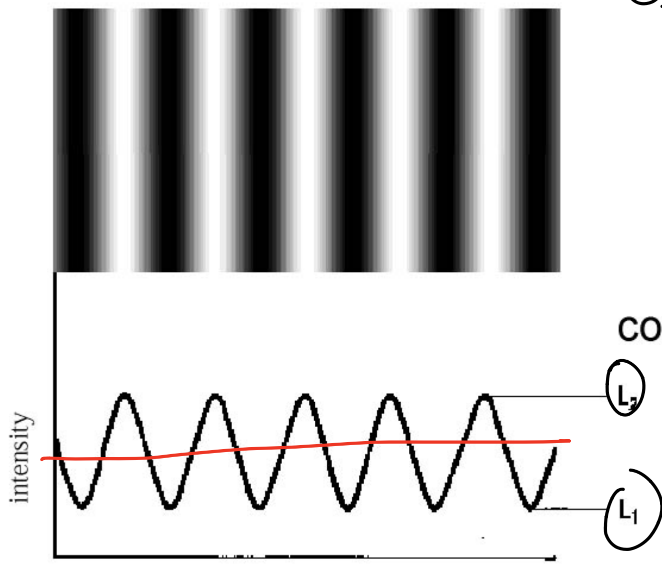
inversely proportional

Sine wave grating



① T ↗



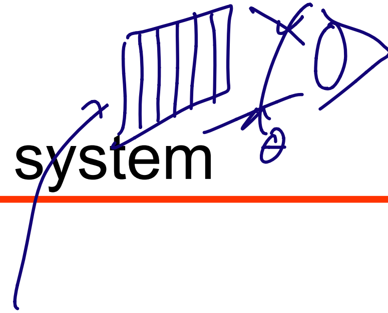


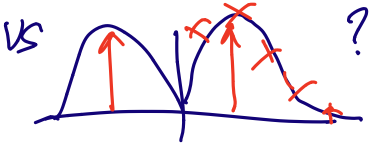
$$\text{contrast ratio} = \frac{L_2 - L_1}{L_2 + L_1}$$

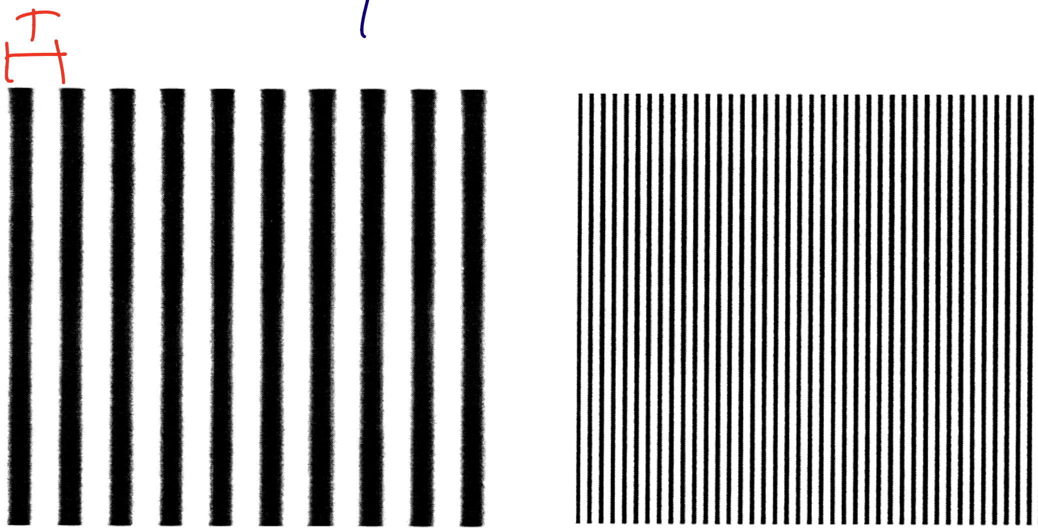
② Amplitude

③

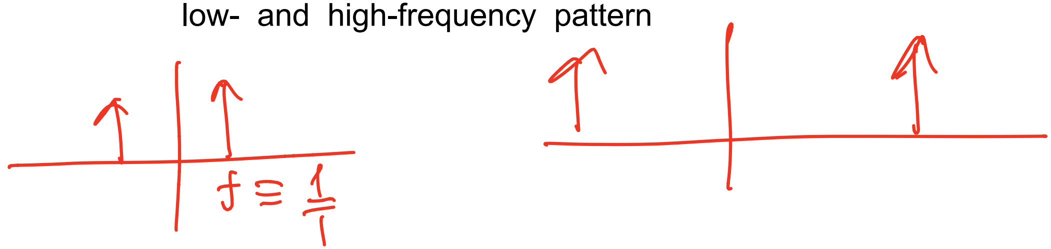
MTF of the visual system







low- and high-frequency pattern

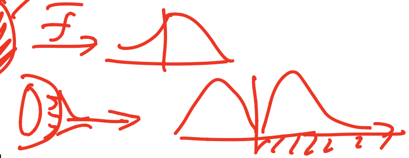


lense

modulation transfer function

(a) $\xrightarrow{F}$

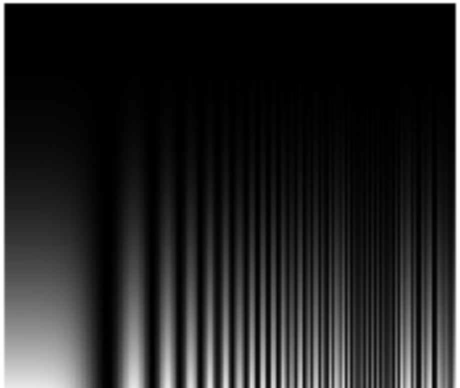
(b) HVS



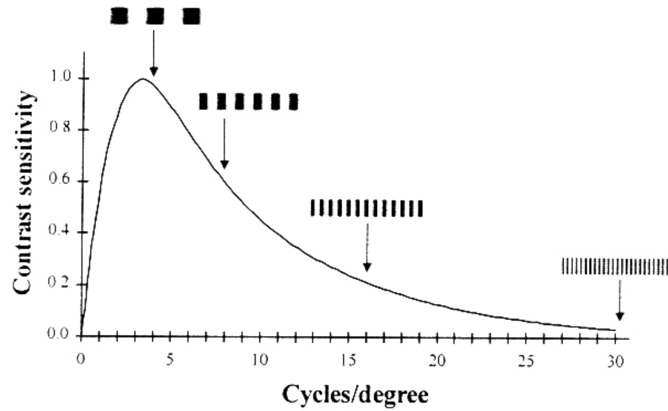
MTF: Modulated Sine Wave Grating

MTF – the measure of visual system in frequency domain

magn.



freq.



$$H(\xi_1, \xi_2) = H_p(\rho) = A\left[\alpha + \frac{\rho}{\rho_0}\right]\exp\left[-\left(\frac{\rho}{\rho_0}\right)^\beta\right]$$

$$\rho = \sqrt{\xi_1^2 + \xi_2^2} \ \ cycles/deg$$

(isotropic approximation)

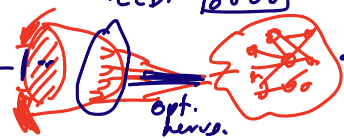
chirp

Lateral inhibition and excitation together lead to a bandpass characteristics of the contrast sensitivity function of the HVS

 → power

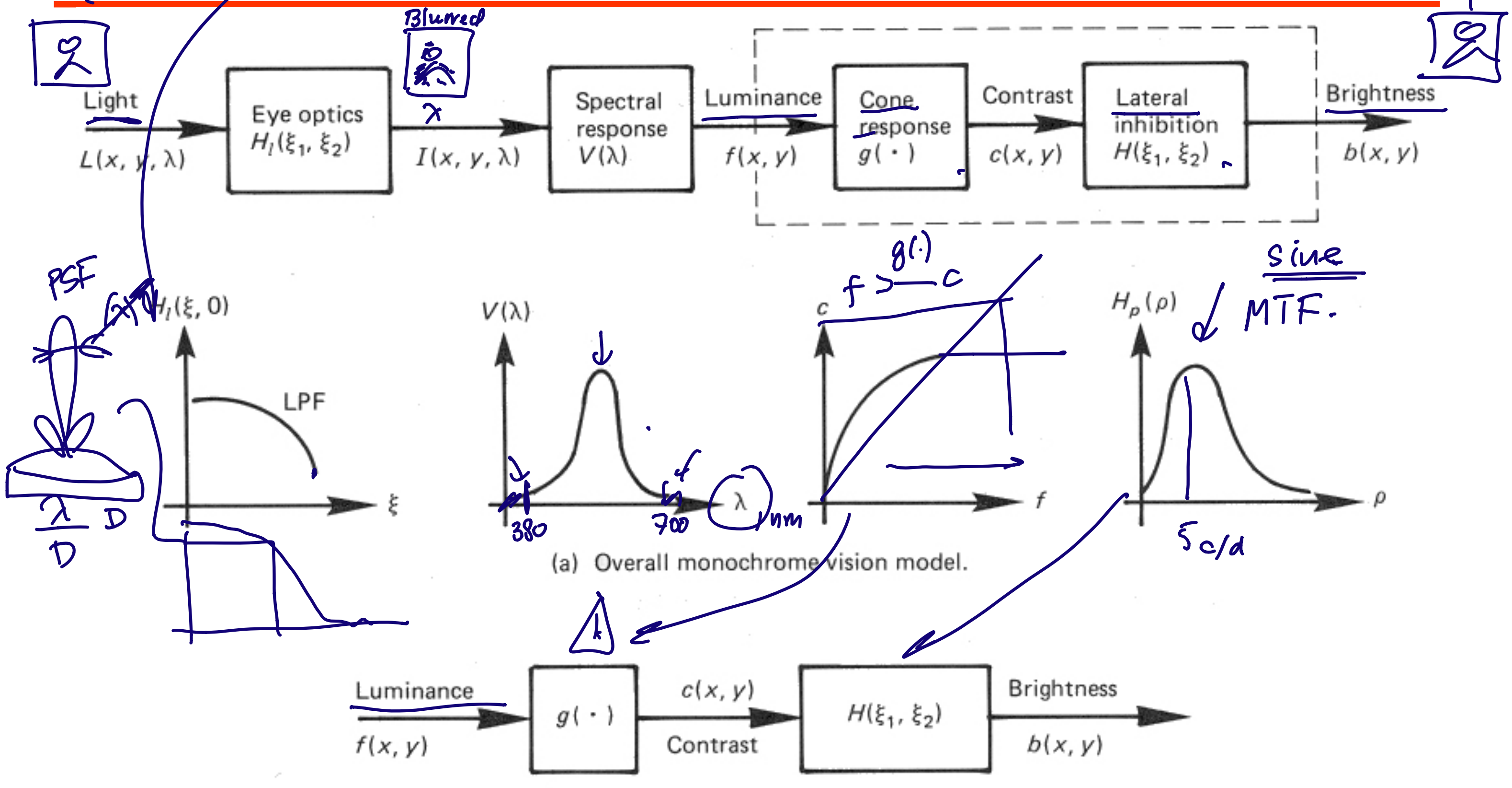
electrical signal

[CCD]



A. Join

Monochrome vision model



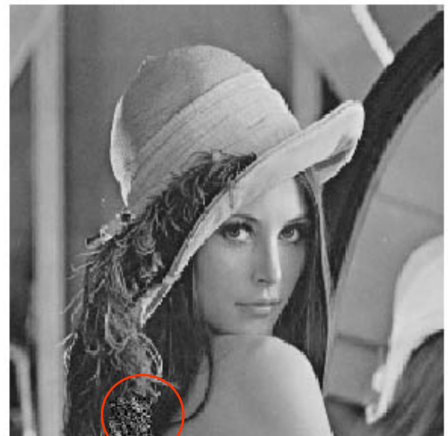
(a) Overall monochrome vision model.

(b) Simplified monochrome vision model.

Visibility function (Higher Order Vision): Masking

flat regions

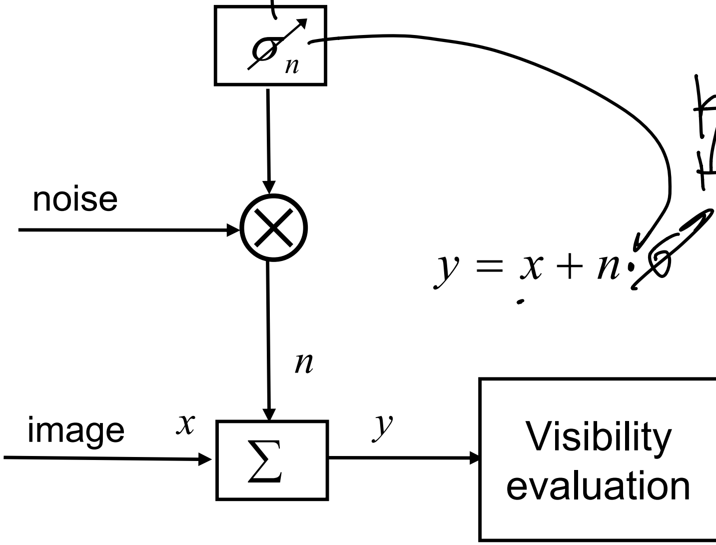
Visibility: very visible



edges & textures:

less visible

Noise Visibility Function (NVF)

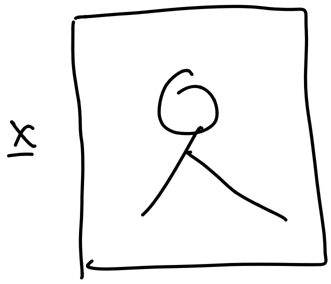


$$NVF\,(i,j) \in (0,1)$$

Behavior of NVF :

- for flat regions - $NVF \to 1,$
- for edge & texture regions - $NVF \to 0.$

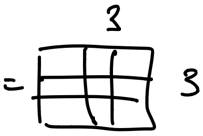
NVF → how to compute



Local:

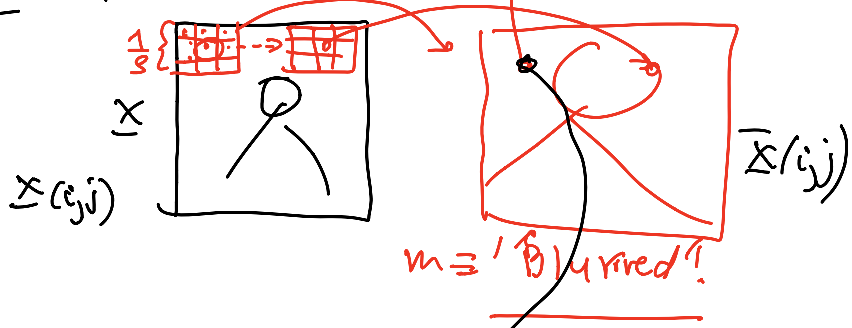
① mean

② std/var

filter $w = $ 

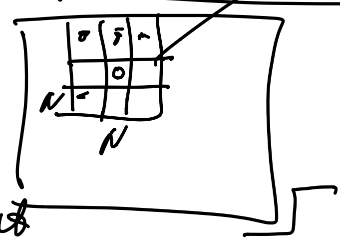
1) Mean: $\bar{x} = x * w$

$\frac{1}{9}\sum_w x$

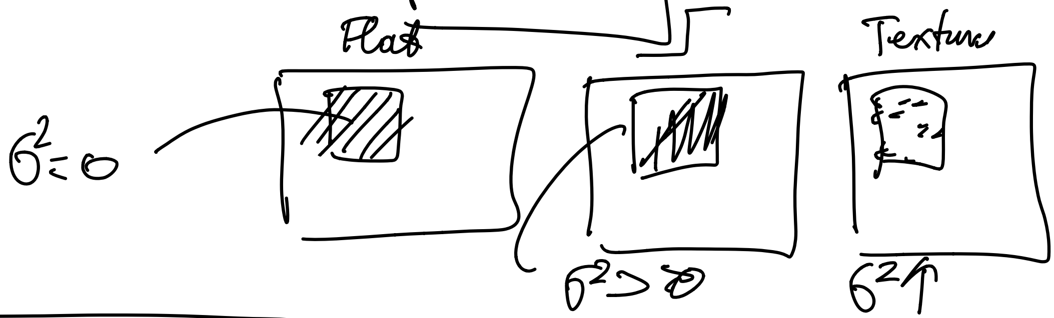


2) Var

$$\sigma_{(i,j)} = \frac{1}{w}\sum \left(x_{(k,l)} - \bar{x}_{(i,j)}\right)^2$$



$\boxed{\text{var\_x} = \text{stdfilter}(x, [N\ N])}$ with $N = 3$, $N = 3$



$$\boxed{NVF_{(i,j)} = \frac{1\ c}{\sigma^2_{(i,j)} + c}}$$

$\sigma^2_{(i,j)} \geq 0$

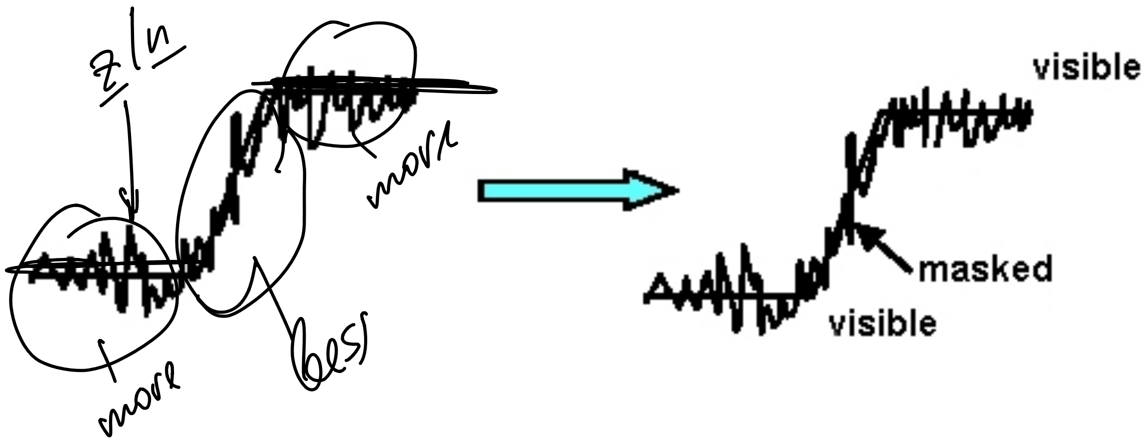
flat: $\sigma^2_{(i,j)} \to 0 : NVF_{(i,j)} \to \frac{1}{c} \to$ max. $\frac{\cancel{c}}{\cancel{c}} \to 1$

e & t: $\sigma^2_{(i,j)} \to \infty : NVF(i,j) \to 0.$

Features of the HVS

Masking Properties of HVS :

Texture masking



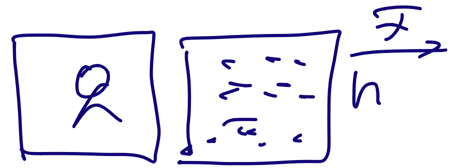
Note: however very sharp edges have higher visibility of distortions.

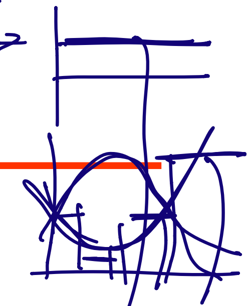
Features of the HVS

Features of the Human Visual System :

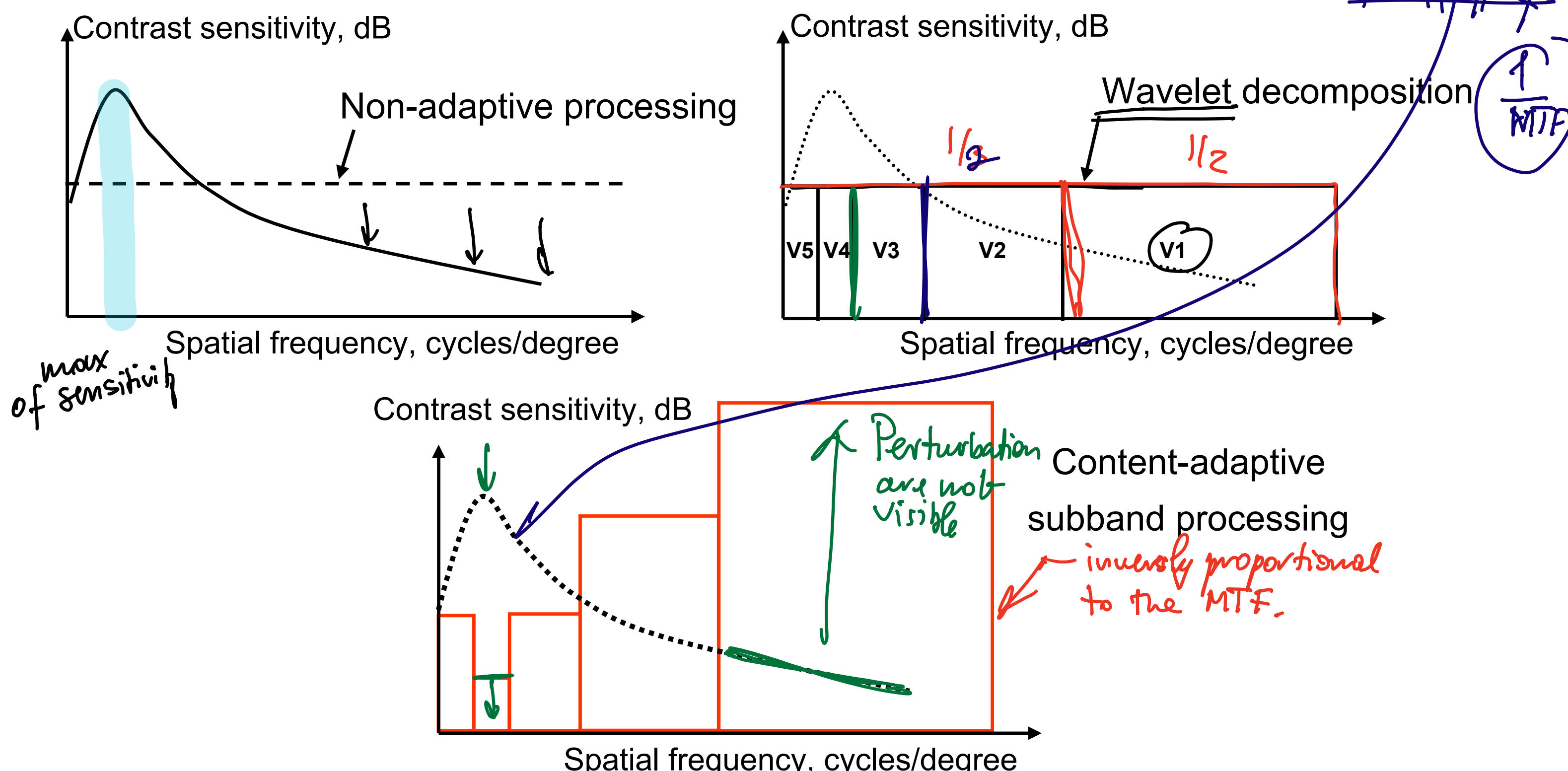
- on the global level:
  - – Modulation Transfer Function (MTF);
  - – anisotropy due to 3 different spatial orientations;
  - – multiresolution.
- on the local level:
  - – Noise Visibility Function (NVF)

Features of the HVS



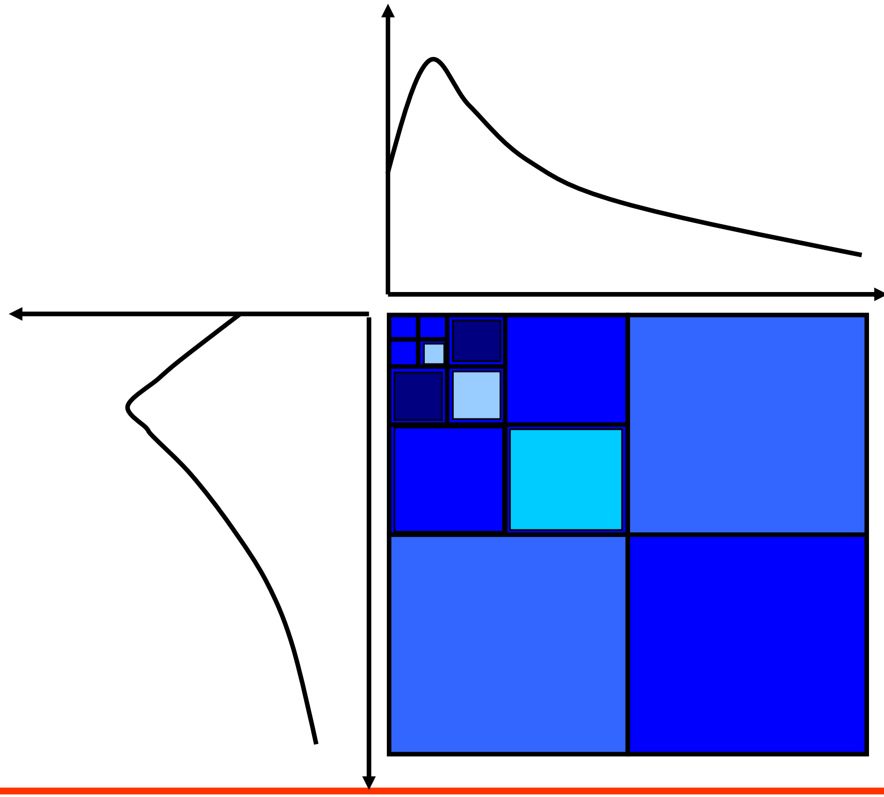


MTF – global features of the HVS



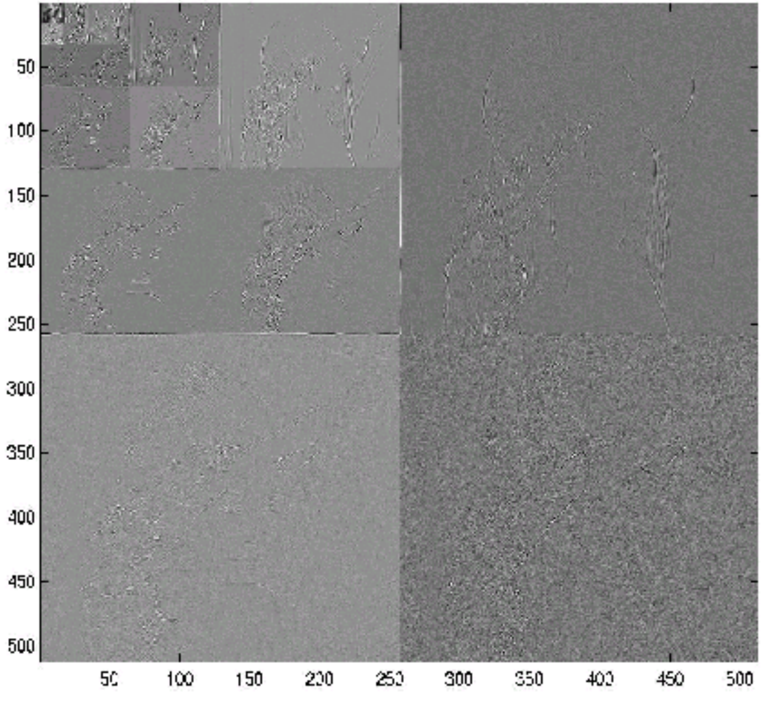
Features of the HVS

Spatial orientation – global features of the HVS



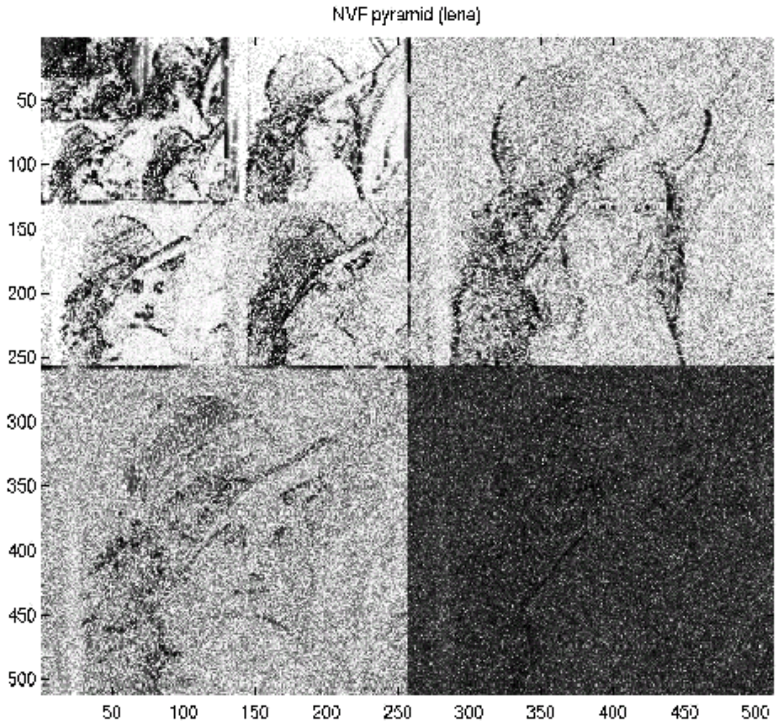
Features of the HVS

Multiresolution – global features of the HVS

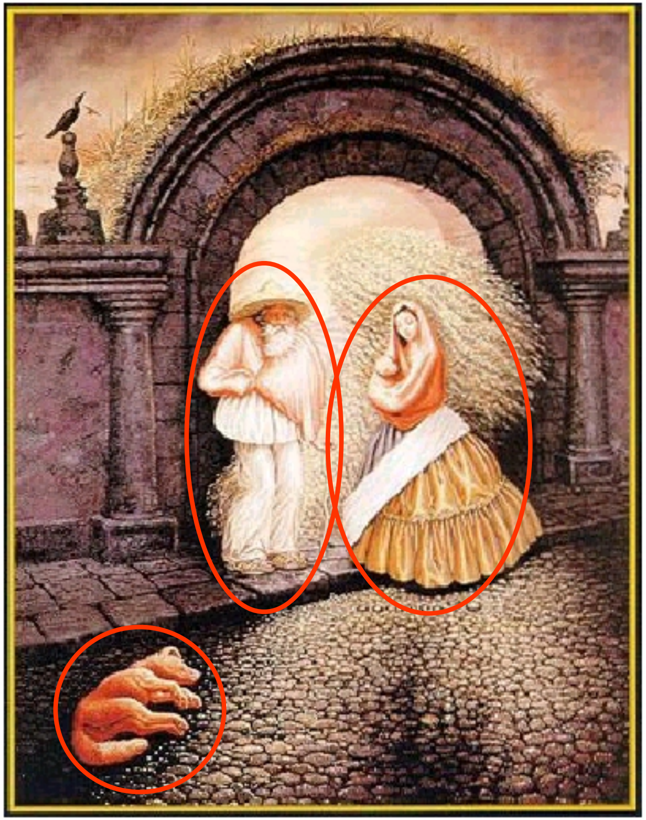


Features of the HVS

NVF – local features of the HVS



Perceptual Ambiguity



Perceptual Ambiguity

Perceptual Ambiguity

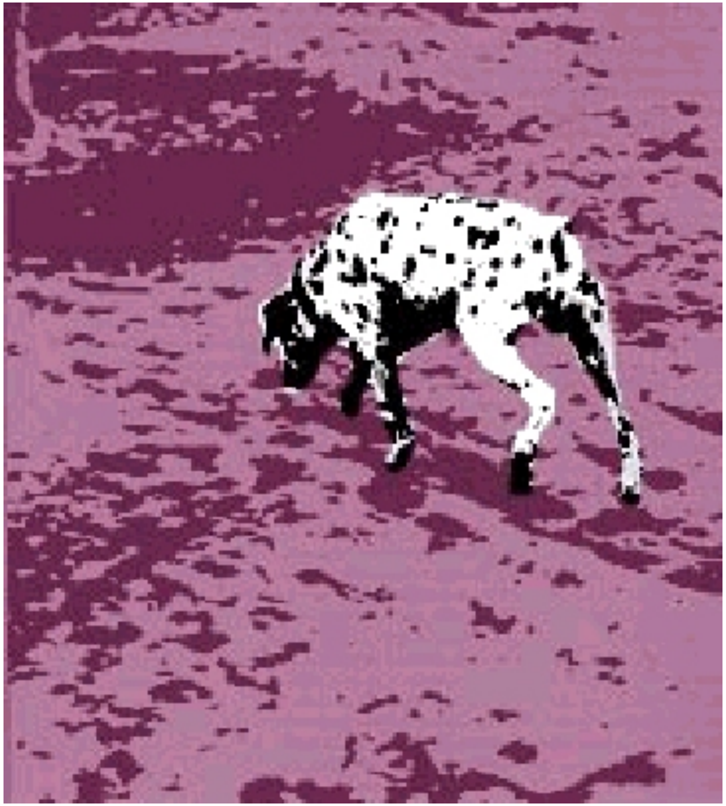


Image quality criteria

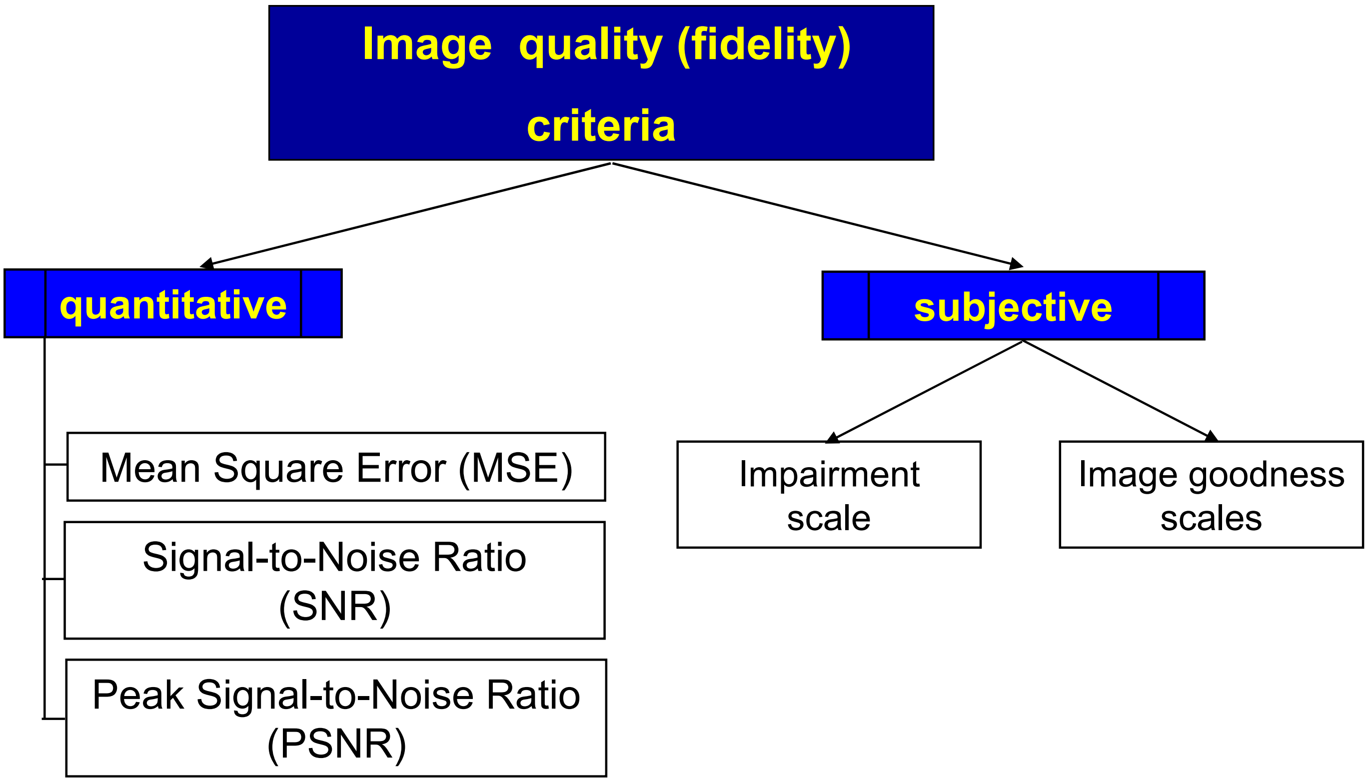


Image quality criteria

$|x(i,j) - x'(i,j)|^2$

	Quantitative criteria	

- MSE (mean square error) criterion: $$MSE = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}\left|x(i,j)-x'(i,j)\right|^2 \geq 0$$

(invariant to geom. distortions)

- SNR (signal-to-noise ratio) : $$SNR\text{, dB} = 10\log_{10}\frac{\sigma_x^2}{MSE}$$

- PSNR (peak signal-to-noise ratio) : $$PSNR\text{, dB} = 10\log_{10}\frac{\max(x)^2}{MSE}$$

255^2

max (x)

- SSIM (Alan Bovik).

Image quality criteria

Subjective criteria

- impairment scale :

Q Factor	Quality	Impairment
5	Excellent	Imperceptible
4	Good	Perceptible, but not annoying
3	Fair	Slightly annoying
2	Poor	Annoying
1	Bad	Very annoying

Image quality criteria: Weighted Metrics

HVS + −

MSE:

$$MSE = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}\left|x(i,j)-x'(i,j)\right|^2$$

Weighted MSE:

$\sigma^2 \to 0 : NVF \to 1$

$\sigma^2 \to \infty : NVF \to 0$

$$wMSE = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}\left(NVF(i,j)\cdot\left|x(i,j)-x'(i,j)\right|^2\right)$$

1

0

PSNR:

$$PSNR,\mathrm{dB} = 10\log_{10}\frac{\max(x)^2}{MSE}$$

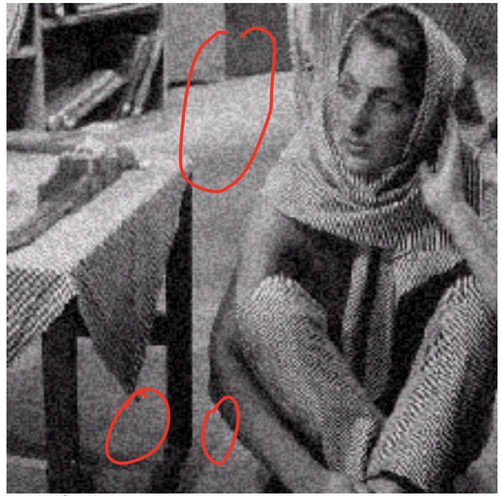
Weighted PSNR:

$$wPSNR,\mathrm{dB} = 10\log_{10}\frac{\max(x)^2}{wMSE}$$

Image quality criteria – comparative analysis

Original image "Barbara"

X + Z



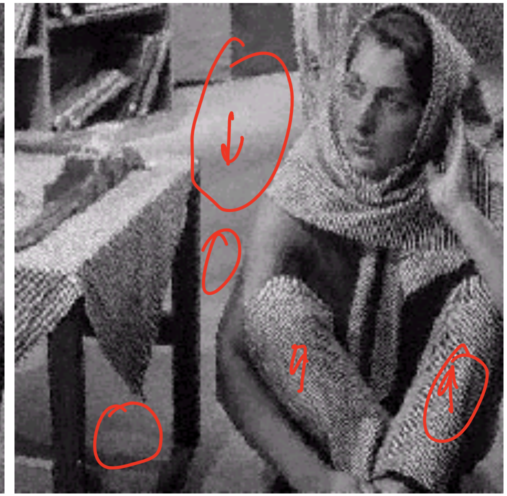
Added Noise

PSNR = 24.6 dB,

wPSNR = 26.4 dB

NVF

→0



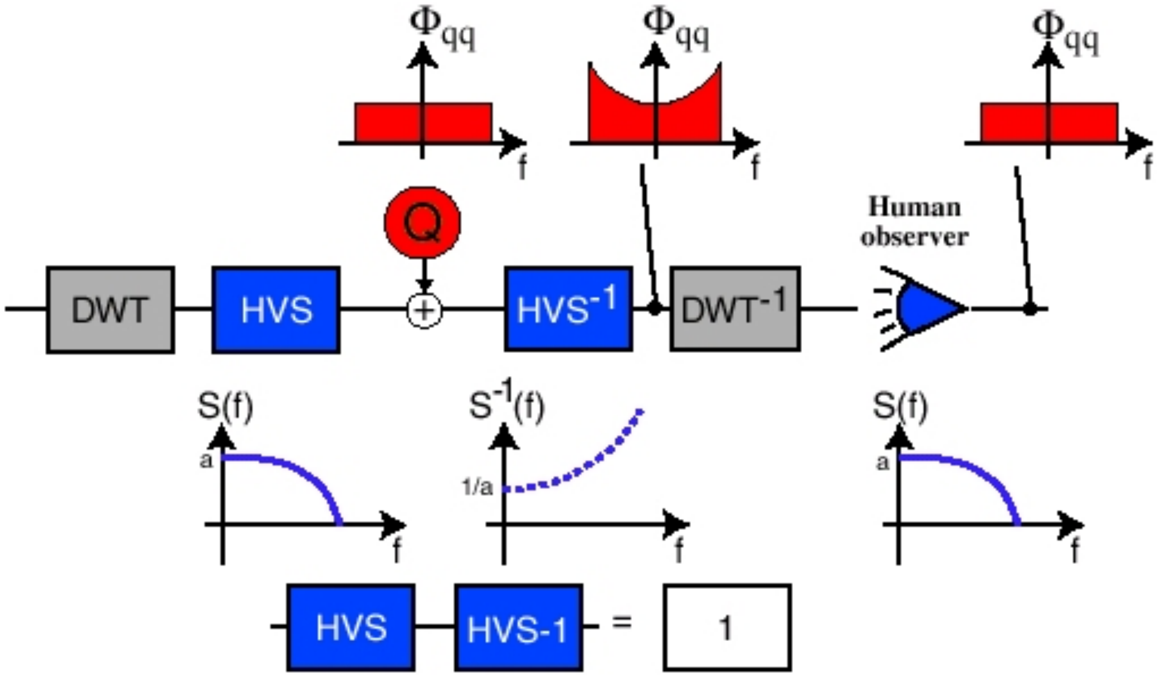
the same

Image with perceptually adopted noise

PSNR = 24.6 dB,

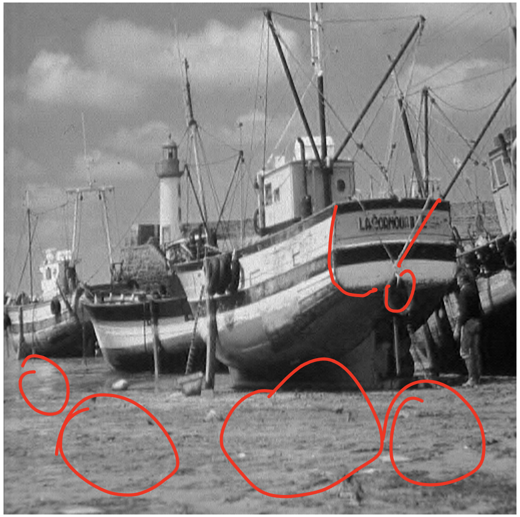
wPSNR = 29.3 dB

How to exploit the properties of the HVS?



Features of the HVS – comparative analysis

Grayscale image



PSNR=33 dB

PSNR=37 dB

Original image

Features of the HVS – comparative analysis

RGB

Color image

PSNR=37 dB

Original image

PSNR=35 dB

Blue → noise → will be almost invisible.

HVS: conclusions

- Spatial frequency components visible up to 60 cpd.
- Logarithmic relationship between luminance and subjective perceived brightness.
- Lateral inhibition -> spatial bandpass character.
- Resolution of HVS depends on the wavelength.
- Resolution of HVS depends on the orientation.
- Visibility threshold is high for the flat regions and in the vicinity of very sharp edges.
- Visibility of distortions is decreased in the texture regions due to perceptual masking.