Computer Graphics

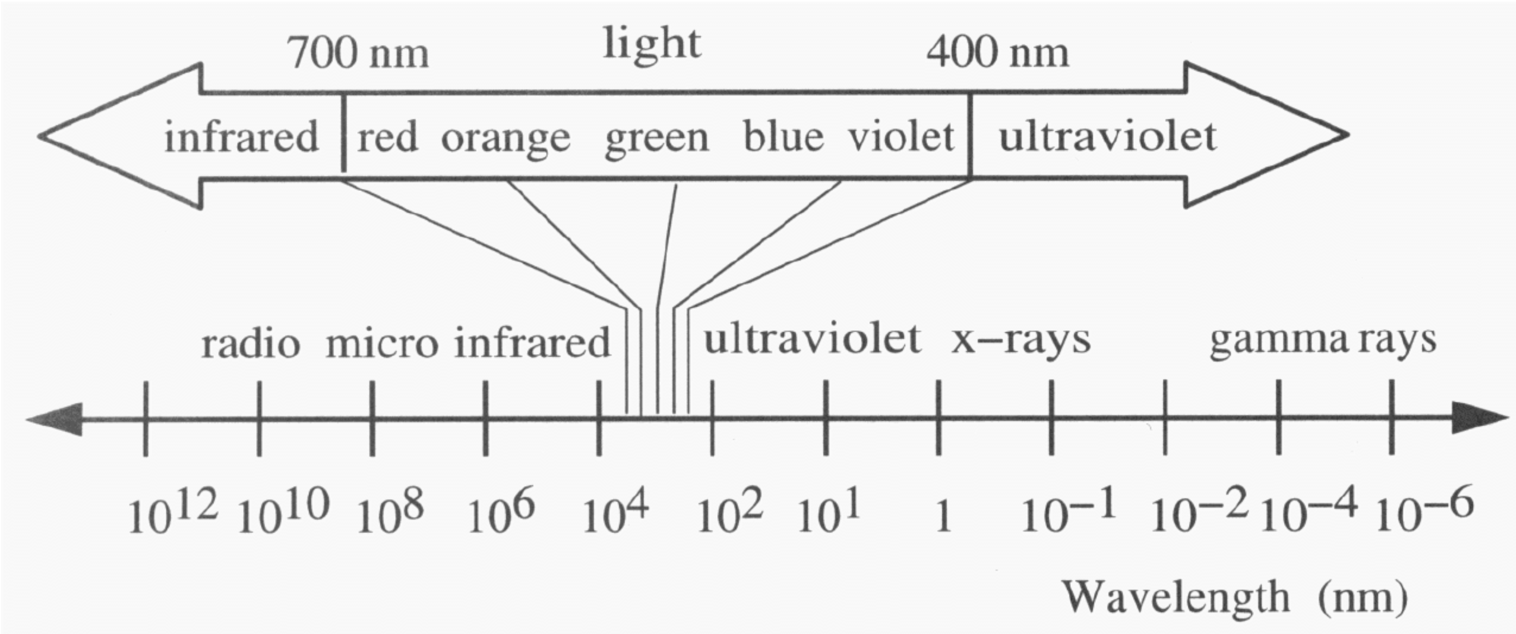
- The Human Visual System -

Overview

- **Last time**
  - Antialiasing
  - Super-Sampling
- **Today**
  - The Human Visual System
    - The eye
    - Early vision
    - High-level analysis
    - Color perception
- **Next lecture**
  - Color spaces

Light

- **Electromagnetic radiation**
- **Visible spectrum: ~ 400 to 700 nm**



Radiation Law

- **Physical model for light**
  - Wave/particle-dualism
    - Electromagnetic radiation wave model
    - Photons: $E_{ph}=h\nu$ particle model & ray optics
  - Plenoptic function
    - $L= L(x, \omega, t, \nu, \gamma)$, 5 dimensional,

Ignored parameters:
- No polarization
- No fluorescence
  - Decoupling of the spectrum
- Not time dependent
  - Instant propagation with speed of light
  - no phosphorescence

Used parameters:
- Direction
- Location

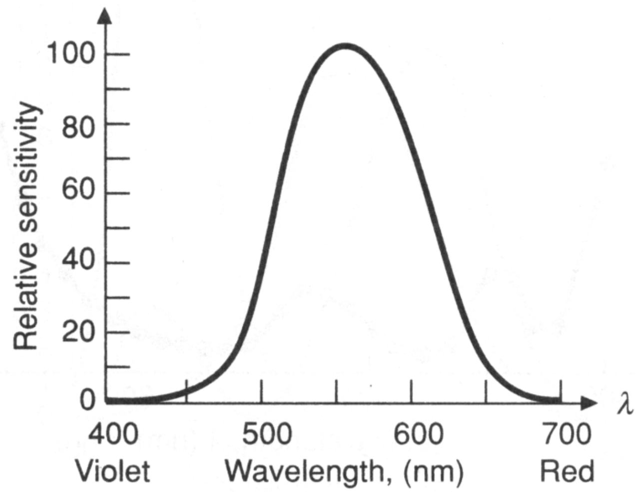
Photometry

- **Equivalent units to radiometry**
  - Weight with **luminous efficiency function** V(λ) (luminous efficiency function)
  - Spectral or “total” units

$$\Phi_v = K_m \int V(\lambda)\Phi_e(\lambda)d\lambda$$

$$K_m = 680\, lm / W$$

  - Distinction in English simple:
    - “rad”: radiometric unit
    - “lum”: photometric unit



Radiometric Units

Specification	**Definition**	**Symbol**	**Unit**	**Notation**
Energie energy		Q_e	[J= Ws] Joule	Strahlungsenergie **radiant energy**
Leistung, Fluß power, flux	dQ/dt	Φ_e	[W= J/s]	Strahlungsfluß **radiant flux**
Flußdichte flux density	dQ/dAdt	E_e	[W/m^2]	Bestrahlungsstärke **Irradiance**
Flußdichte flux density	dQ/dAdt	$M_e = B_e$	[W/m^2]	Radiom. Emissionsvermögen **Radiosity**
	dQ/dA$^\Phi$dωdt	L_e	[W/m^2/sr]	Strahlungsdichte **Radiance**
Intensität intensity	dQ/dωdt	I_e	[W/sr]	Strahlungsstärke radiant **intensity**

Photometric Units

With luminous efficiency function weighted units

Specification	**Definition**	**Symbol**	**Units**	**Notation**
Energie energy		Q_v	[talbot]	Lichtmenge **luminous energy**
Leistung, Fluß power, flux	dQ/dt	Φ_v	[lm (Lumen) = talbot/s]	Lichtstrom **luminous flux**
Flußdichte flux density	dQ/dAdt	E_v	[lux= lm/m^2]	Beleuchtungsstärke **Illuminance**
Flußdichte flux density	dQ/dAdt	[M_v=] B_v	[lux]	Photom. Emissionsvermögen **Luminosity**
	dQ/dA$^\Phi$dωdt	L_v	[lm/m^2/sr]	Leuchtdichte **Luminance**
Intensität intensity	dQ/dωdt	I_v	[cd (candela) = lm/sr]	Lichtstärke radiant **intensity**

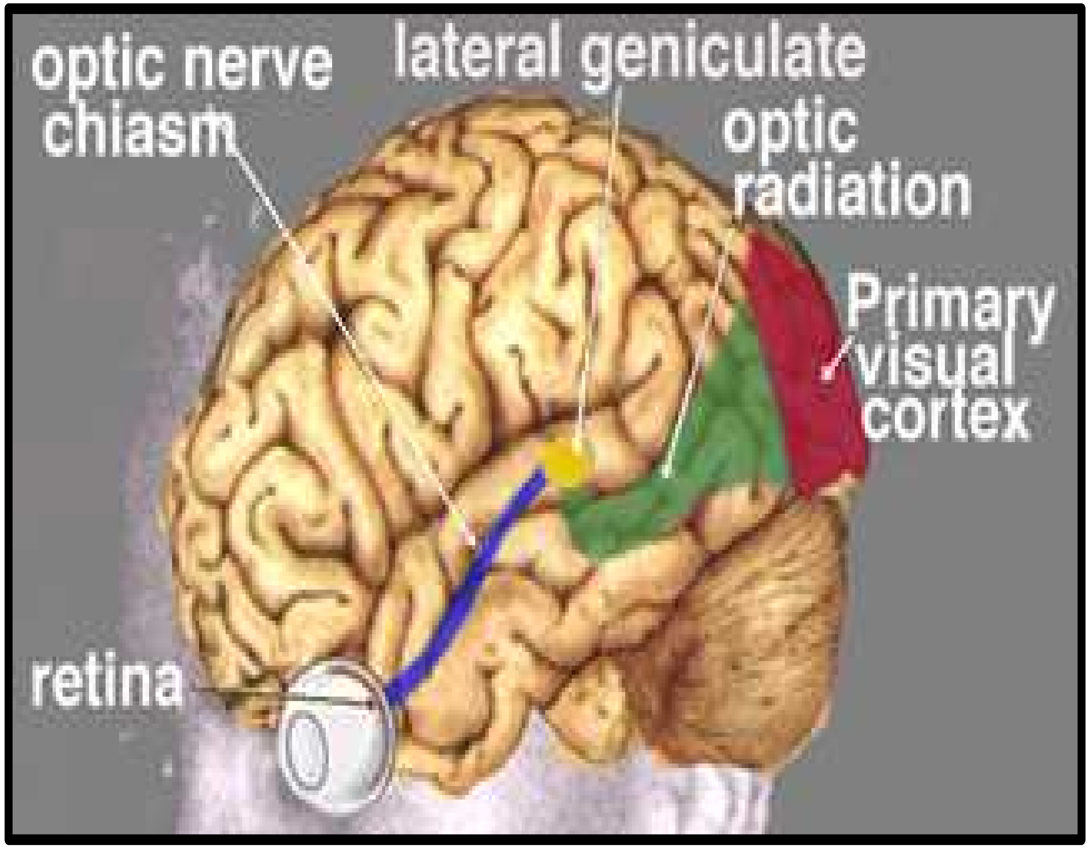
Illumination: samples

- **Typical illumination intensities**

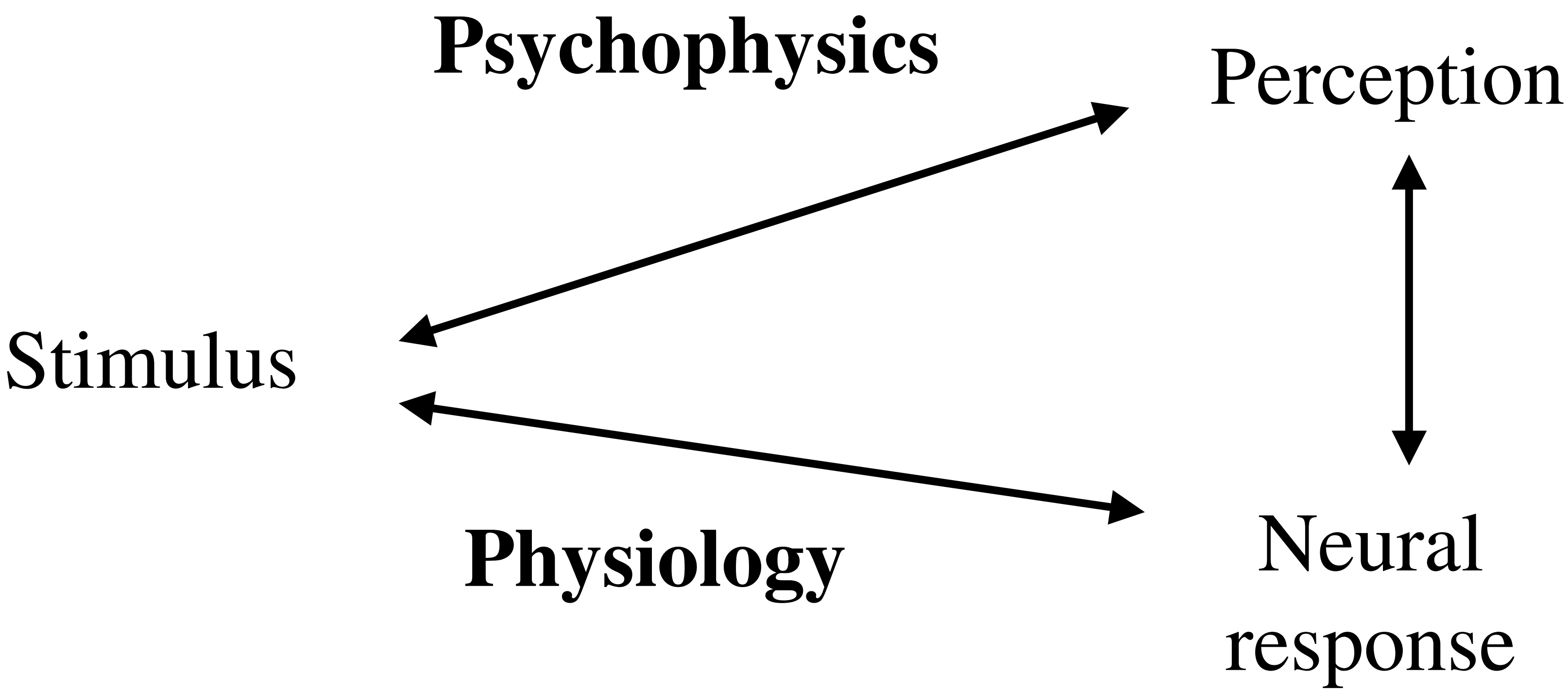
Light source	Illumination intensity [lux]
Direct solar radiation	25.000 – 110.000
Day light	2.000 – 27.000
Sunset	1 – 108
Moon light	0.01 – 0.1
Starry night	0.0001 – 0.001
TV studio	5.000 – 10.000
Shop lighting	1.000 – 5.500
Office lighting	200 – 550
Home lighting	50 – 220
Street lighting	0.1 – 20

Human Visual System

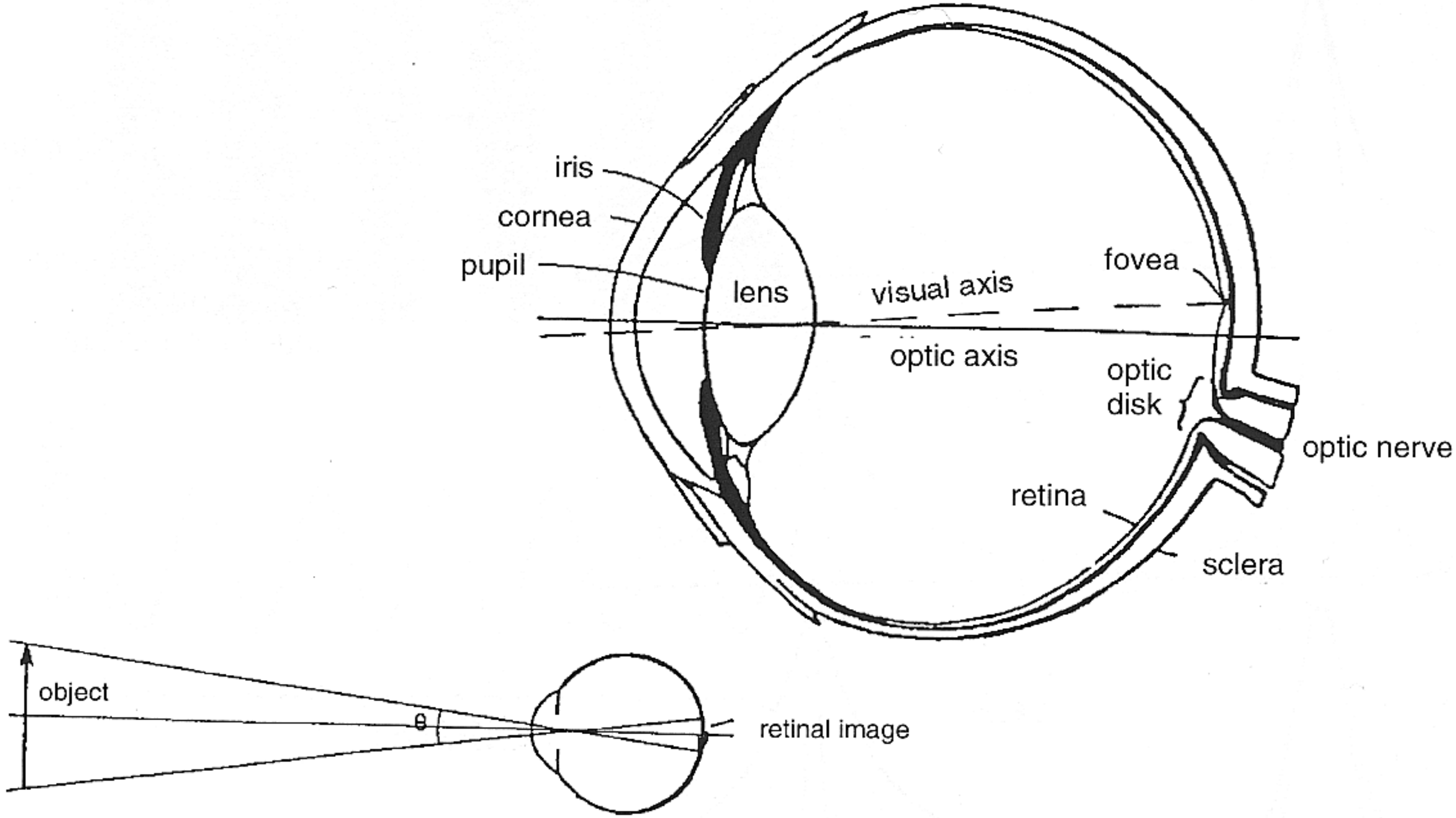
- **Physical structure well established**
- **Perceptual behaviour is a complex process**



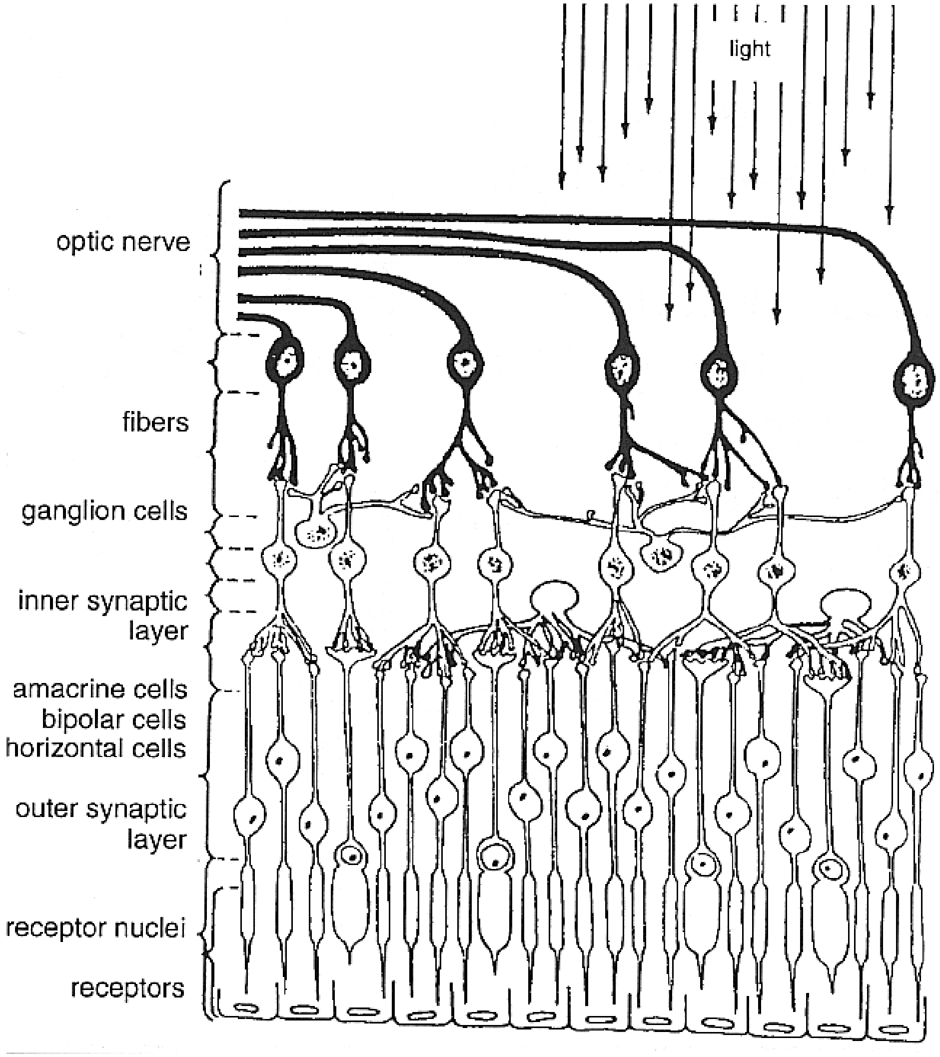
HVS - Relationships



Perception and Eye



Retina

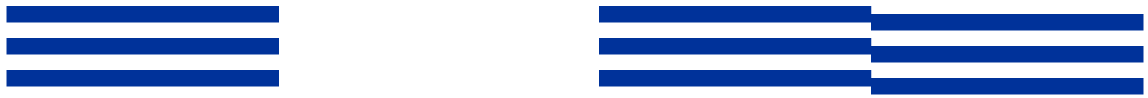

light
optic nerve
fibers
ganglion cells
inner synaptic layer
amacrine cells
bipolar cells
horizontal cells
outer synaptic layer
receptor nuclei
receptors

Eye

- **Eye:**
  - Fovea: Ø 1-2 visual degrees
    - 6-7 Mio. ***cones***, circa 0.4 arc seconds sized
    - No rods
    - Three different cone types: L(ong), M(edium), S(hort wavelength)
    - Linked directly with optical nerves
    - Resolution: 10 arc minutes (S, blue), 0.5 arc minutes (L, M)
    - Adaptation of light intensity only through cones
  - Periphery:
    - 75-150 Mio. ***rods***, night vision, S/W
    - Response to stimulation of approx. 5 photons/sec. (@ 500 nm)
    - Many thousands of cells are linked with nerves
      - Bad resolution
      - Good flickering sensitivity

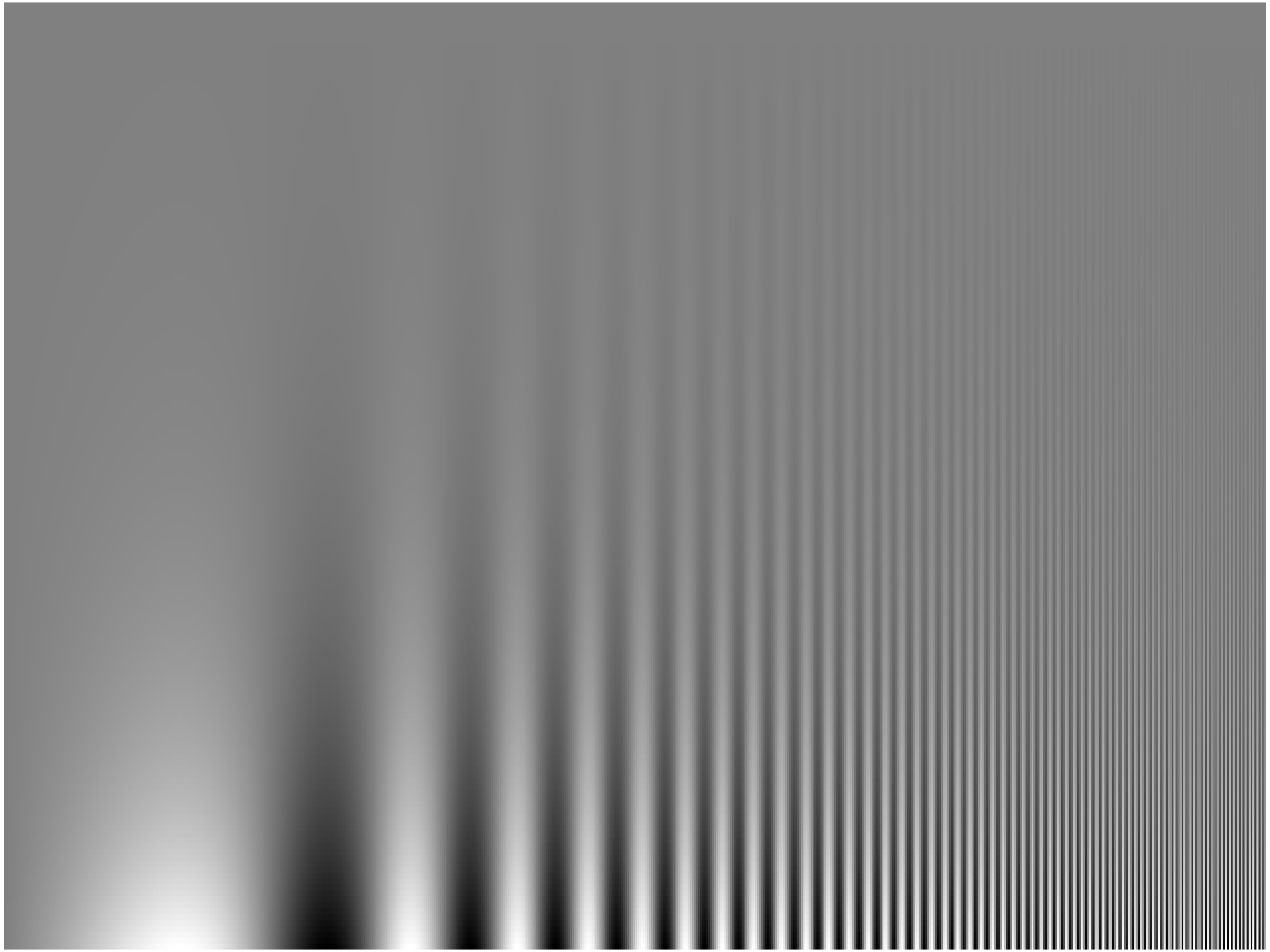
Resolution of the Eye

- **Resolution-experiments**
  - Line pairs: 50-60/degree ➔ resolution .5 arc minutes
  - Line offset: 5 arc seconds = 1/6 !! (hyperacuity)



  - Eye micro-tremor: 60-100 Hz, 5 µm (2-3 photoreceptor spacings)
  - Super-resolution
  - 19“ display at 60 cm: 18.000 x 18.000 (3000 x 3000) Pixel
- **Eye fixates itself**
  - Automatic gaze tracking
  - Overall high resolution
- **Visual acuity increased by**
  - Brighter objects
  - High contrast

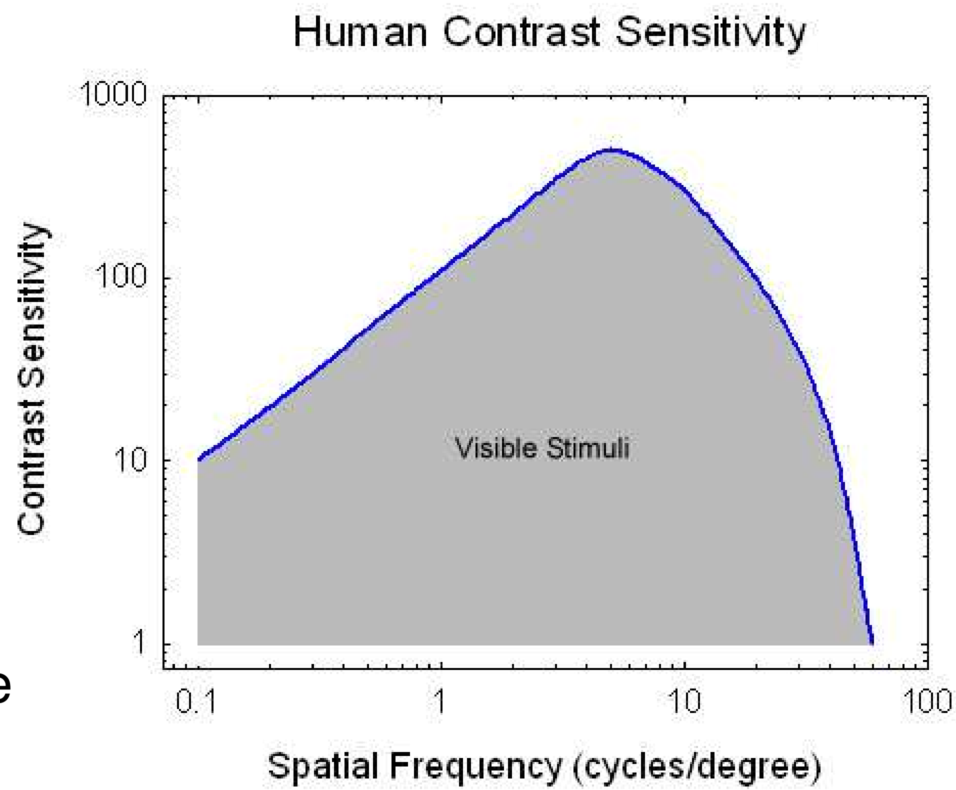
Luminance Contrast Sensitivity



Campbell-Robson contrast sensitivity chart

Contrast Sensitivity

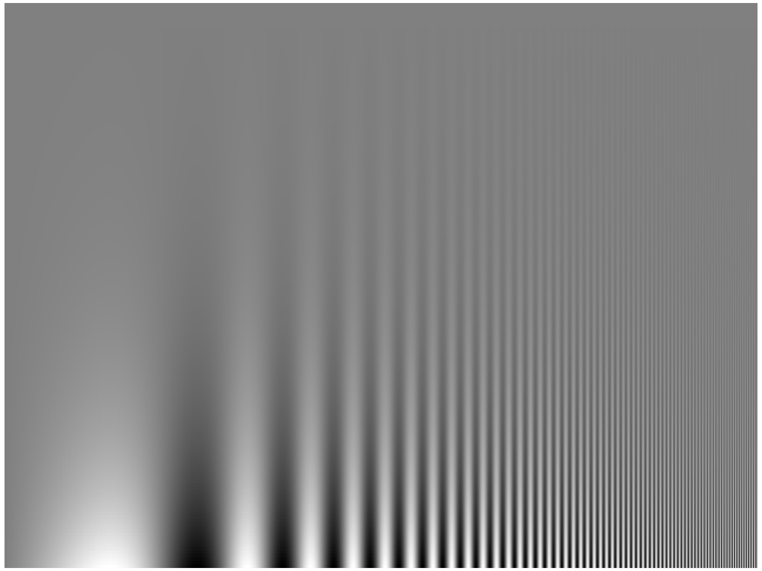
- **Sensitivity:**
  1 / threshold contrast
- **Maximum acuity:**
  5 cycles/degree (0.2 %)
  – Decrease toward low frequencies: lateral inhibition
  – Decrease toward high frequencies: sampling rate (Poisson disk)
  – Upper limit: 60 cycles/degree

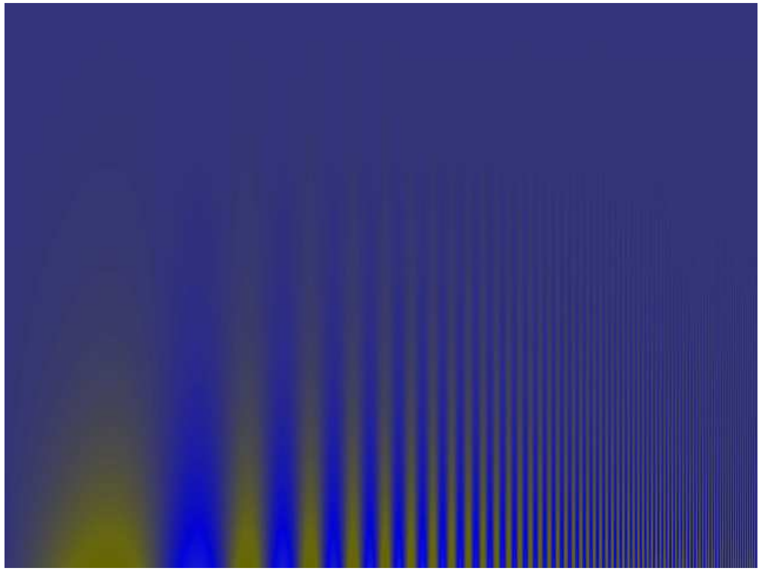


- **Medical diagnosis**
  – Glaucoma (affects peripheral vision: low frequencies)
  – Multiple sclerosis (affects optical nerve: notches in contrast sensitivity)

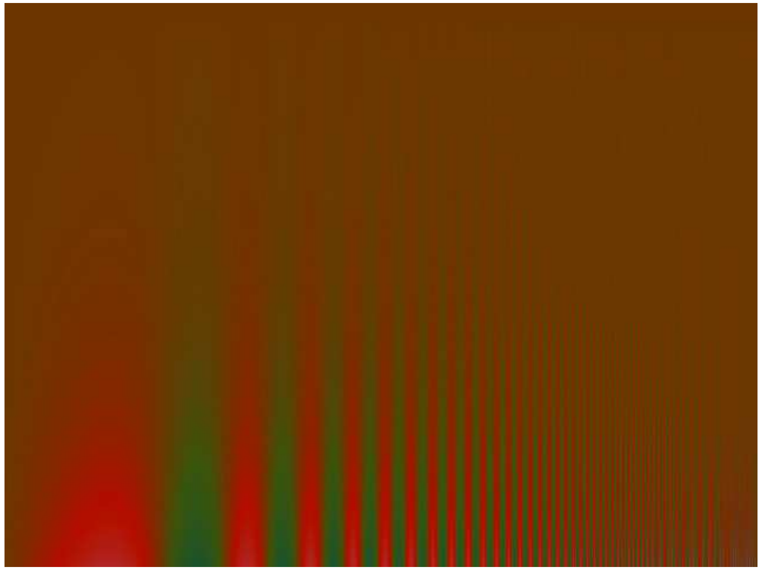
www.psychology.psych.ndsu.nodak.edu

Color Contrast Sensitivity





- **Color vs. luminance vision system**
  - Higher sensitivity at lower frequencies
  - High frequencies less visible
- **Image compression**

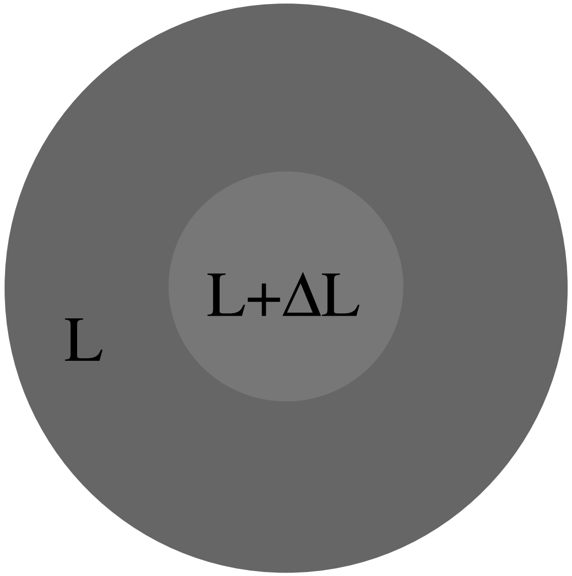


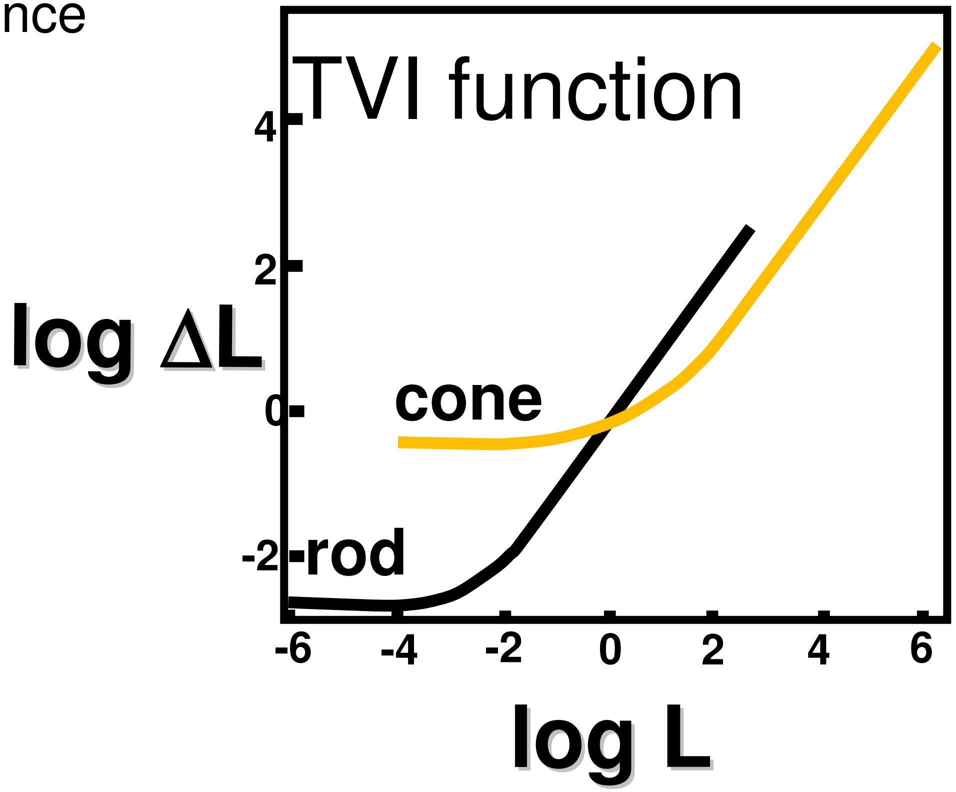
Threshold Sensitivity Function

- **Weber-Fechner Law**
  - Perceived brightness = log (radiant intensity)

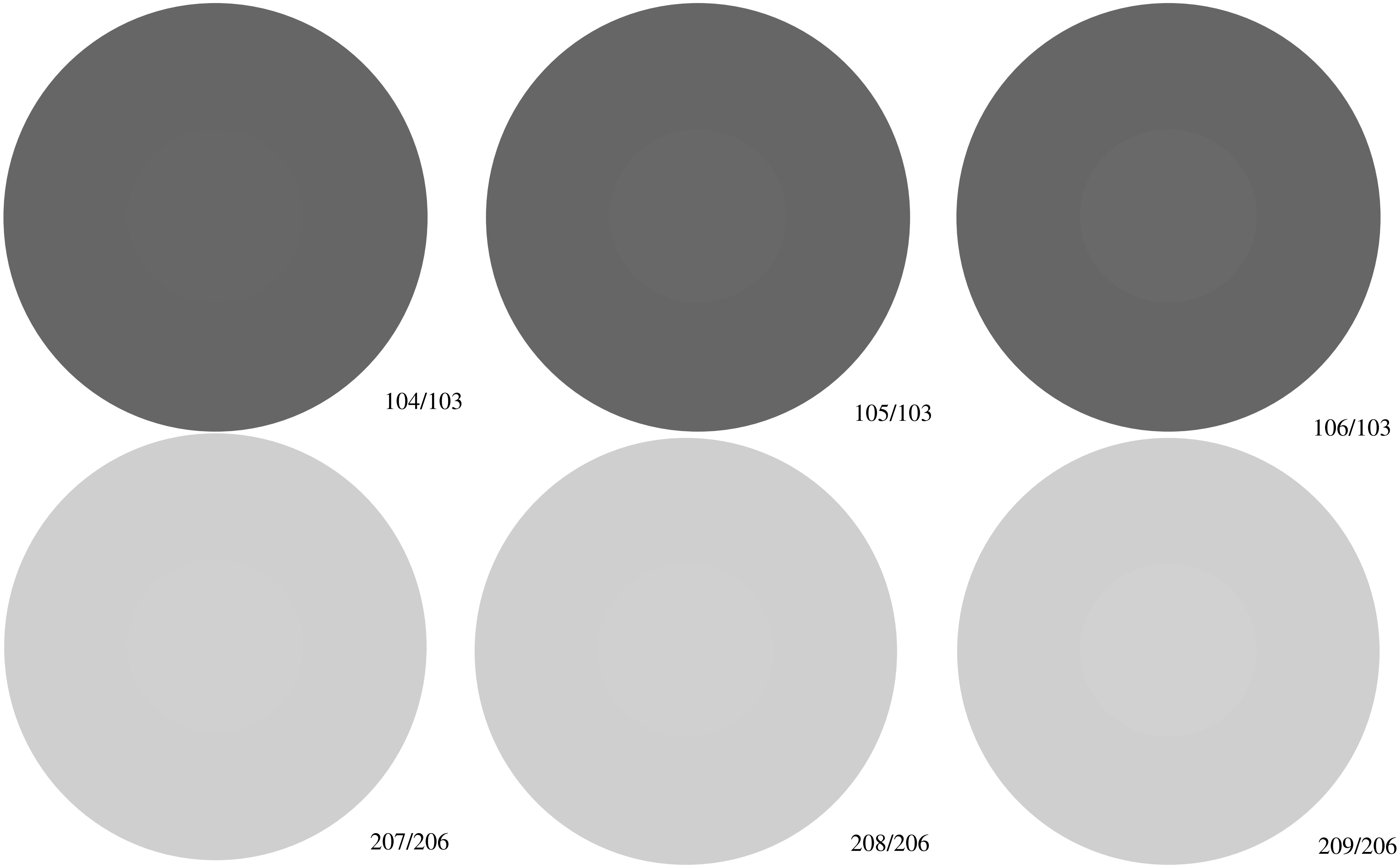
    $$\mathbf{E=K+c \log I_v}$$

  - Perceivable intensity difference
    - 10 cd vs. 12 cd: **ΔL=2cd**
    - 20 cd vs. 24 cd: **ΔL=4cd**
    - 30 cd vs. 36 cd: **ΔL=6cd**

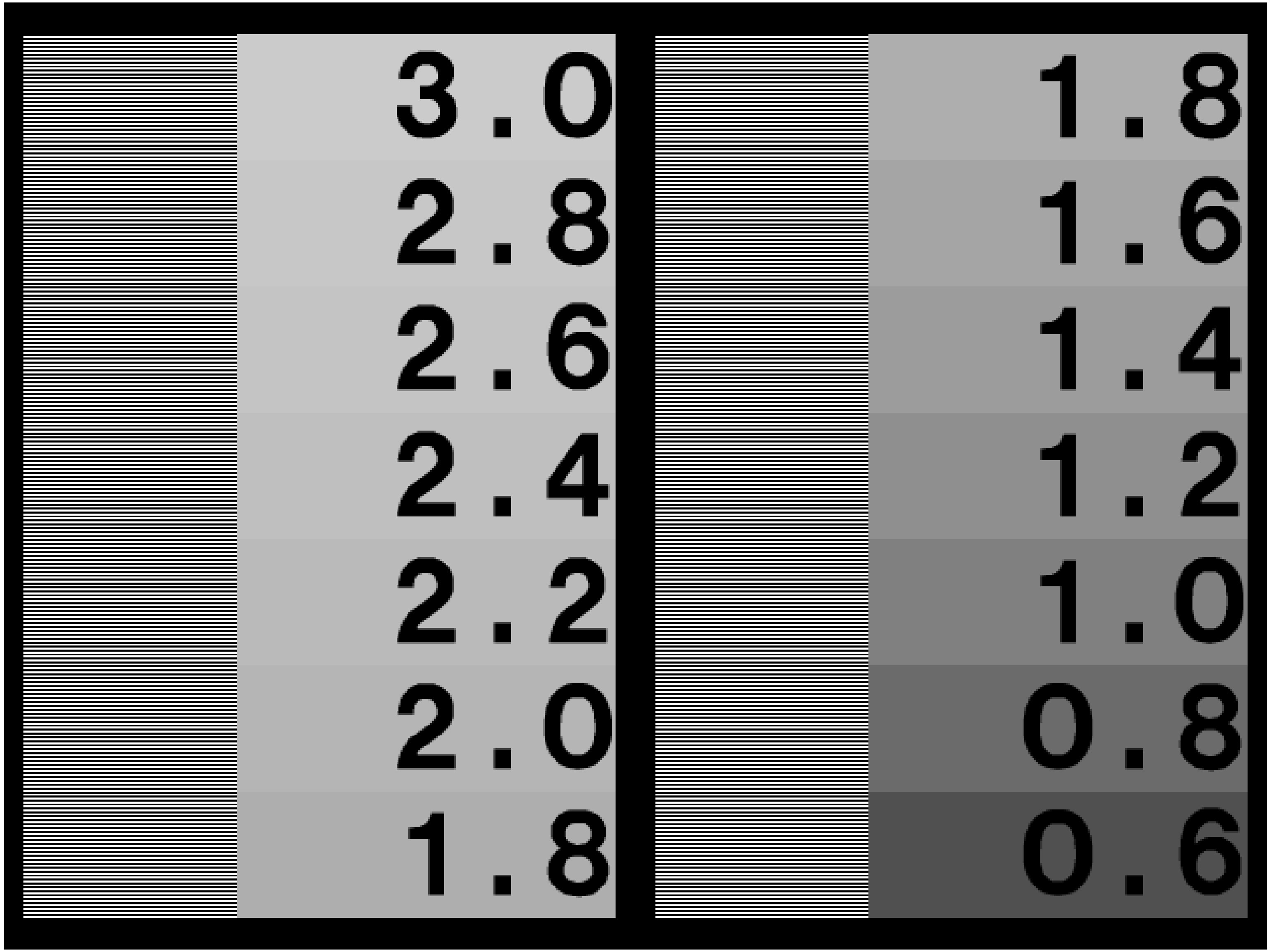




Weber-Fechner Examples

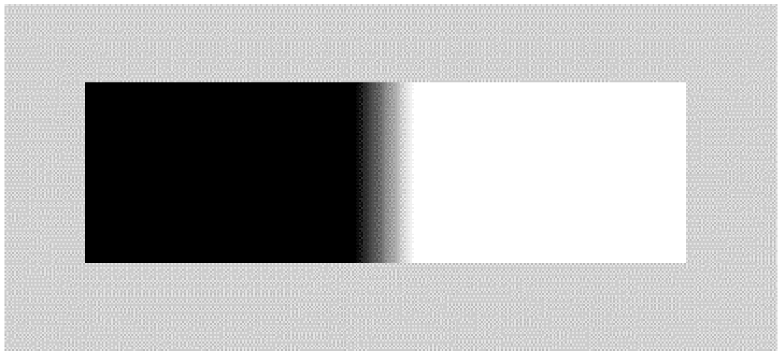


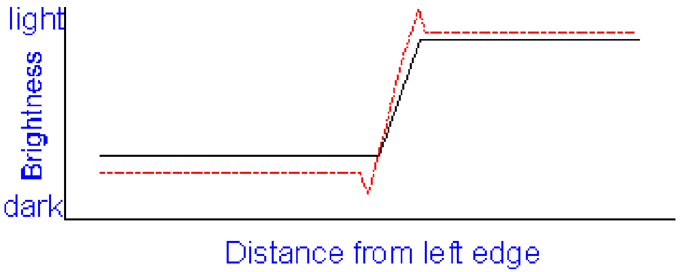
Intermediate: Gamma Test

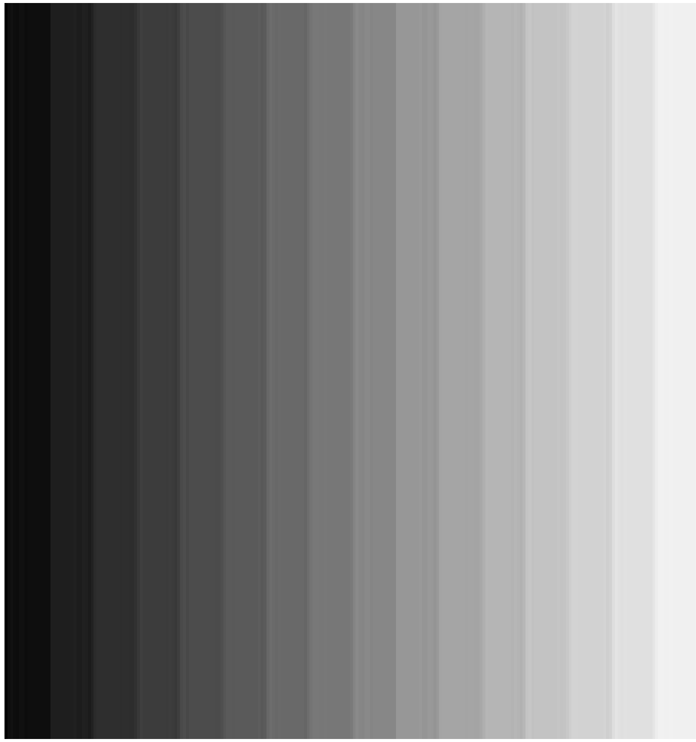


Mach Bands

- **“Overshooting“ along edges**
  - Extra-bright rims on bright sides
  - Extra-dark rims on dark sides
- **Lateral Inhibition**

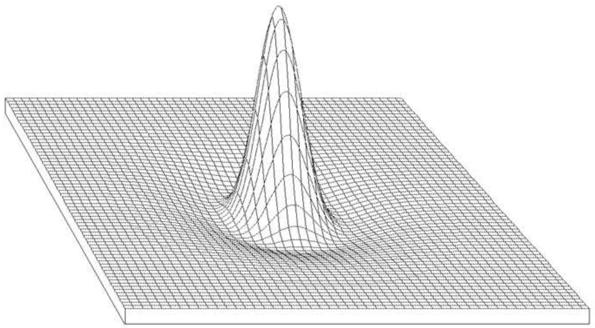


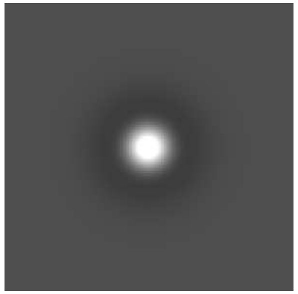


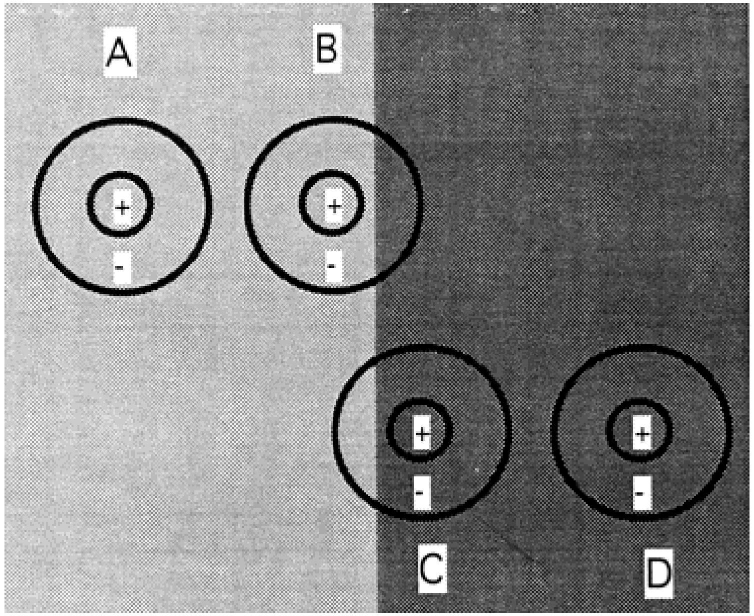


Lateral Inhibition

- **Pre-processing step within retina**
  - Surrounding brightness level weighted negatively
    - A: bright stimulus, maximal bright inhibition
    - B: bright stimulus, partial bright inhibition => stronger response
    - C: dark stimulus, partial dark inhibition => weaker response
    - D: dark stimulus, maximal dark inhibition
- **High-pass filter**
  - Enhances contrast along edges
  - Difference-of-Gaussians (DOG) function

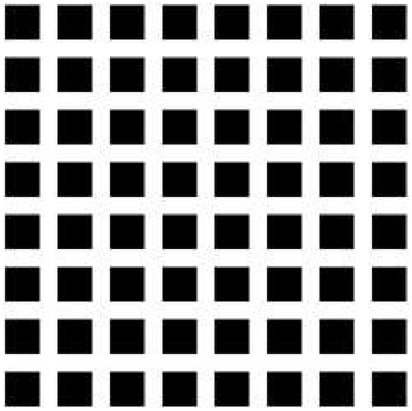


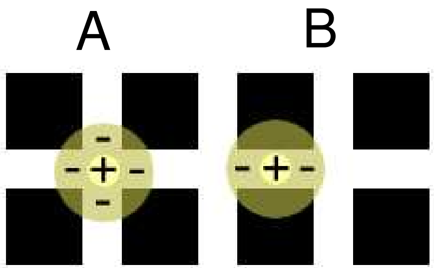


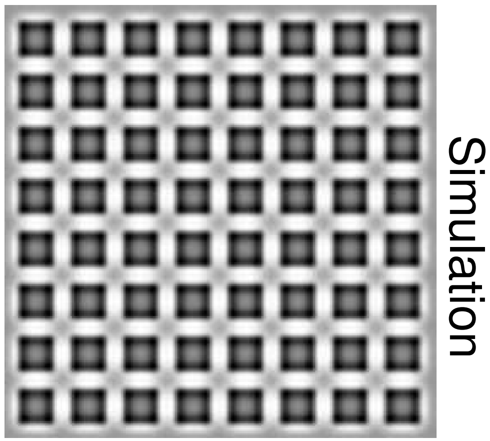


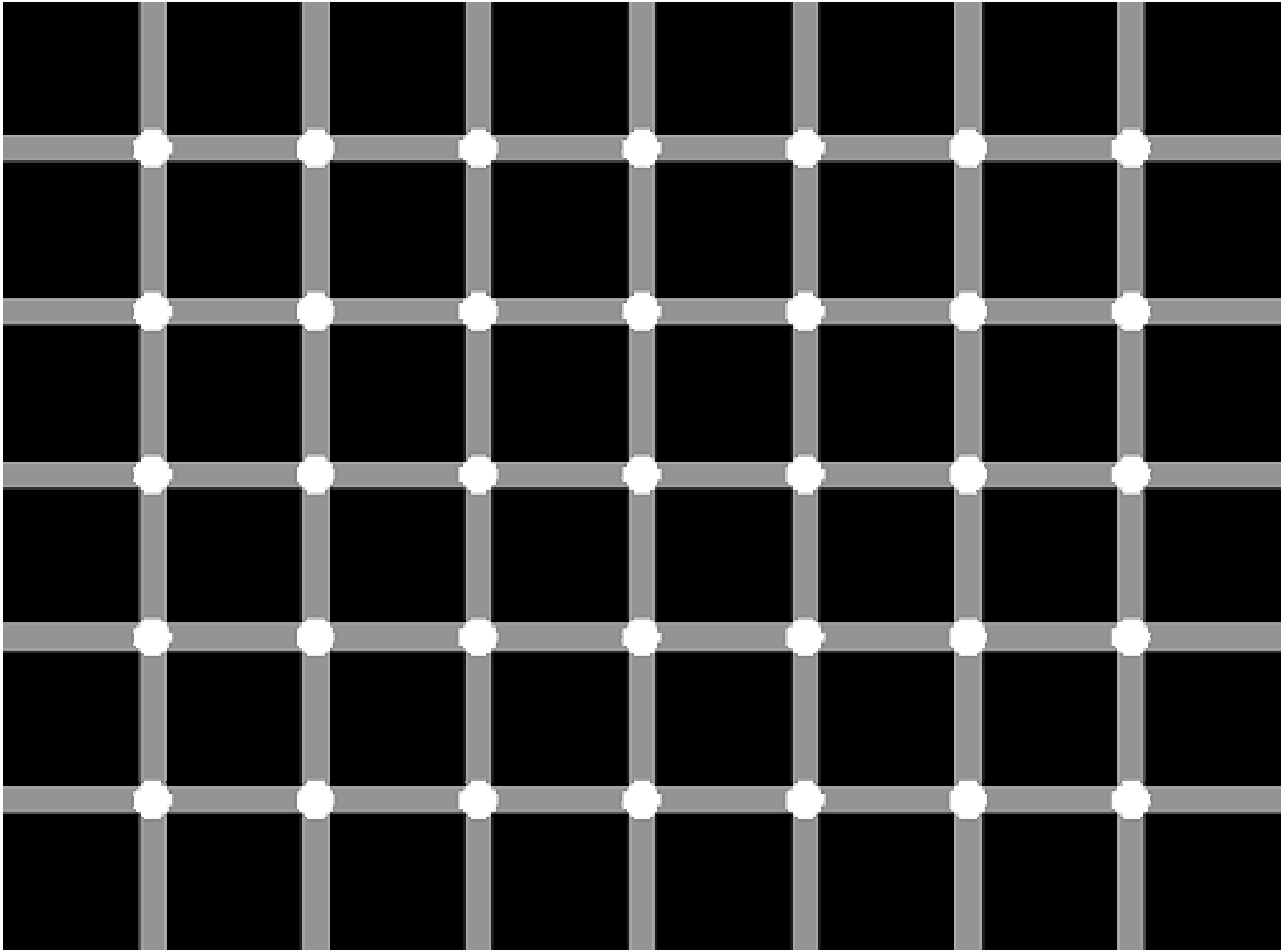
Lateral Inhibition: Hermann Grid

- **Dark dots at crossings**
- **Explanation**
  - Crossings (A)
    - More surround stimulation (more bright area)
    - ⇒ More inhibition
    - ⇒ Weaker response
  - Streets (B)
    - Less surround stimulation
    - ⇒ Less inhibition
    - ⇒ Greater response
- **Filtered with DOG function**
  - Darker at crossings, brighter in streets
  - Appears more steady
  - What if reversed ?

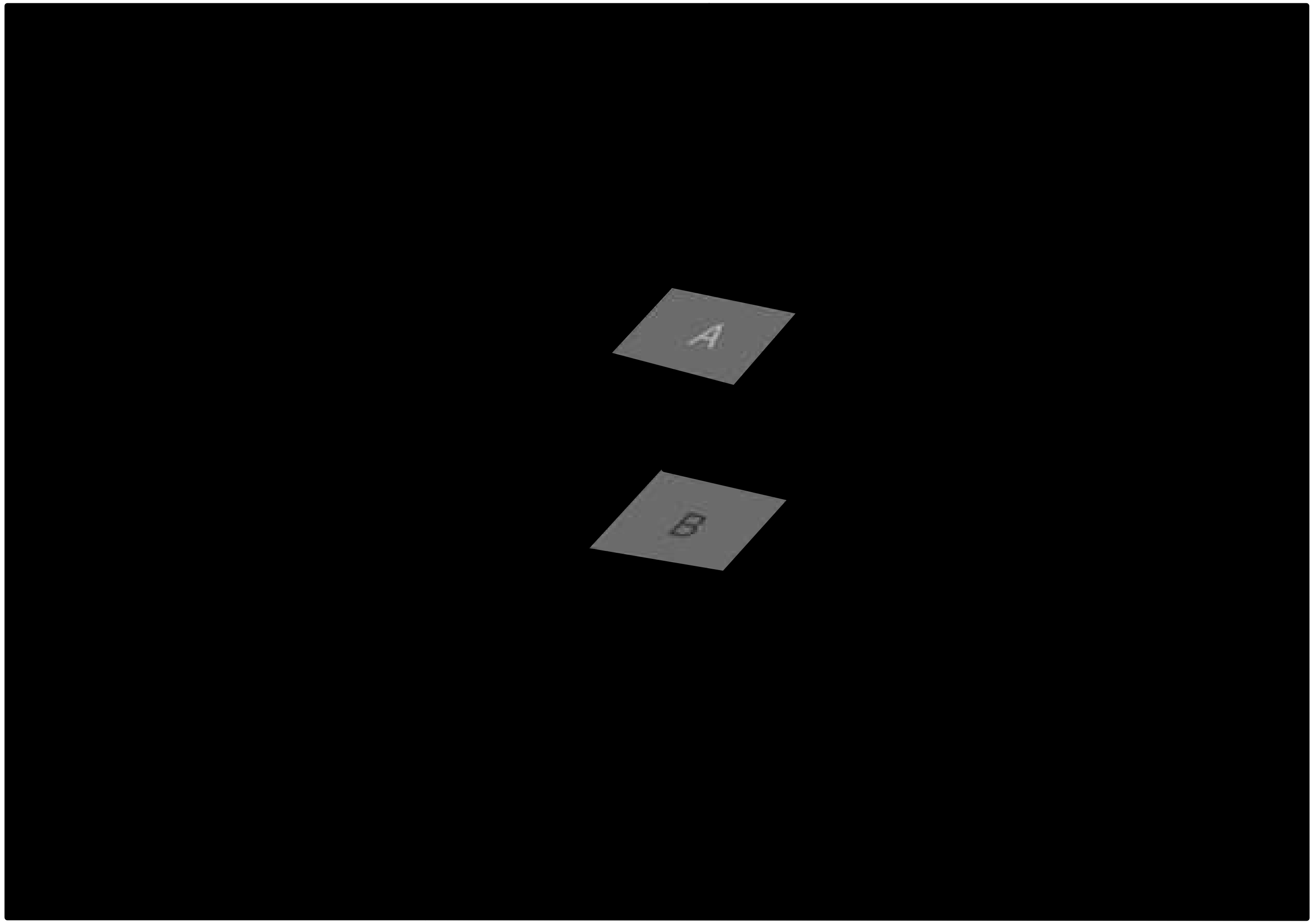




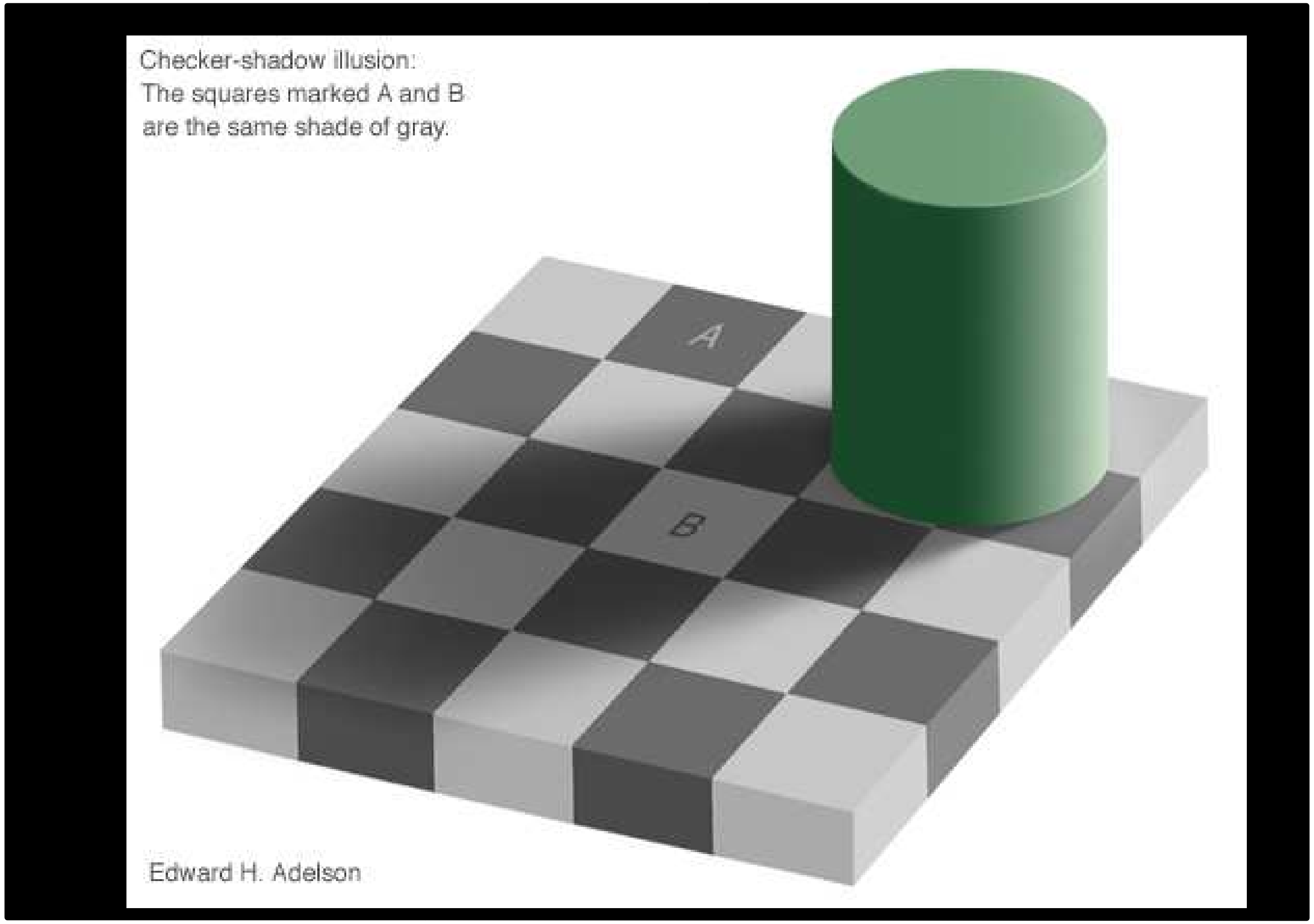




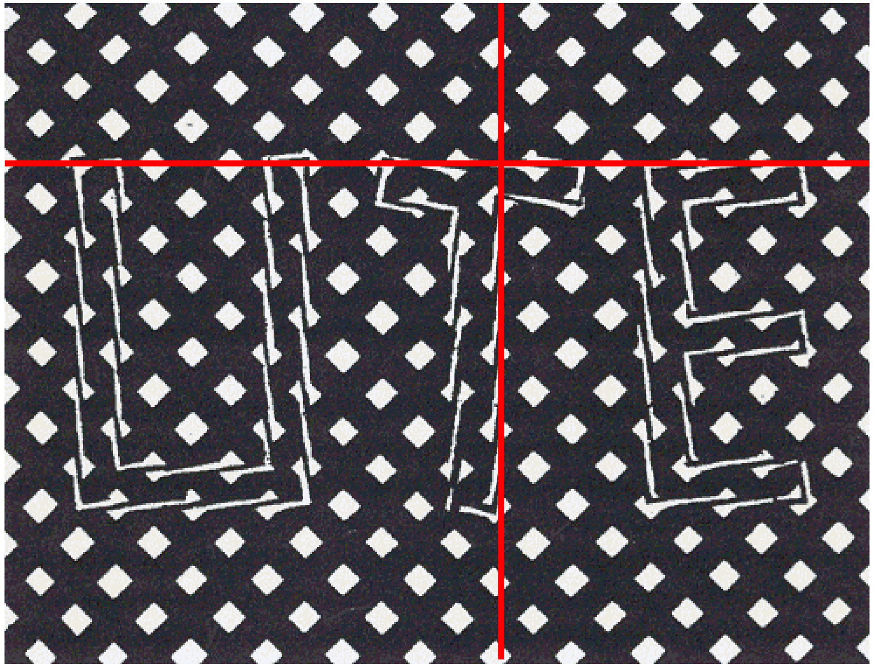
High-Level Contrast Processing

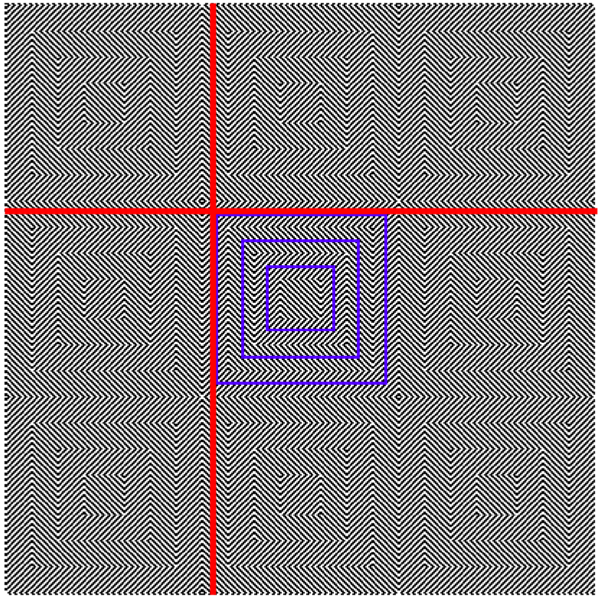


High-Level Contrast Processing

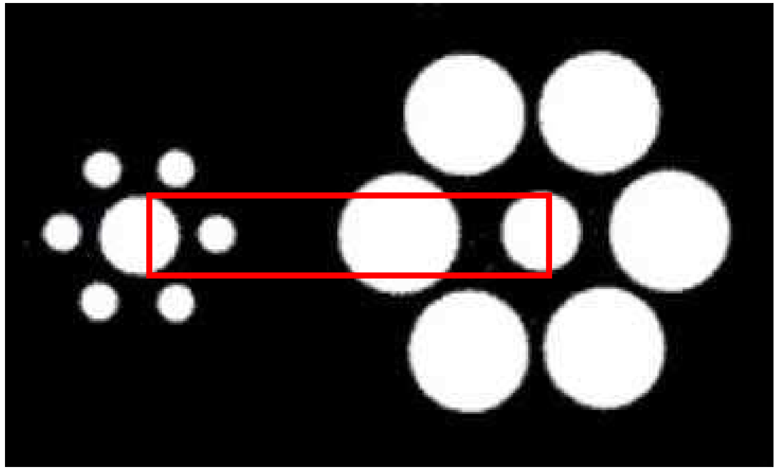


Shape Perception



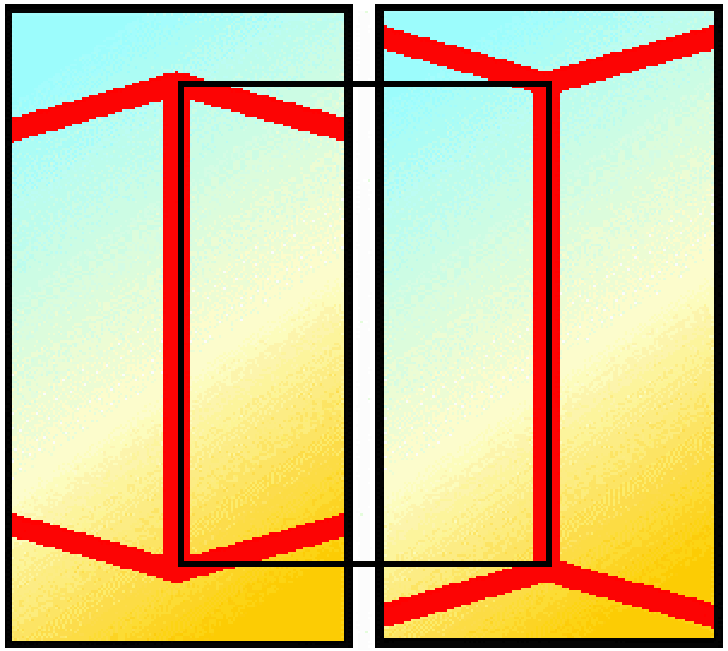


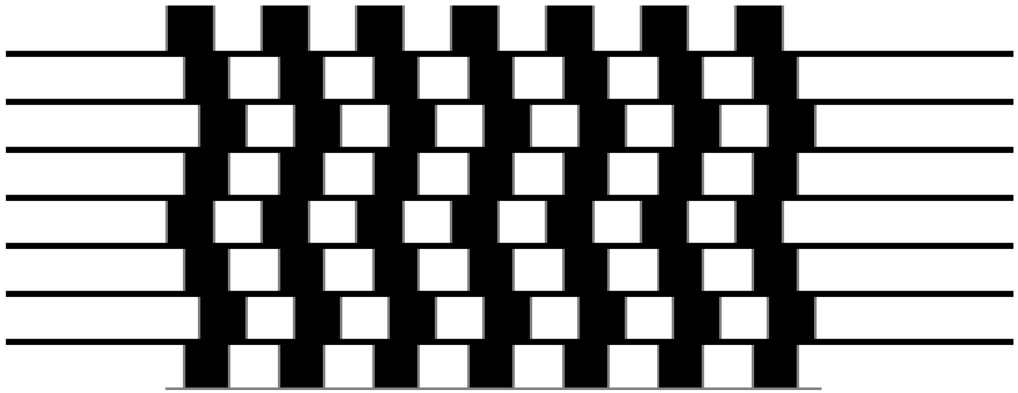
- **Depends on surrounding primitives**
  - Directional emphasis
  - Size emphasis



http://www.panoptikum.net/optischetaeuschungen/index.html

Shape Processing: Geometrical Clues

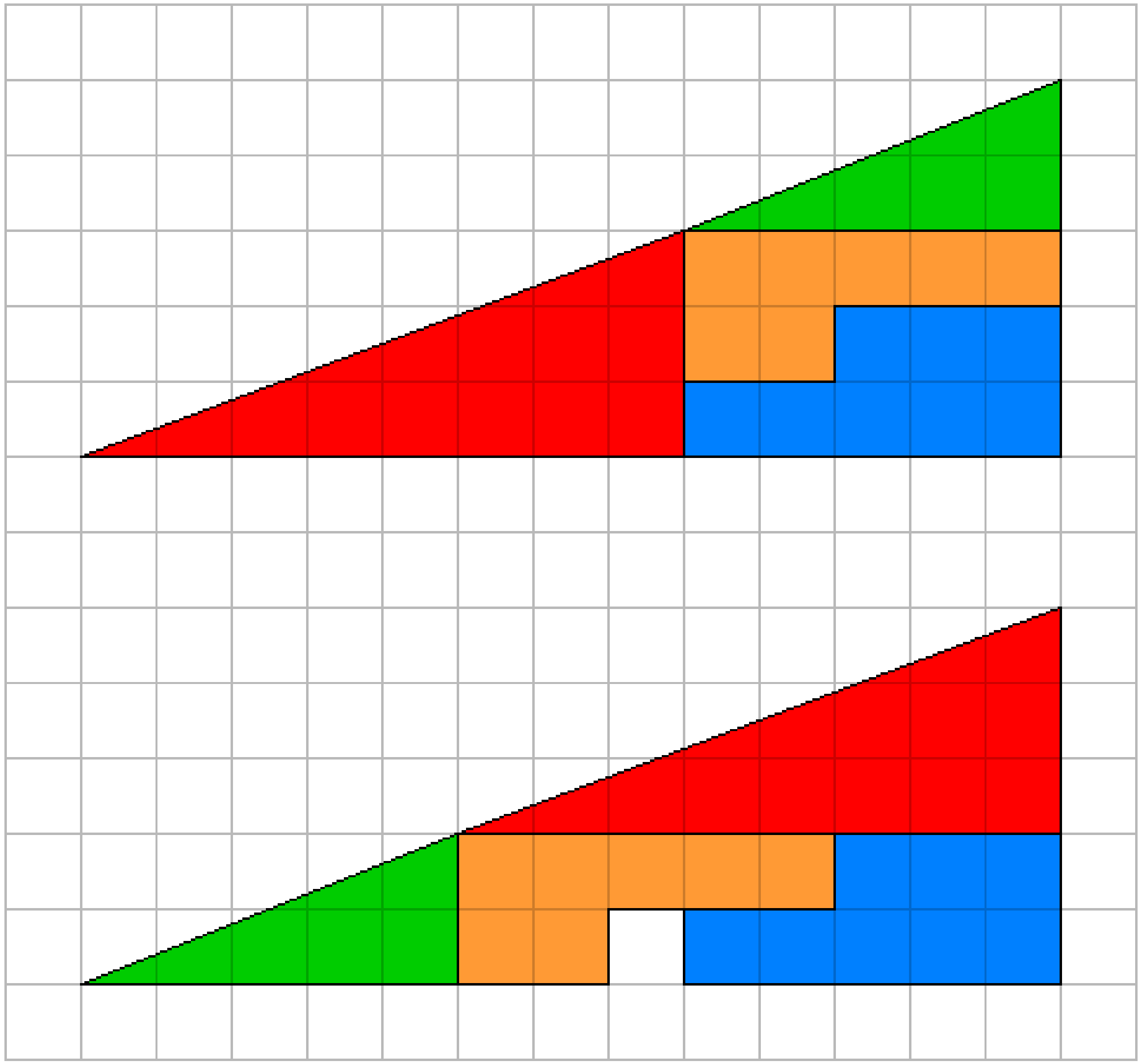




http://www.panoptikum.net/optischetaeuschungen/index.html

- **Automatic geometrical interpretation**
  - 3D perspective
  - Implicit scene depth

Visual “Proofs”



http://www.panoptikum.net/optischetaeuschungen/index.html

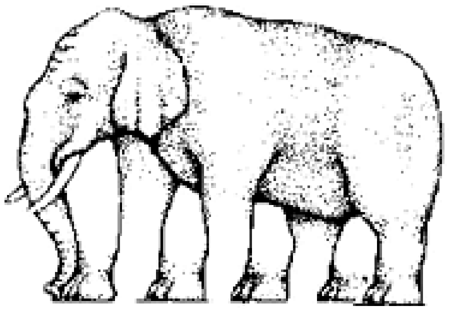
HVS: High-Level Scene Analysis

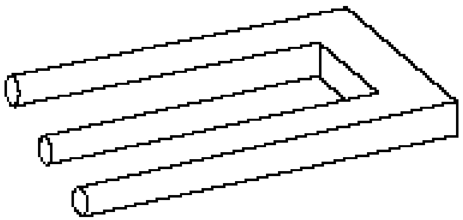
- **Experience**
- **Expectation**
- **Local clue consistency**

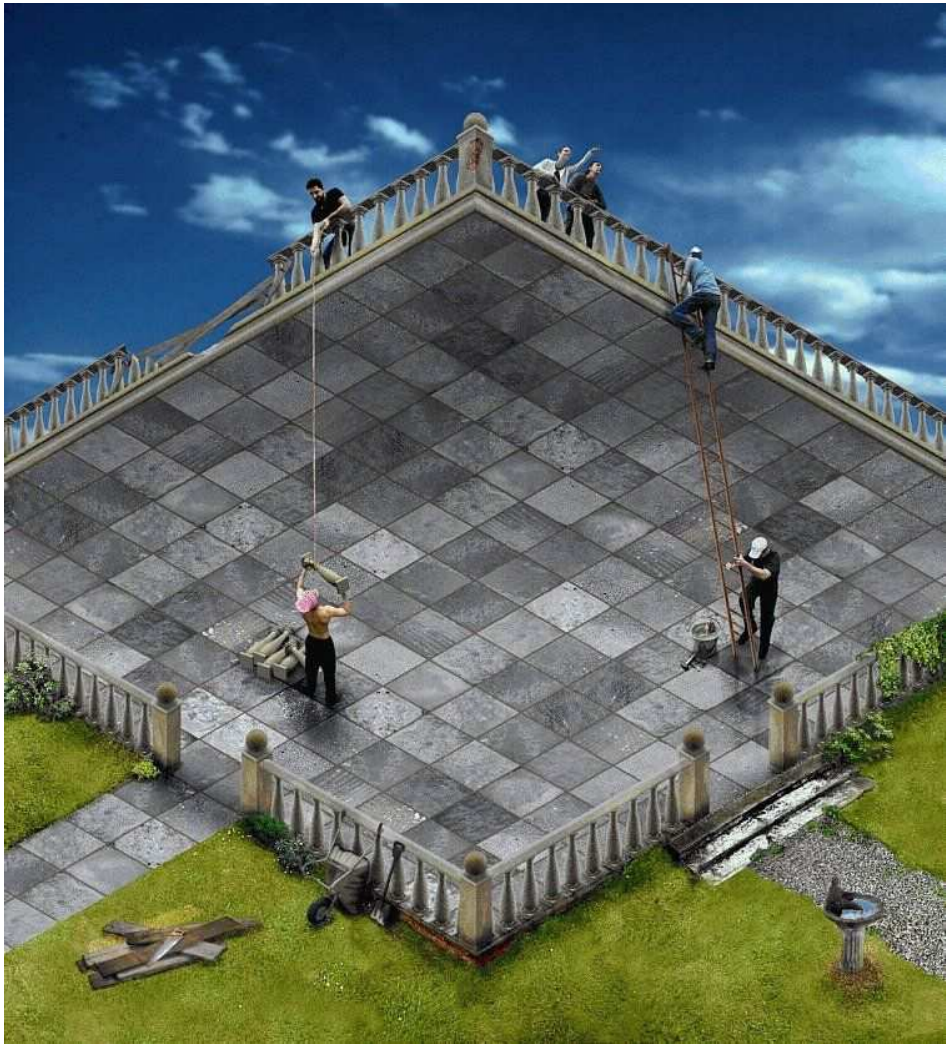
http://www.panoptikum.net/optischetaeuschungen/index.html

Impossible Scenes

- **Escher et.al.**
  – Confuse HVS by presenting contradicting visual clues







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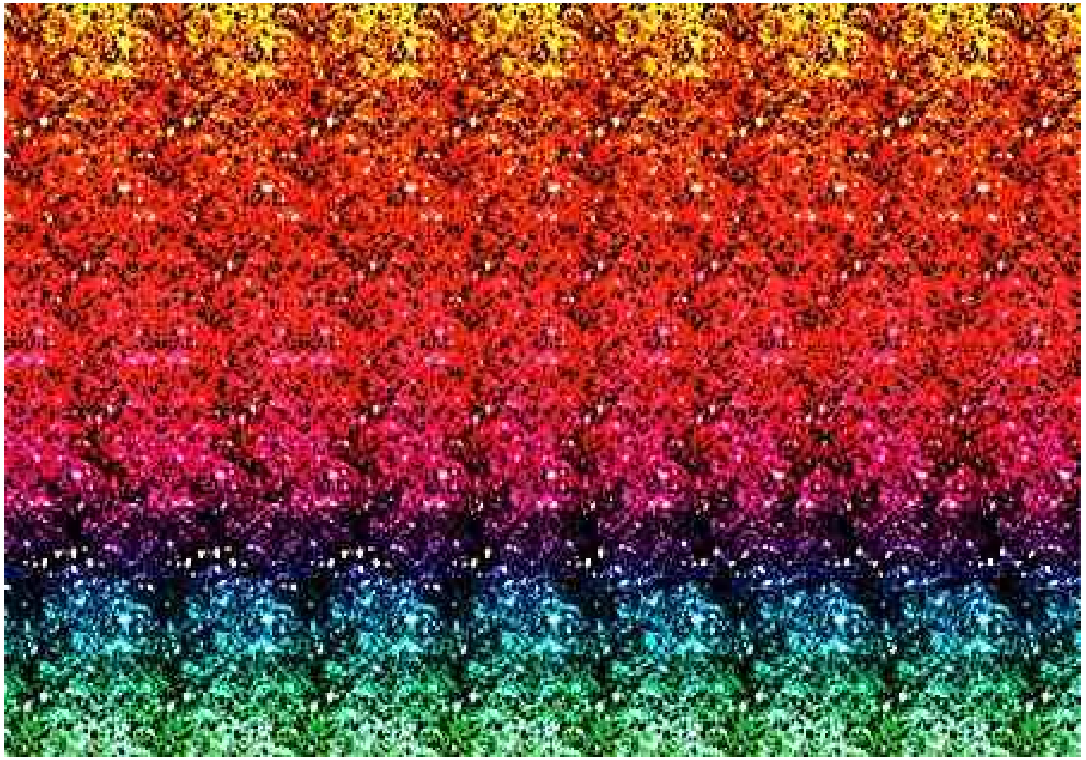
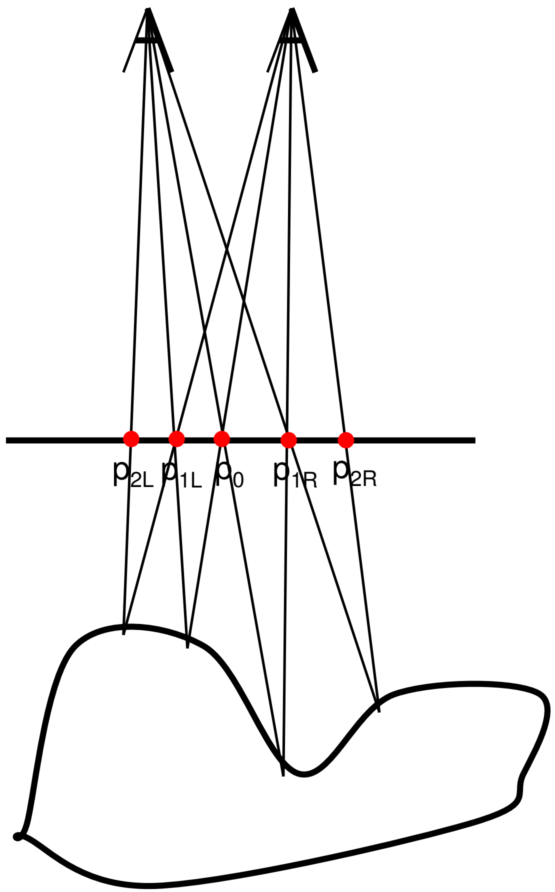
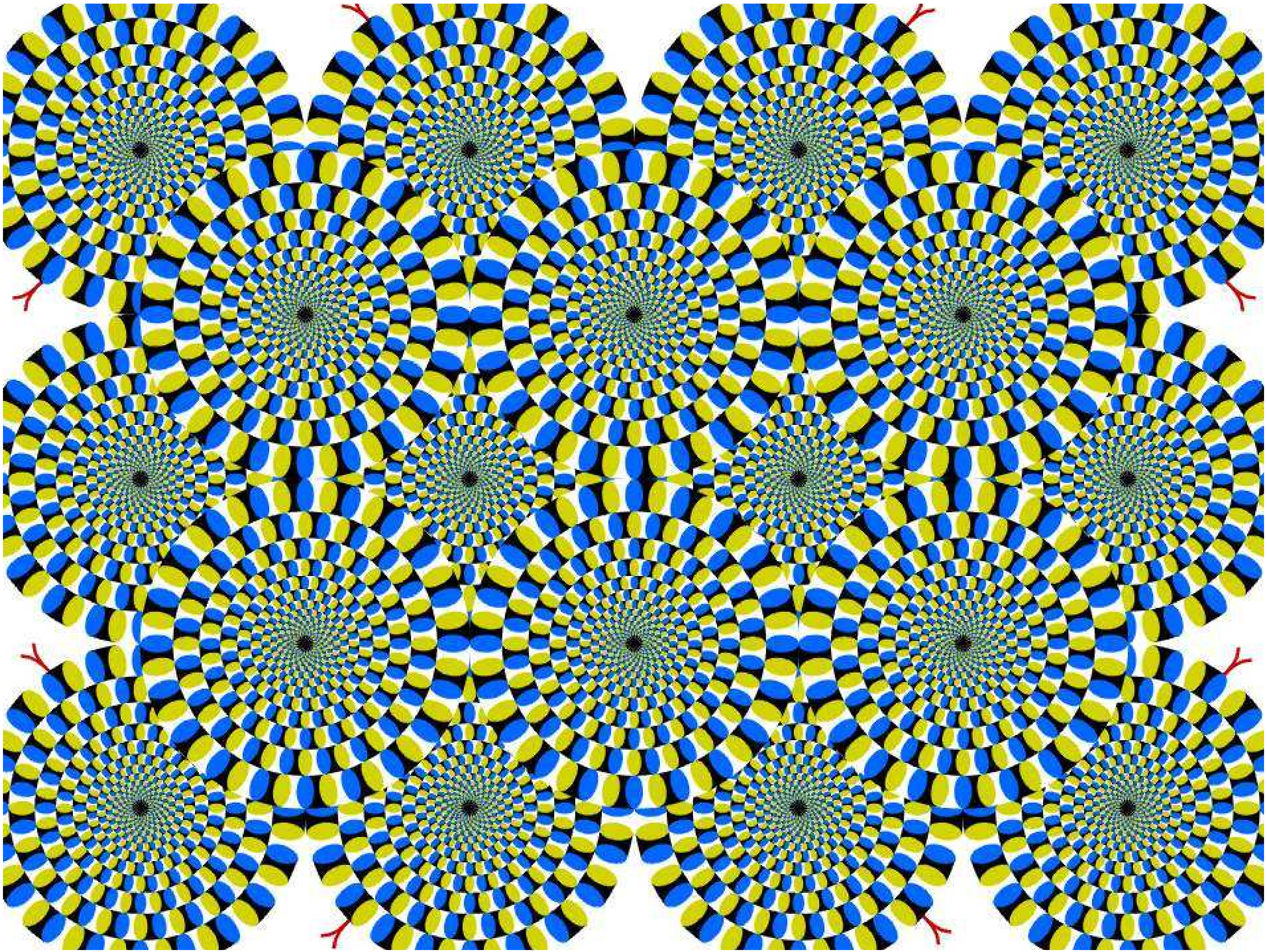
Single Image Random Dot Stereograms



SIRDS Construction

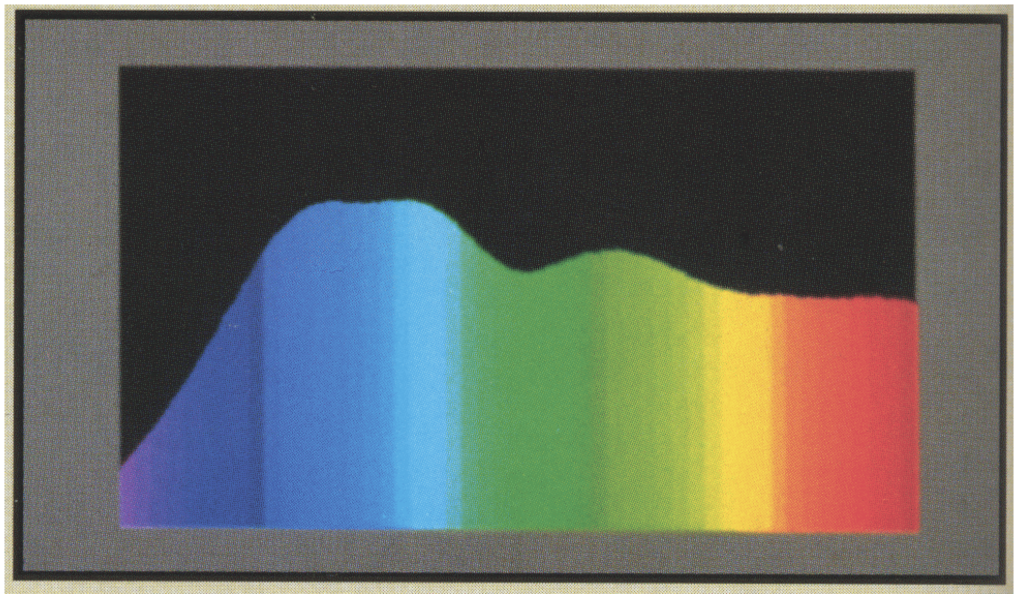
- Assign arbitrary color to p_0 in image plane
- Trace from eye points through p_0 to object surface
- Trace back from object to corresponding other eye
- Assign color at p_0 to intersection points p_{1L},p_{1R} with image plane
- Trace from eye points through p_{1L},p_{1R} to object surface
- Trace back to eyes
- Assign p_0 color to p_{2L},p_{2R}
- Repeat until image plane is covered

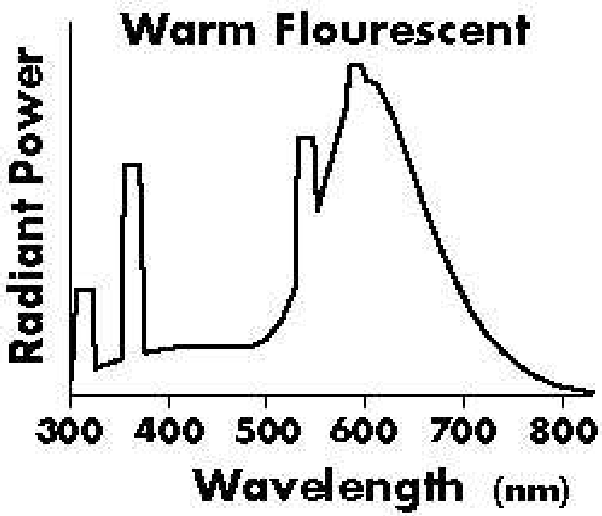




Color

- **Physics**
  - Continuous spectral energy distribution
- **Human color perception**
  - Cones in retina
  - 3 different cone types
  - Spectral mapping to 3 channels

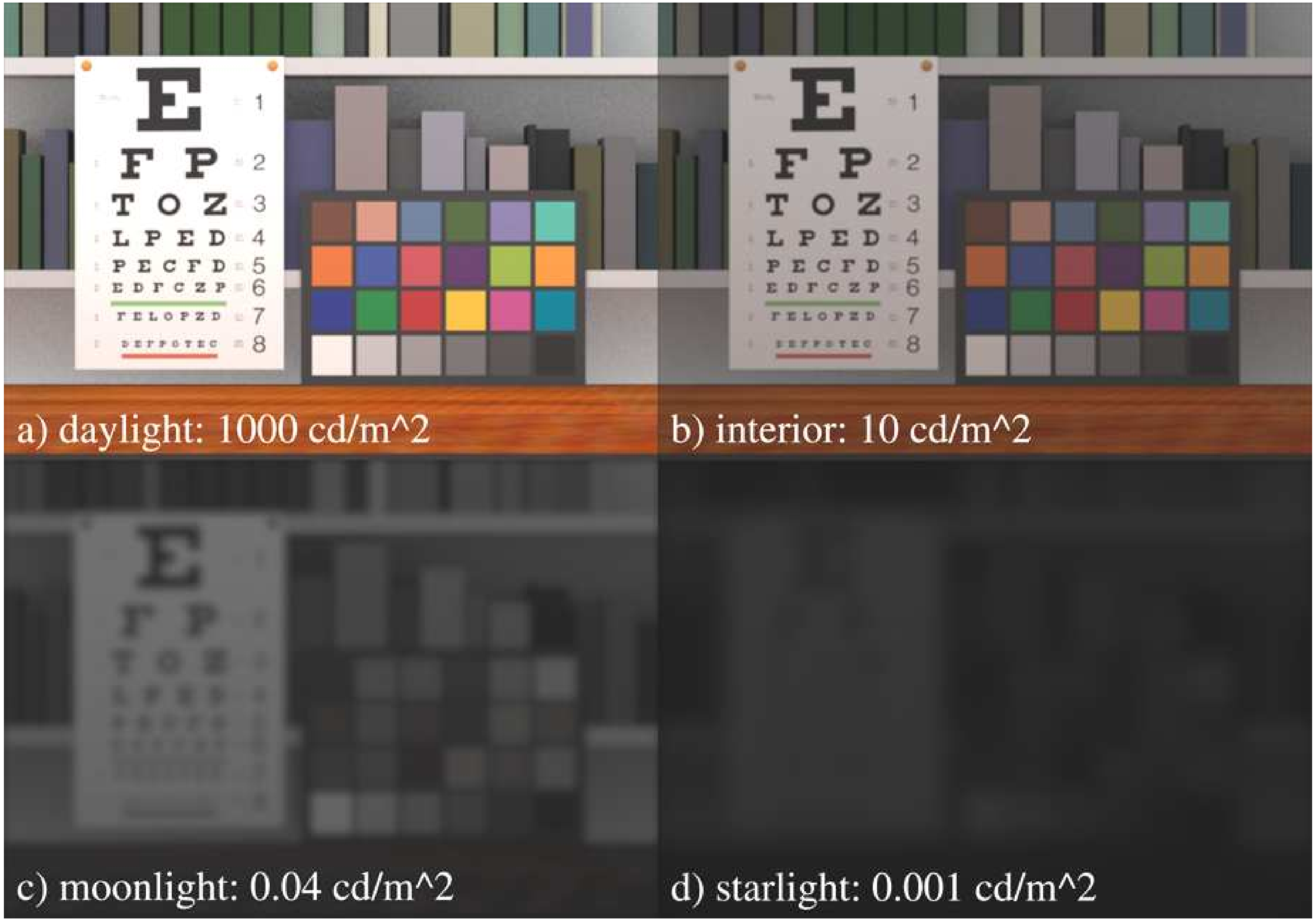




Visual Acuity and Color Perception

Photopic vision

Mesopic/photopic transition



Scotopic/mesopic transition

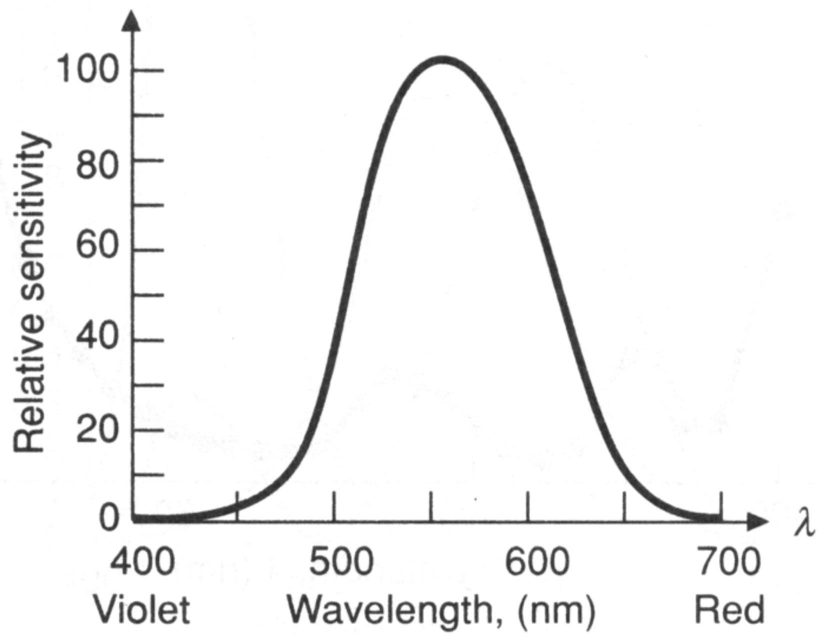
Scotopic vision

Color Comparison

- **Luminance**
  - Compare a color source with a gray source
  - „Luminous Efficiency Function“

$$Y = \int V(\lambda) L(\lambda) d\lambda$$

  - Average value from the „spectral sensitivity“ of all receptors
  - Photopic: day vision (cones)
  - Scotopic: night vision (rods)
  - Mesopic: mixed conditions (rods and cones)

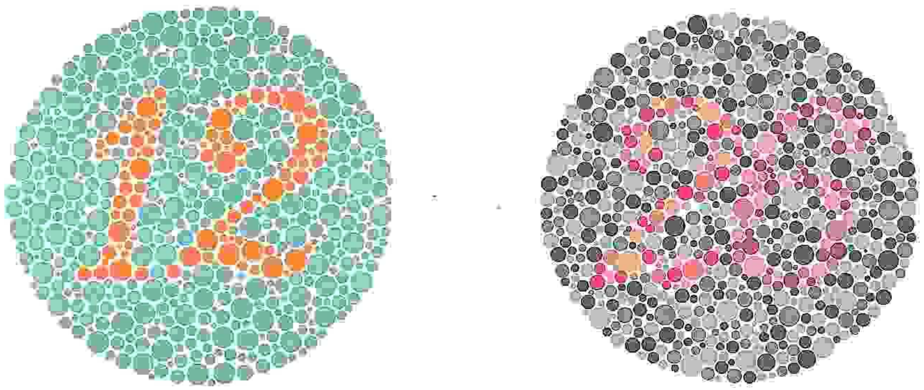


Luminous Efficiency Function (V)

Color Perception

- **Di-chromaticity (dogs, cats)**
  - Yellow & blue-violet
  - Green, orange, red indistinguishable
- **Tri-chromaticity (humans, monkeys)**
  - Red, green, blue
  - Color-blindness
    - Most often men, green color-blindness

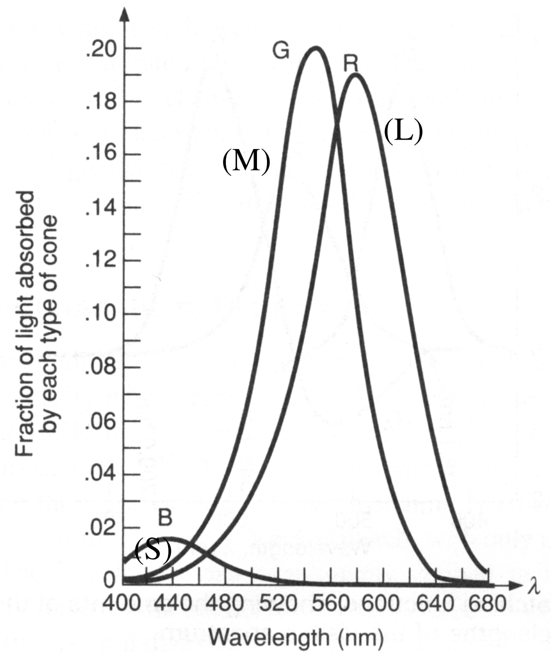
www.lam.mus.ca.us/cats/color/



www.colorcube.com/illusions/clrblnd.html

Color Mapping

- **Spectrum mapping onto perceptual color space**
  - Infinitely many wavelengths
    => 3 color channels
  - Cone absorption spectra (S,M,L)
  - Overlap of absorption characteristics
  - Metamerism
    - Same perceived color for different spectral distributions



- **Grassmann's law**
  - Any perceivable color can be represented as a mixture of three primary colors
  - Colors add linearly
  - From tri-stimulus at every wavelength, total response can be calculated by integration
  - But: Tri-stimulus response **NOT** proportional to absorption spectrum !

Standard Color Space CIE-*RGB*

- **Wide range of colors can be mixed from three monochromatic primary colors 438.1, 546.1, and 700 nm**
  - Colors in the vicinity of 500 nm can only be matched by "subtracting" certain amount of r(λ)
  - Inhibitory behavior (=> contrast !)
  - "Negative"color values

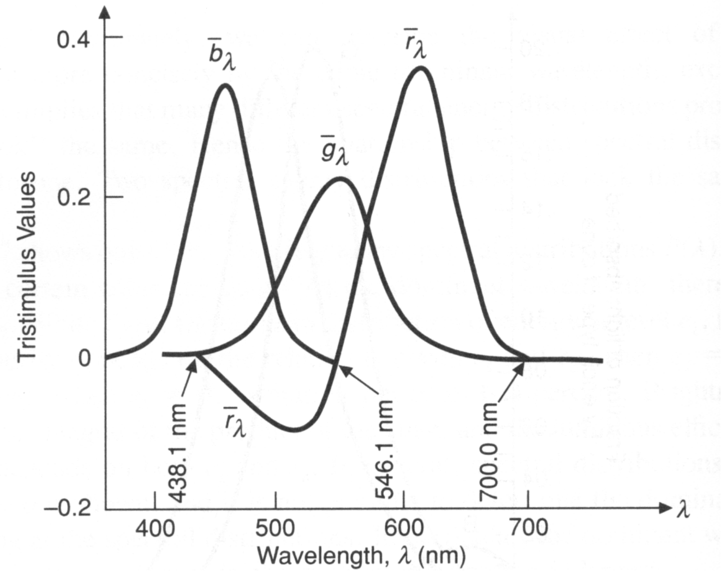
RGB **are called tristimulus values:**

$$R = K_m \int L(\lambda)\overline{r}(\lambda)d\lambda,$$

$$G = K_m \int L(\lambda)\overline{g}(\lambda)d\lambda,$$

$$B = K_m \int L(\lambda)\overline{b}(\lambda)d\lambda$$

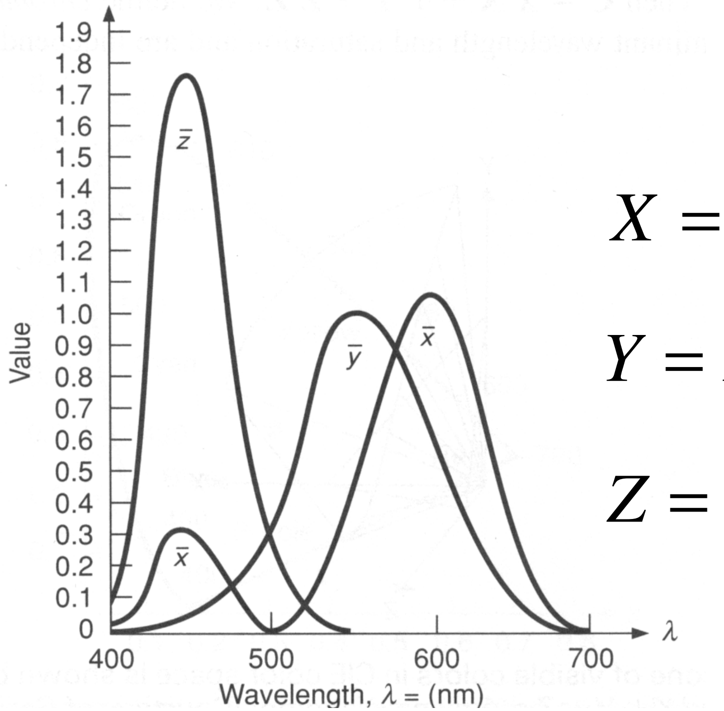
$$K_m = 680\ lm/W$$



Color-matching functions for given monochromatic primary colors

Standard Color Space CIE-*XYZ*

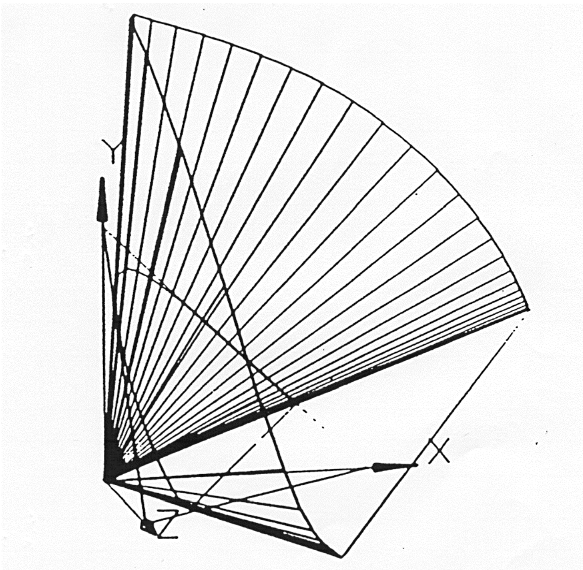
- **Standardized imaginary primaries CIE** *XYZ* (1931)
  - Non-realizable super-saturated primary colors
  - Reproduces all perceivable colors by additive mixing
  - Only positive weights
  - Y is equivalent to luminance
  - Perceivable colors span irregular cone in XYZ space



$$X = K_m \int L(\lambda)\bar{x}(\lambda)d\lambda,$$

$$Y = K_m \int L(\lambda)\bar{y}(\lambda)d\lambda,$$

$$Z = K_m \int L(\lambda)\bar{z}(\lambda)d\lambda$$

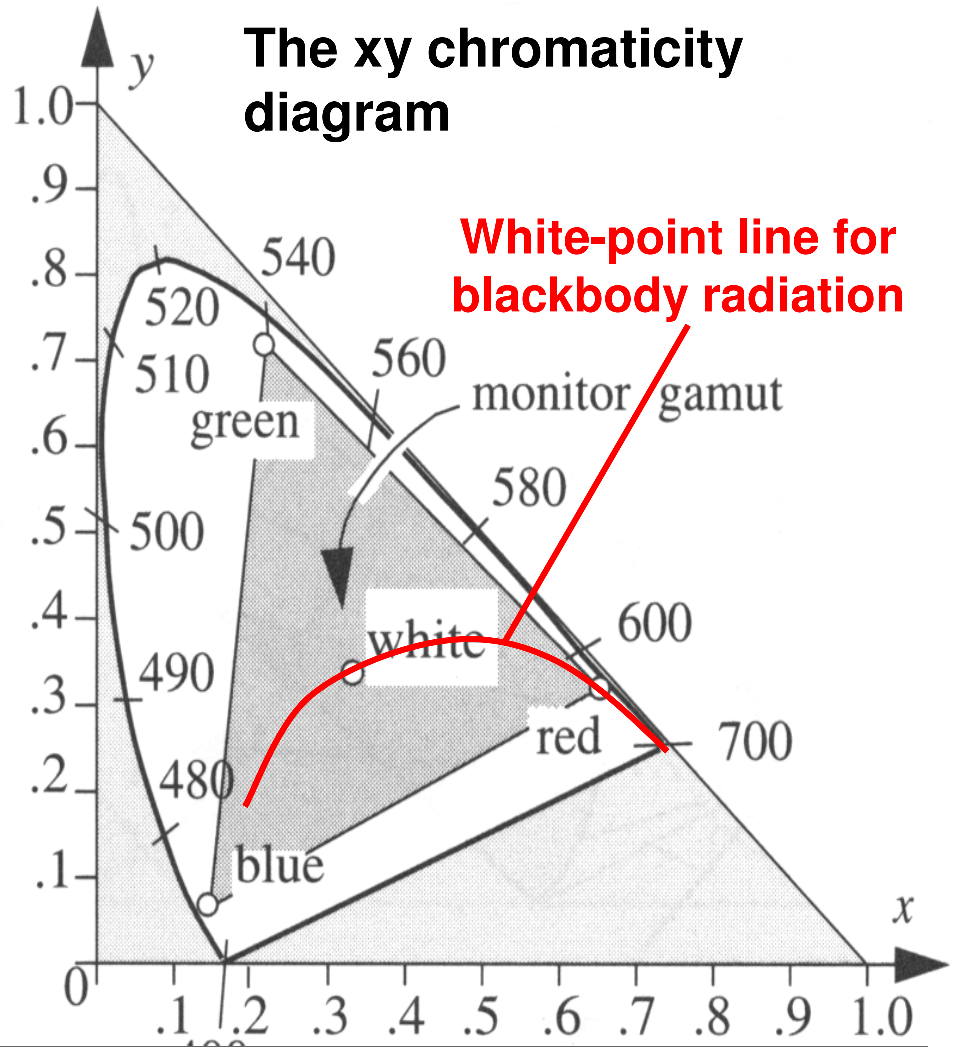


CIE Chromaticity Diagram

- **Normalization:**
  - $x = \dfrac{X}{X+Y+Z}$ etc

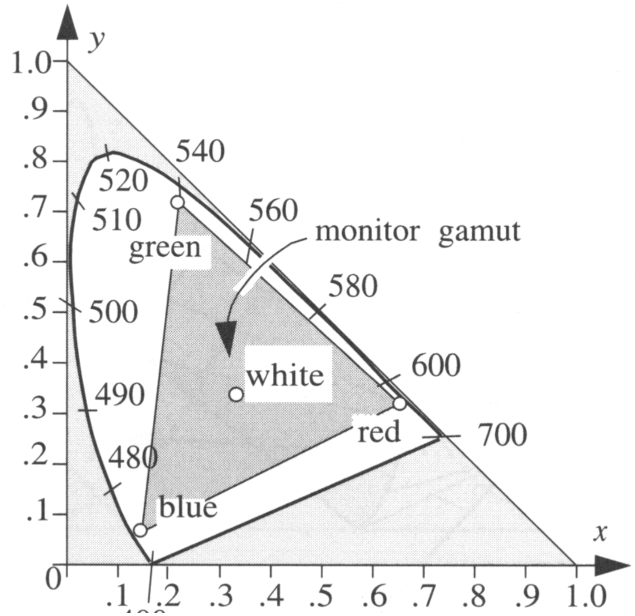
    Projection on the plane of the prime valences

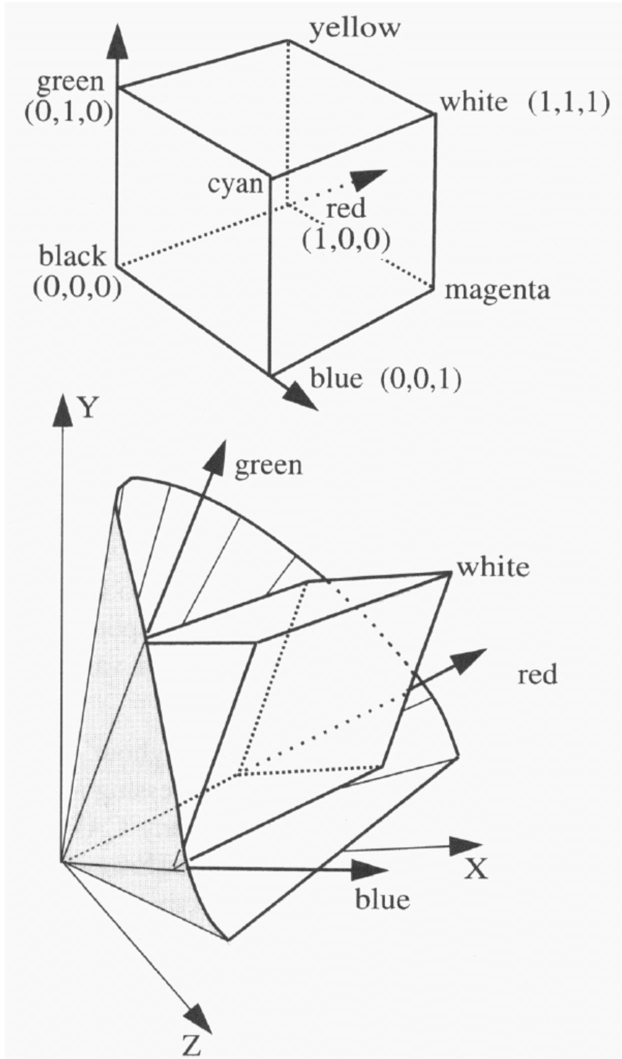
    z= 1-x-y
  - Chromaticity diagram: 2D-Plot over x and y
  - Points called as color locations
  - White point: ~(0.3, 0.3)
    - Device dependent
    - Adaptation of the eye
  - Saturation: Distance to the white point
  - Complementary colors



Monitor Color Gamut

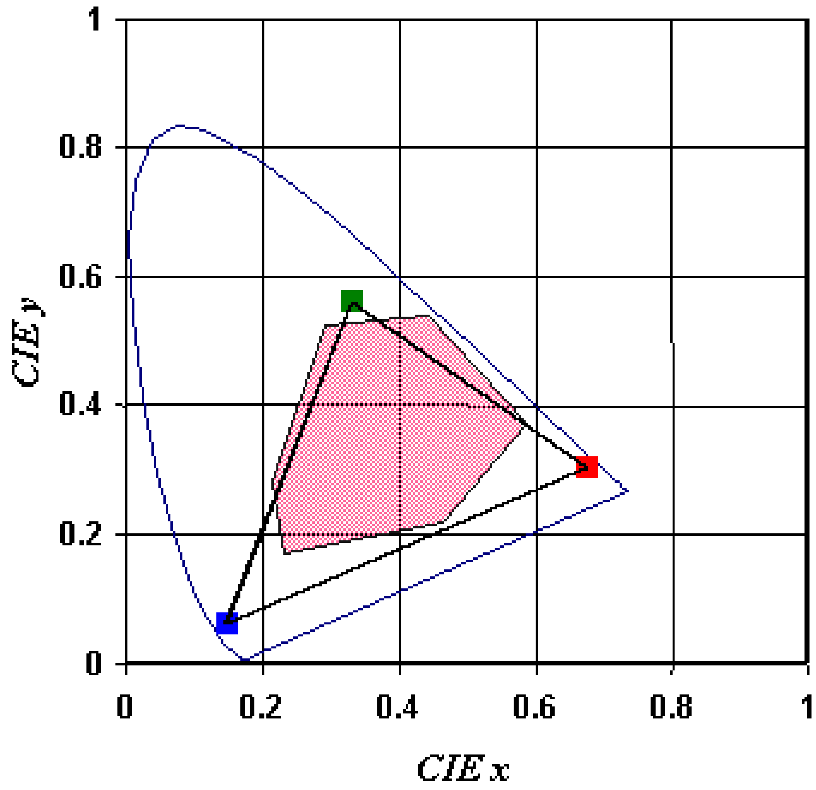
- **CIE XYZ gamut**
  - Device-independent (repeatable)
- **Device color gamut**
  - Triangle inside color space, additive color blend





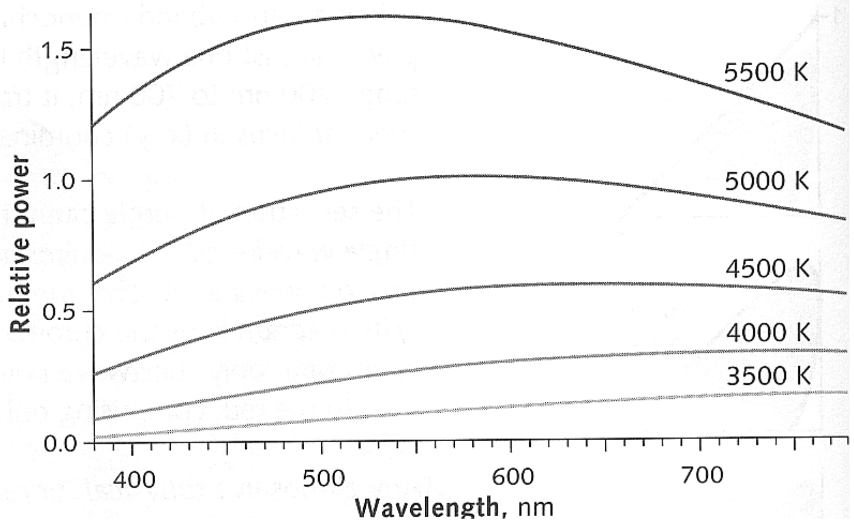
Printer Color Gamut

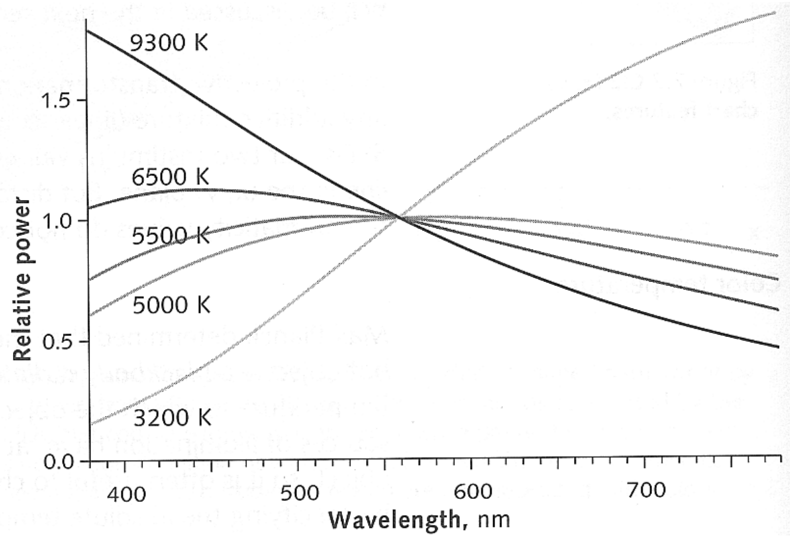
- **Color Gamut**
  - Complex for printer, because of subtractive color blend
  - Complex interactions between printed color points
  - Depends on printer colors and printer technique
- **Gamut compression**
  - Each device should replace of-gamut colors nearest approximate
  - Possible significant color printed ➔ scanned ➔ displayed in



Color Temperature

- **Theoretical light source: A black body radiator**
  - Perfect emitter of energy, the whole energy emitted due only to thermal excitation
  - Has a fixed frequency spectrum $\rho = \rho(\lambda, T)$ (Planck's law)
  - Spectrum can be converted to color
    - Energy shifts toward shorter wavelengths as the temperature of the black body increases
    - Normalizing of the spectrum (at 550 nm)
  - Color specification through temperatures





CIE Standard Illuminants

- **Defining the properties of illuminant is important to describe color in many applications**
  - **Illuminant A – incandescent lighting conditions with a color temperature of about 2856°K**
  - **Illuminant B – direct sunlight at about 4874°K**
  - **Illuminant C – indirect sunlight at about 6774°K**
  - **Illuminants D_{50} and D_{65} – different daylight conditions at color temperatures 5000°K and 6500°K, respectively**
- **The spectral data of CIE Standard Illuminants are available and often used in the CG applications**