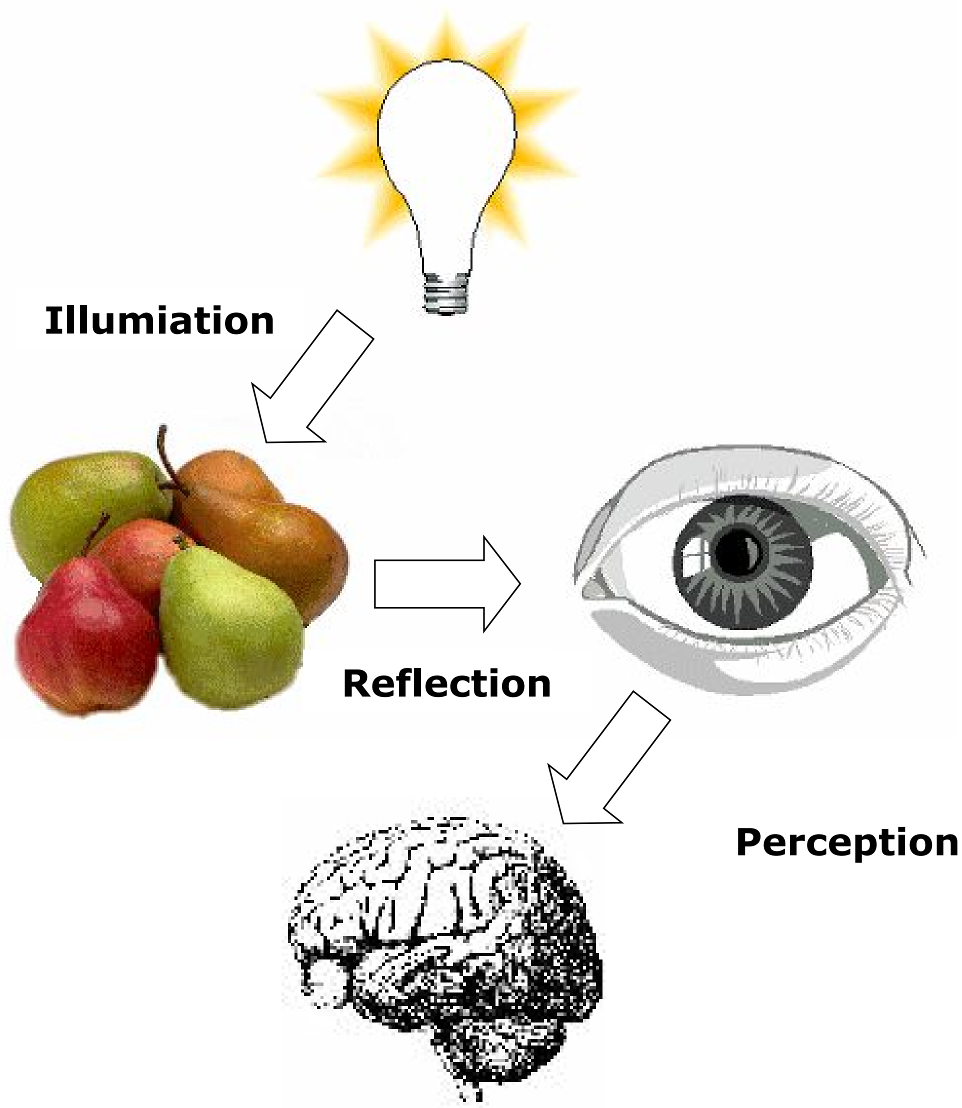
Berner Fachhochschule
Haute école spécialisée bernoise
Bern University of Applied Sciences

Introduction to Computer Vision:

Basic Principles

Marcus Hudritsch (hsm4)

Basics: Visual Perception



Basics: The Light

- **Ray Model** explains reflection and refraction
- **Photon Model** explains interaction between light and matter
- **Wave Model** explains color spectrum and polarisation

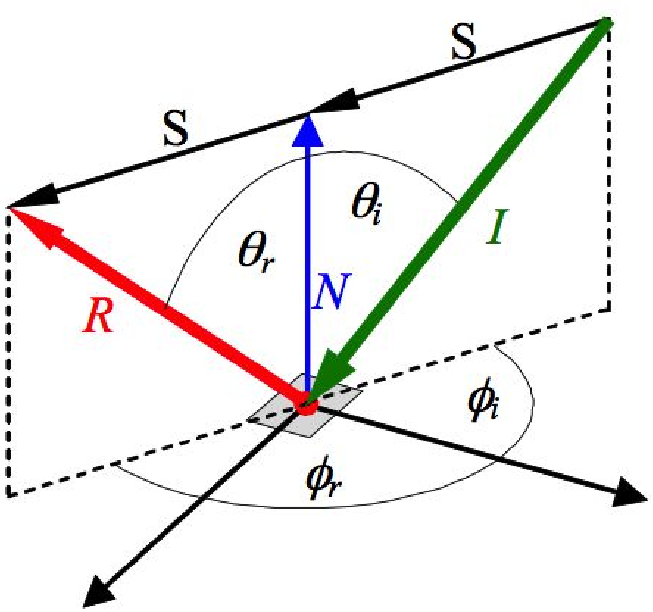
Basics: Light: Ray Model

On a surface a light ray can be:

- reflected
- refracted
- absorbed

Mostly it is a mix of all three.

Perfect Reflection: Ideal mirror: Incident angle = Emergent angle



$$\cos\theta = -I \cdot N$$
$$S = (-I \cdot N)\, N + I$$
$$R = (-I \cdot N)\, N + S$$
$$R = (-I \cdot N)\, N + (-I \cdot N)\, N + I$$
$$R = 2(-I \cdot N)\, N + I$$
$$R = I - 2(I \cdot N)\, N$$

Basics: Light: Ray Model: Refraction

Refraction

- On the border between two materials with different optical densities a change in light direction and speed of light occurs.
- The **index of refraction η** (eta) is the ratio of the speed of light in the material to the speed of light in vacuum (c = 299'792'458 m/s).

Material	Index of Refraction η
Vakuum:	1.0
Air:	1.0003
Water:	1.333
Cornea:	1.37
Glas:	1.5 - 1.6
Diamond:	2.417

The speed of light in a diamond is therefore c / 2.417

Basics: Light: Ray Model

Refraction

- The calculation of a refracted vector is based on the law of Snell (1621)

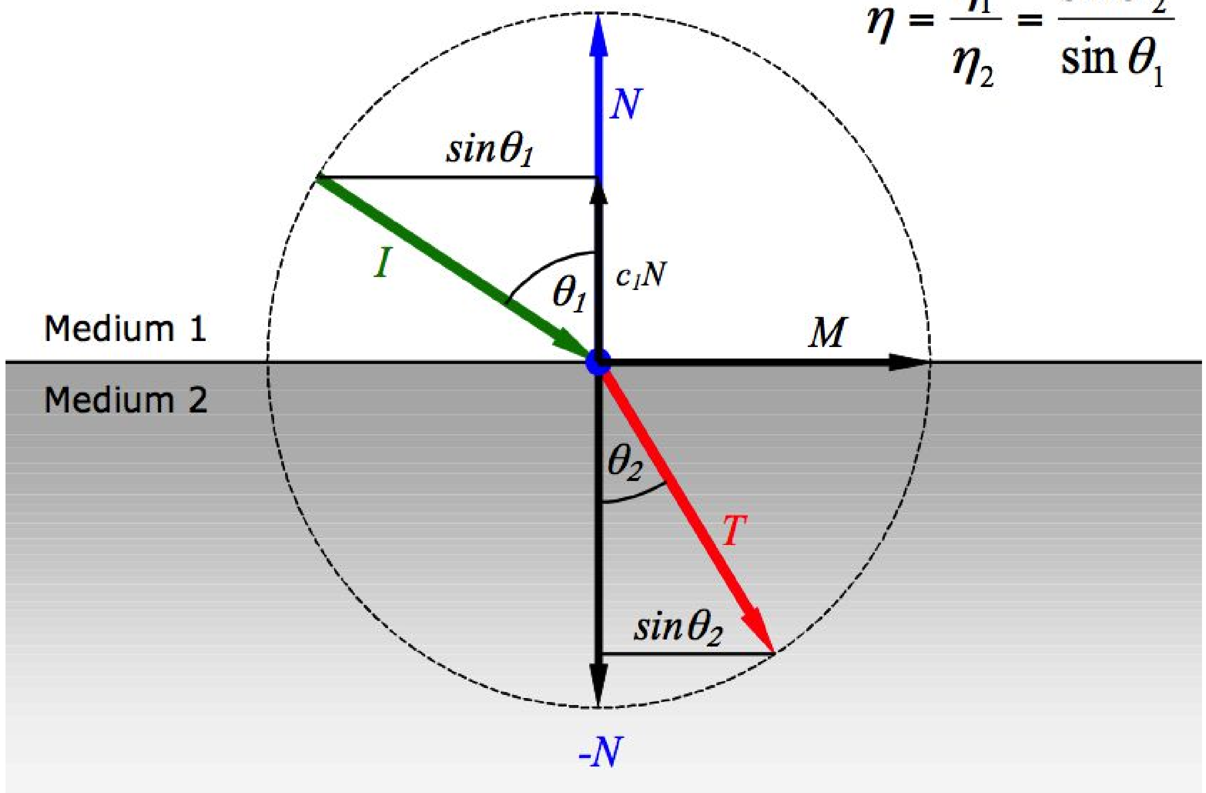
$$T = \eta I + \left(\eta c_1 - \sqrt{c_2}\right) N$$

$$mit$$

$$c_1 = \cos\theta_1 = -I \cdot N$$

$$c_2 = 1 - \eta^2 \left(1 - c_1\right)$$

$$\eta = \frac{\eta_1}{\eta_2} = \frac{\sin\theta_2}{\sin\theta_1}$$



Basics: Light: Ray Model

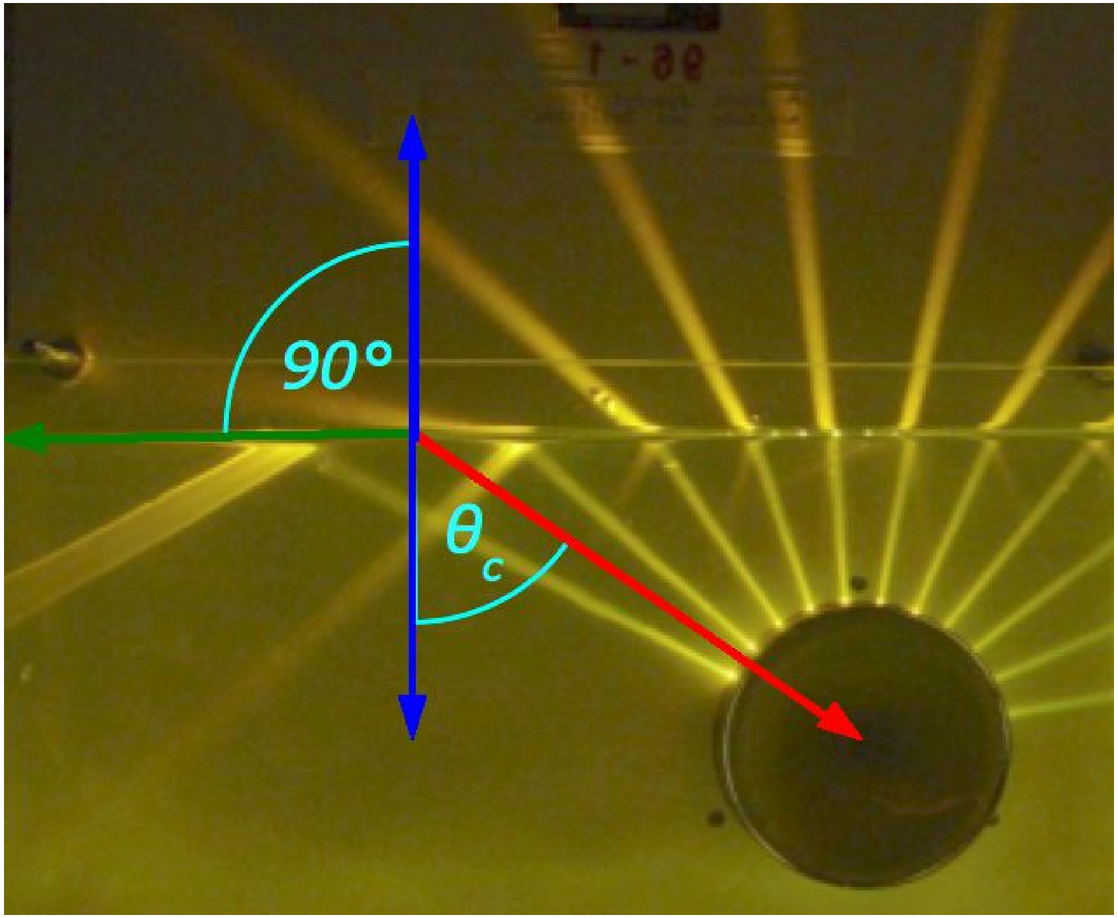
Total Internal Reflection (TIR)

$$\frac{\eta_1}{\eta_2} = \frac{\sin\theta_c}{\sin\frac{\pi}{2}}$$

$$\eta_1 \sin\theta_c = \eta_2 \sin\frac{\pi}{2} = \eta_2$$

$$\sin\theta_c = \frac{\eta_2}{\eta_1}$$

$$\arcsin\left(\frac{1.003}{1.33}\right) = 48.95\,°$$



Basics: Light: Photon Model

Photon Model:

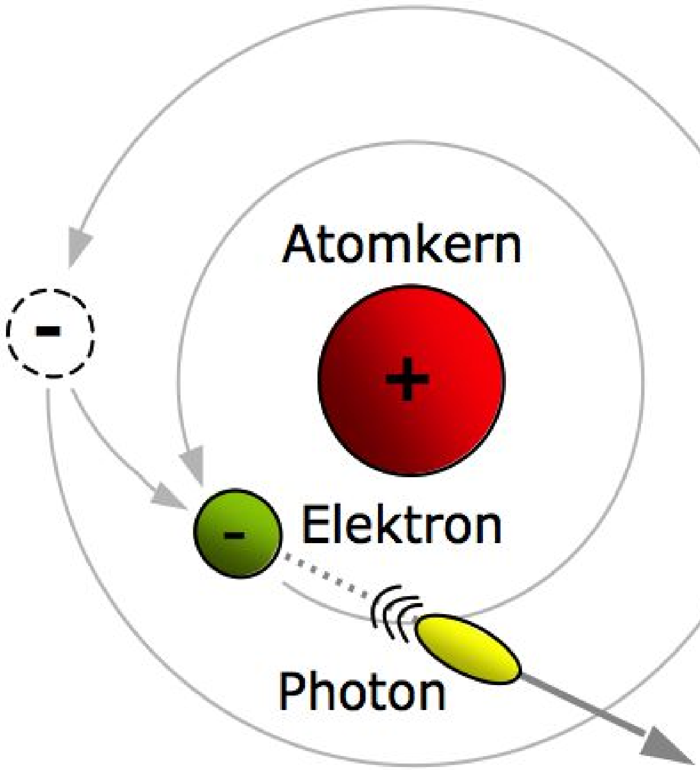
- Light is also an **energy transport** phenomena.
- It look as light comes in **packets of energy**.
- Such a packet is called **light particle** or **photon** (Greek for light quantum).
- The photon model was invented by **Albert Einstein**.

- Light has its source and sink in the **atomic model**.
- Light can be **emmited** or **absorped**.

Basics: Light: Photon Model

Light Emission

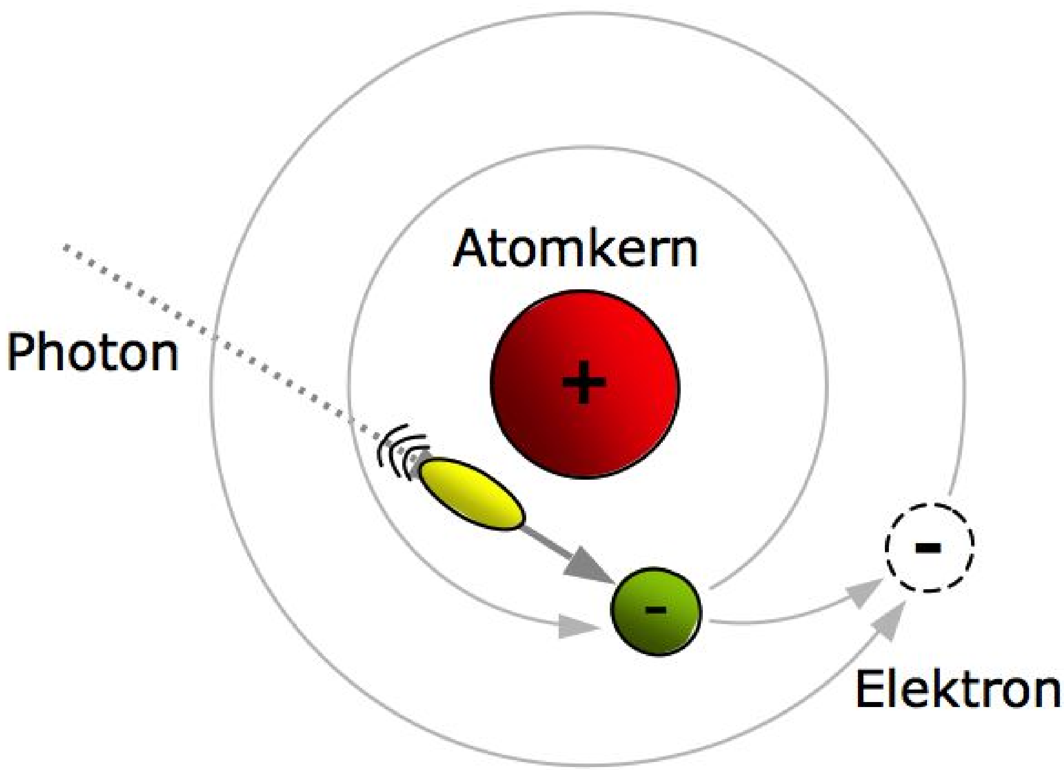
- When an electron change its orbit to a lower energy orbit it releases the energy in form of a photon.
- Because photons have no electric charge they can not be distracted by electromagnetic fields.



Basics: Light: Photon Model

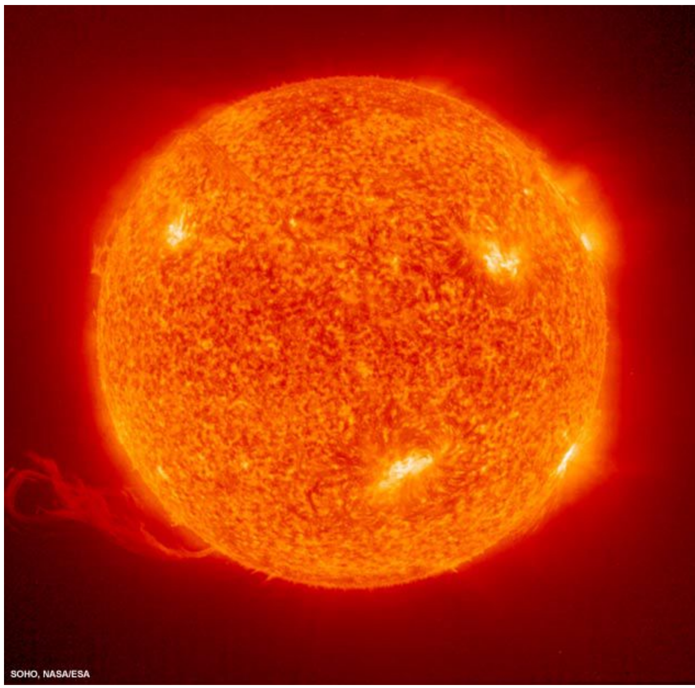
Light Absorption

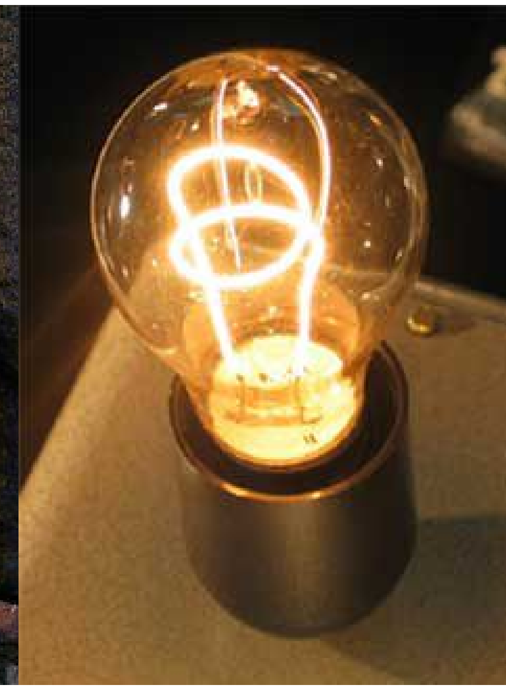
- When a photon hits an electron, the electron is thrown to a higher orbit and absorbs the energy of the photon.
- After a while the electron falls back to its original orbit an releases energy as heat.



Basics: Light: Photon Model: Light Sources

- **Two Groups of Light Sources**
- **Heat radiation** comes from thermal motion of particles by a burning process or through electric energy:



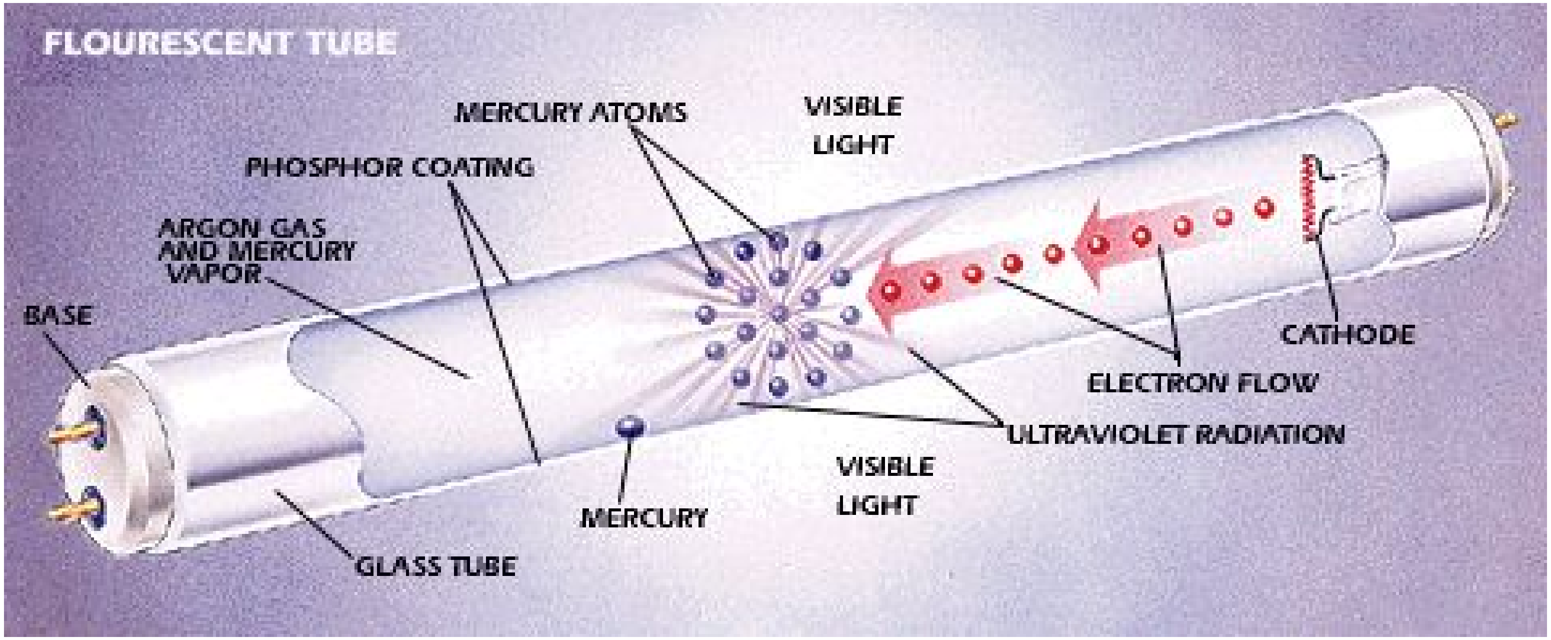



Basics: Light: Photon Model: Light Sources

- **Luminesence Radiators** light without burning or glowing:
  - They are also called **cold radiators**.
  - Depending on the **source of energy** we distinguish:
  - **Photoluminescence**: Stimulation through photons

Basics: Light: Photon Model: Light Sources

- **Luminesence Radiators** light without burning or glowing:
  - **Photoluminescence**: Stimulation through photons
  - **Electroluminescence**: Stimulation through electric power:
    - Neon light tube



Basics: Light: Photon Model: Light Sources

- **Luminesence Radiators** light without burning or glowing:
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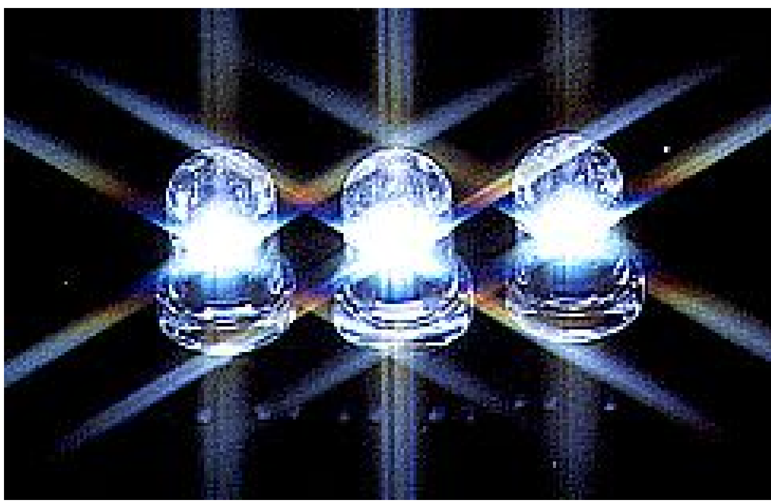
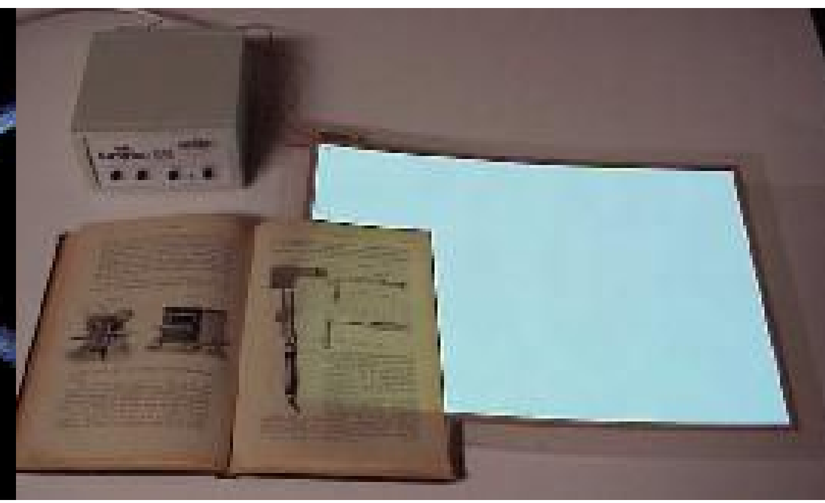
    - Neon light tube
    - Light emitting diods (LED)
    - Light emitting condensators (LEC)

Basics: Light: Photon Model: Light Sources

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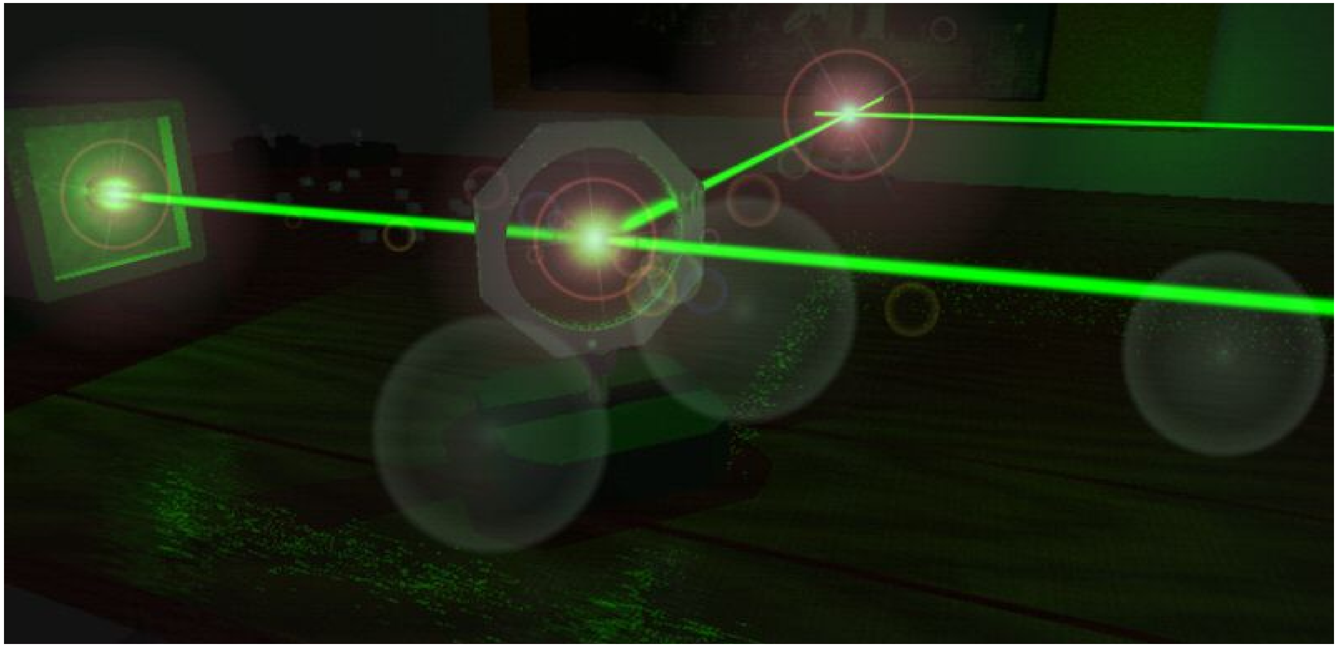
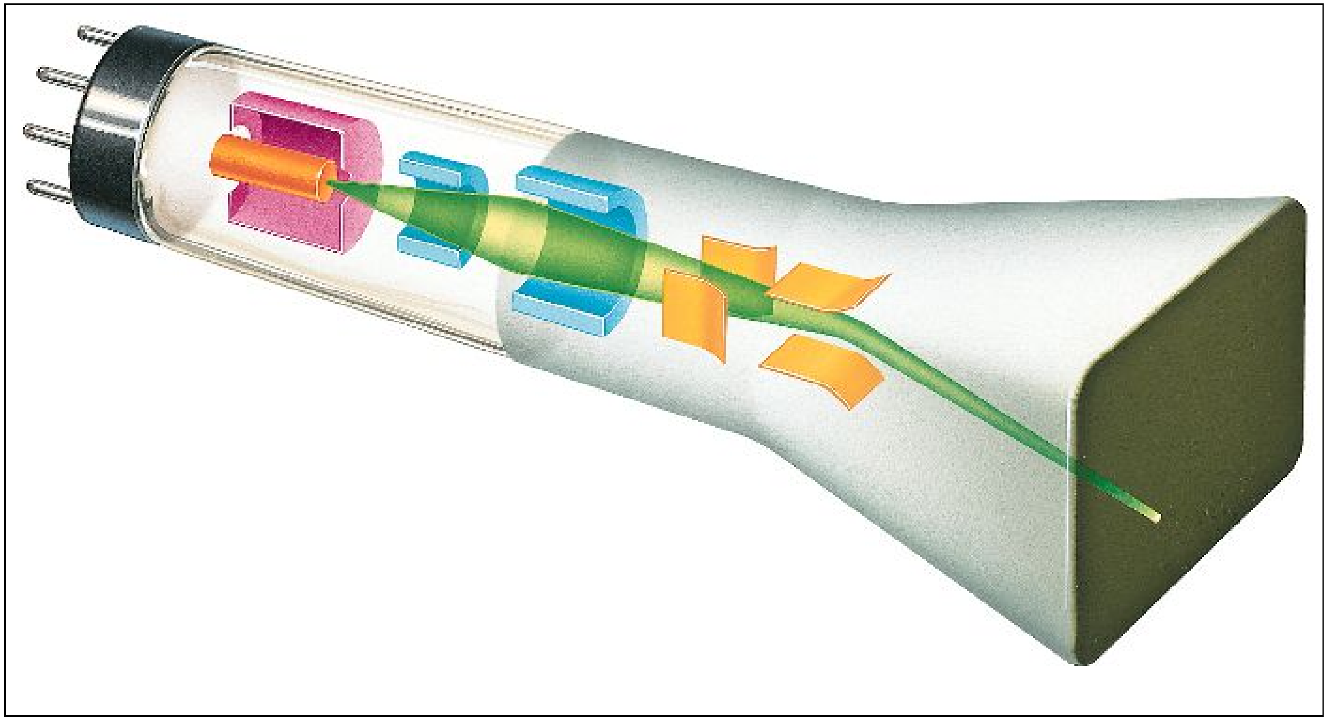
    - Neon light tube
    - Light emitting diods (LED)
    - Light emitting condensators (LEC)
    - Laser (Light Amplification by Stimulated Emission of Radiation)



Basics: Light: Photon Model: Light Sources

- **Luminesence Radiators** light without burning or glowing:
  - **Photoluminescence**: Stimulation through photons
  - **Electroluminescence**: Stimulation through electric power
  - **Cathodeluminescence**: Stimulation through an electron beam



Basics: Light: Photon Model: Light Sources

- **Luminesence Radiators** light without burning or glowing:
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  - **Chemoluminescence**: Stimulation through chemical reaction

Basics: Light: Photon Model: Light Sources

- **Luminesence Radiators** light without burning or glowing:
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  - **Bioluminescence**: Stimulation through biochemical reaction


Basics: Light: Photon Model: Light Sources

- **Luminesence Radiators** light without burning or glowing:
  - **Photoluminescence**: Stimulation through photons
  - **Electroluminescence**: Stimulation through electric power
  - **Cathodeluminescence**: Stimulation through an electron beam
  - **Chemoluminescence**: Stimulation through chemical reaction
  - **Bioluminescence**: Stimulation through biochemical reaction
  - **Radioluminescence**: Stimulation through radioacitve radiation

Basics: Light: Photon Model: Light Energy

Light is energy

- The **energy E** of a photon and the **frequency** of the lightwave are **proportional**.
- The higher the **frequency v** the higher is the energy.
- The constant **h** is called **Planck Constant**:

$$E = h \cdot v \qquad [\,\mathrm{eV}\,]$$

1 eV (electron volt) is $1.6*10^{-19}$ J (Joul)

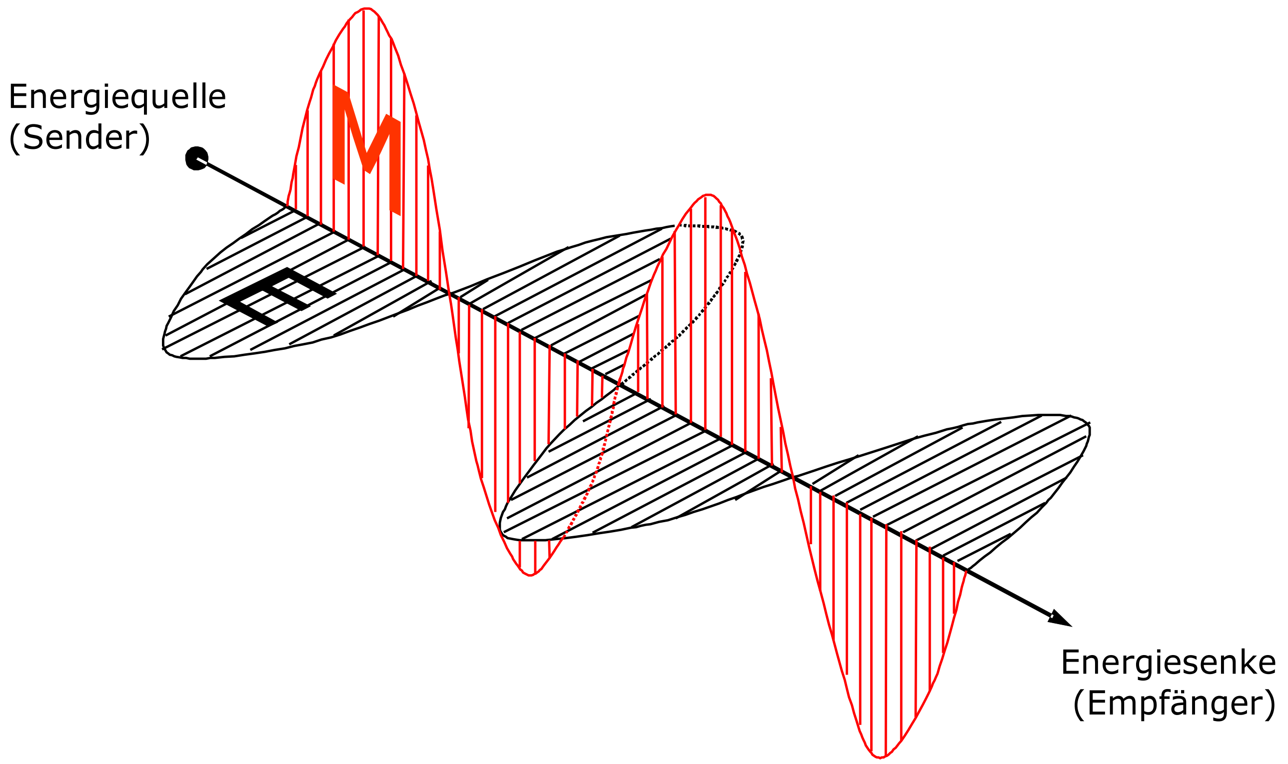
- The **wavelength** is inverse proportional to the energy E:

$$E = h \cdot \frac{c}{\lambda}$$

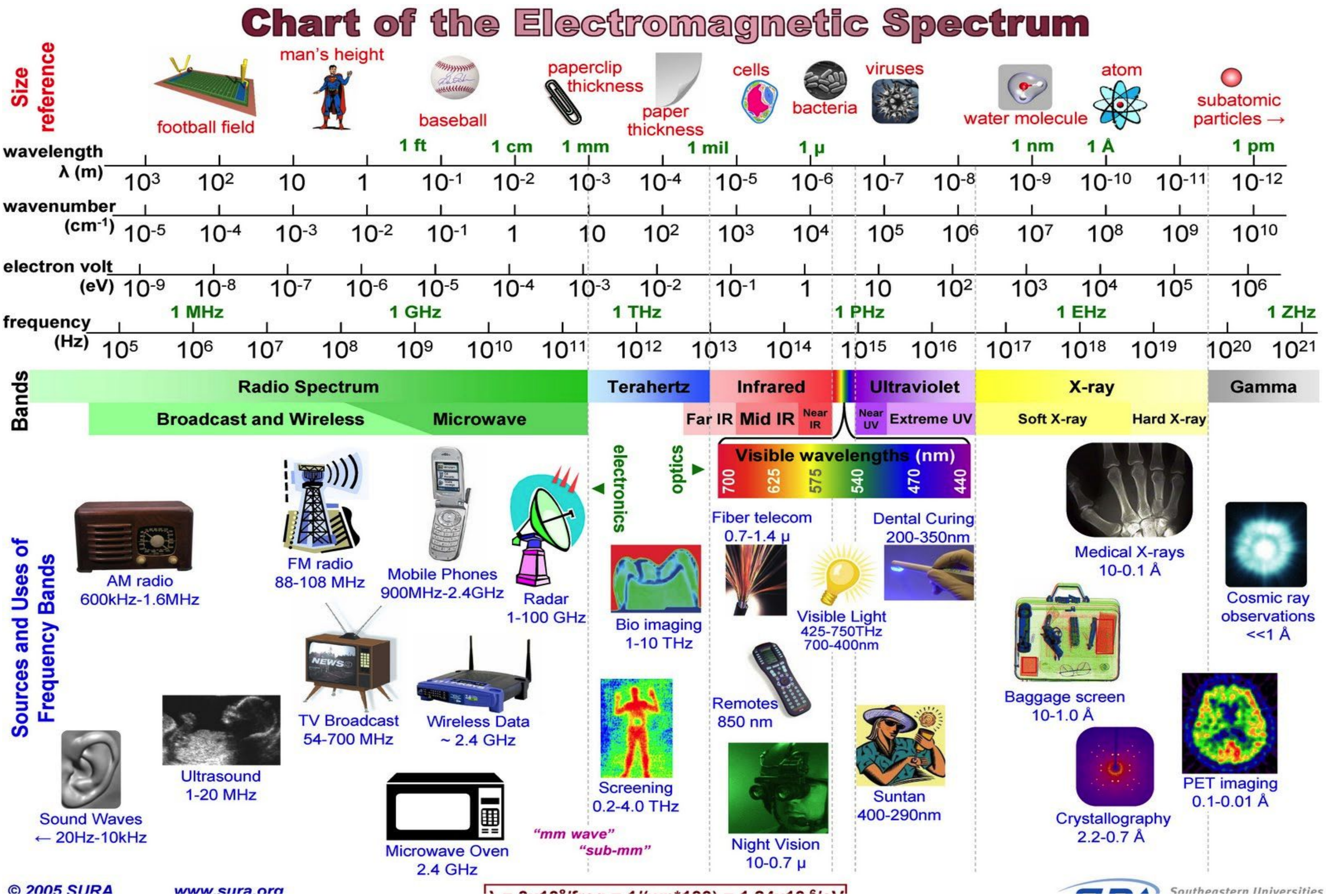
- c is the speed of light in vacuum (299'792'458 m/s)

Basics: Light: Wave Model

- The light can be interpreted as an **electromagnetic wave**.
- Light propagates in vacuum with speed of light.
- The electric and magnetic field component are perpendicular to each other

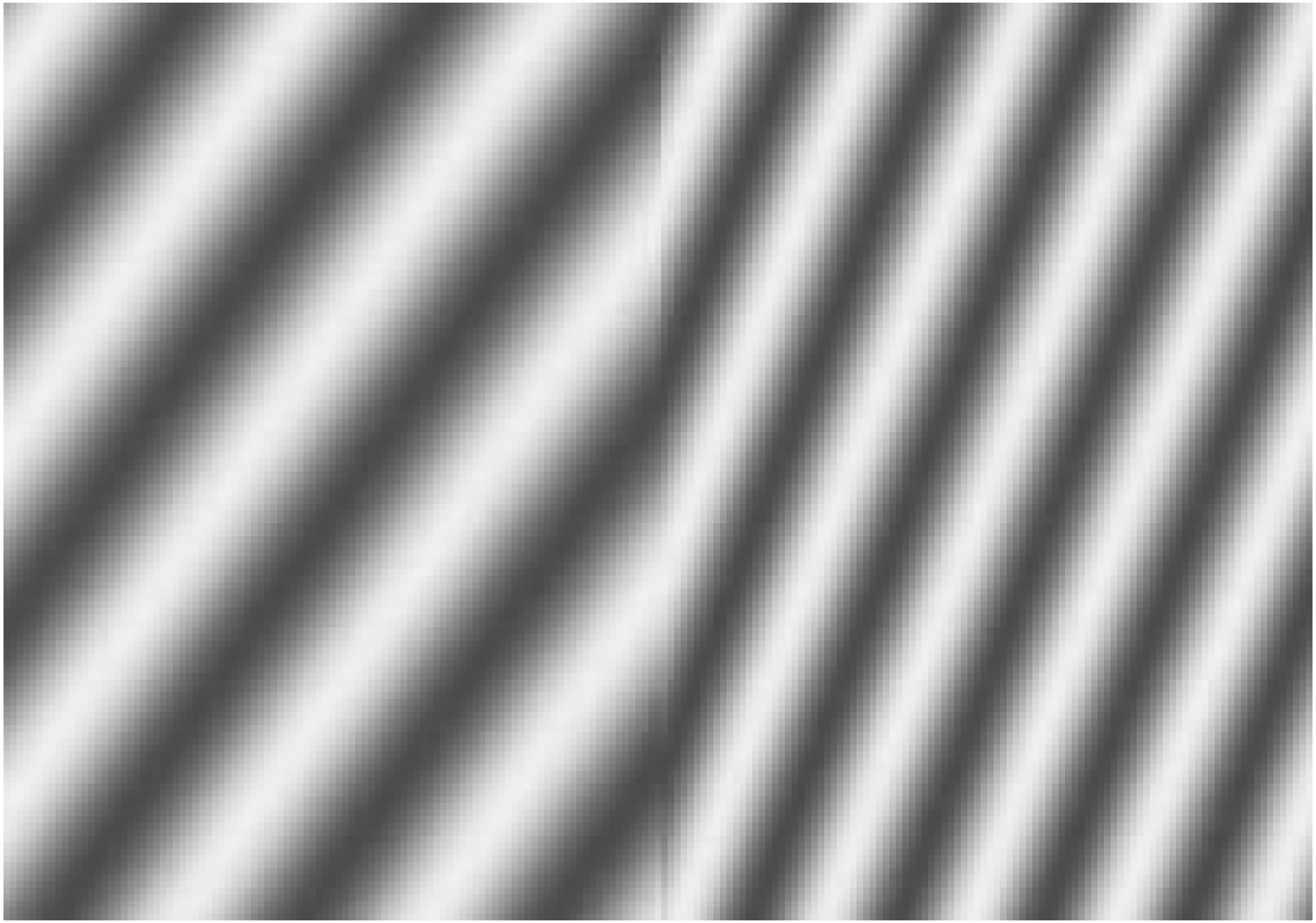


Light: Wave Model: Electromagnetic Spectrum



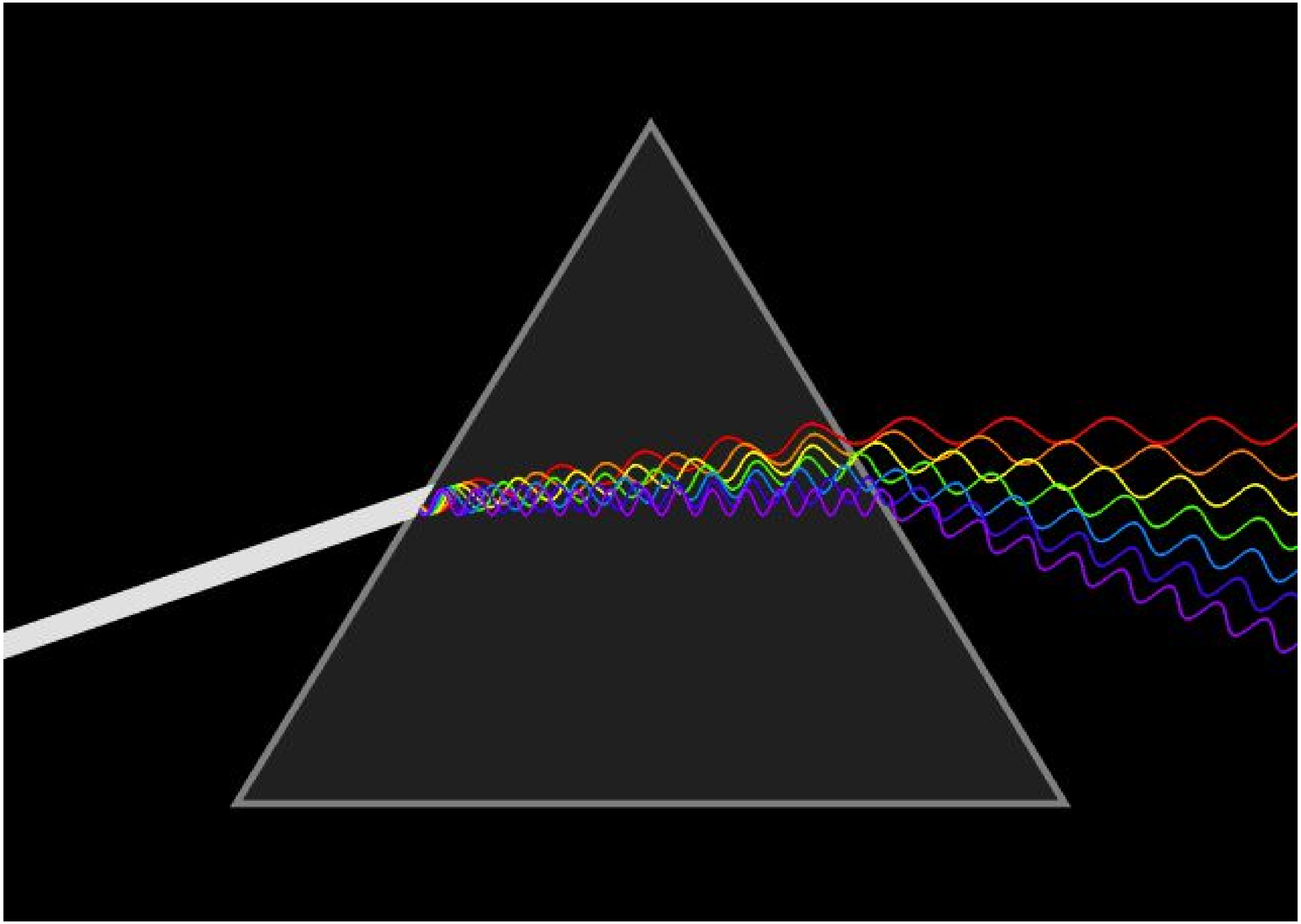
Basics: Light: Wave Model: Refraction

Why does a light ray get bended?



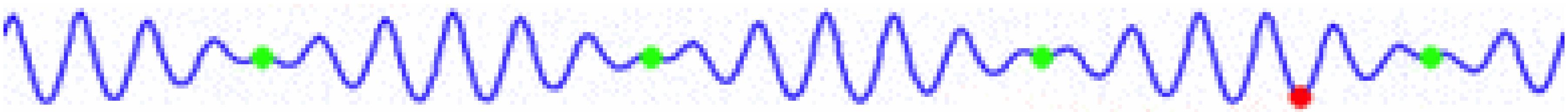
Basics: Light: Wave Model: Refraction

The phase velocity depends on the wavelength of the light:



Basics: Light: Wave Model: Refraction

- The **phase velocity** is the speed of a single monochromatic wave.
- The **group velocity** is the speed of polychromatic wave group.
- In **vacuum both velocities are the same** and equal to the speed of light.
- View this animation: http://de.wikipedia.org/wiki/Phasengeschwindigkeit



Basics: Light: Wave Model: Refraction

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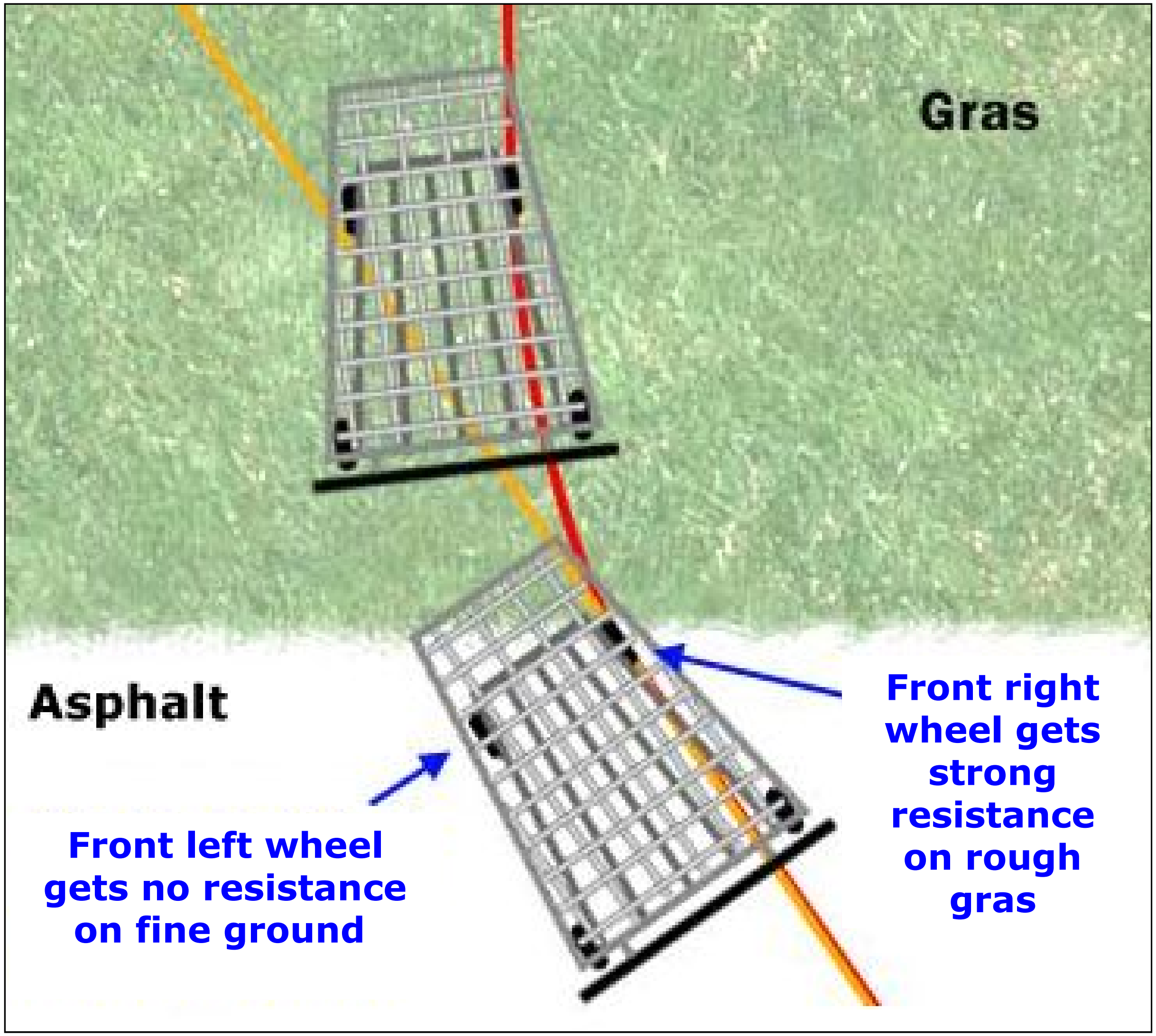


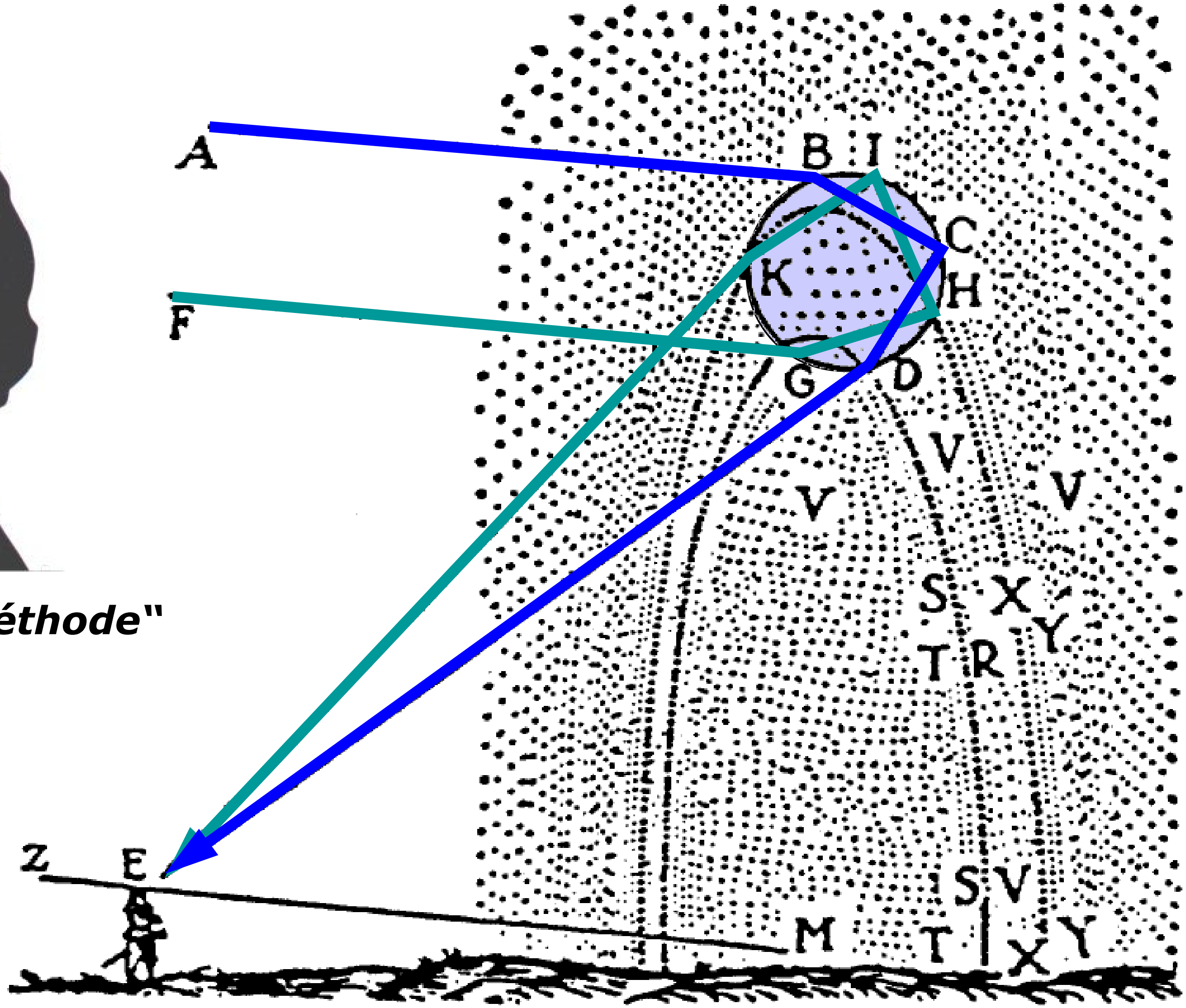
Light: Wave Model: What causes a rainbow?

Light: Wave Model: What causes a rainbow?

Light: Wave Model: What causes a rainbow?

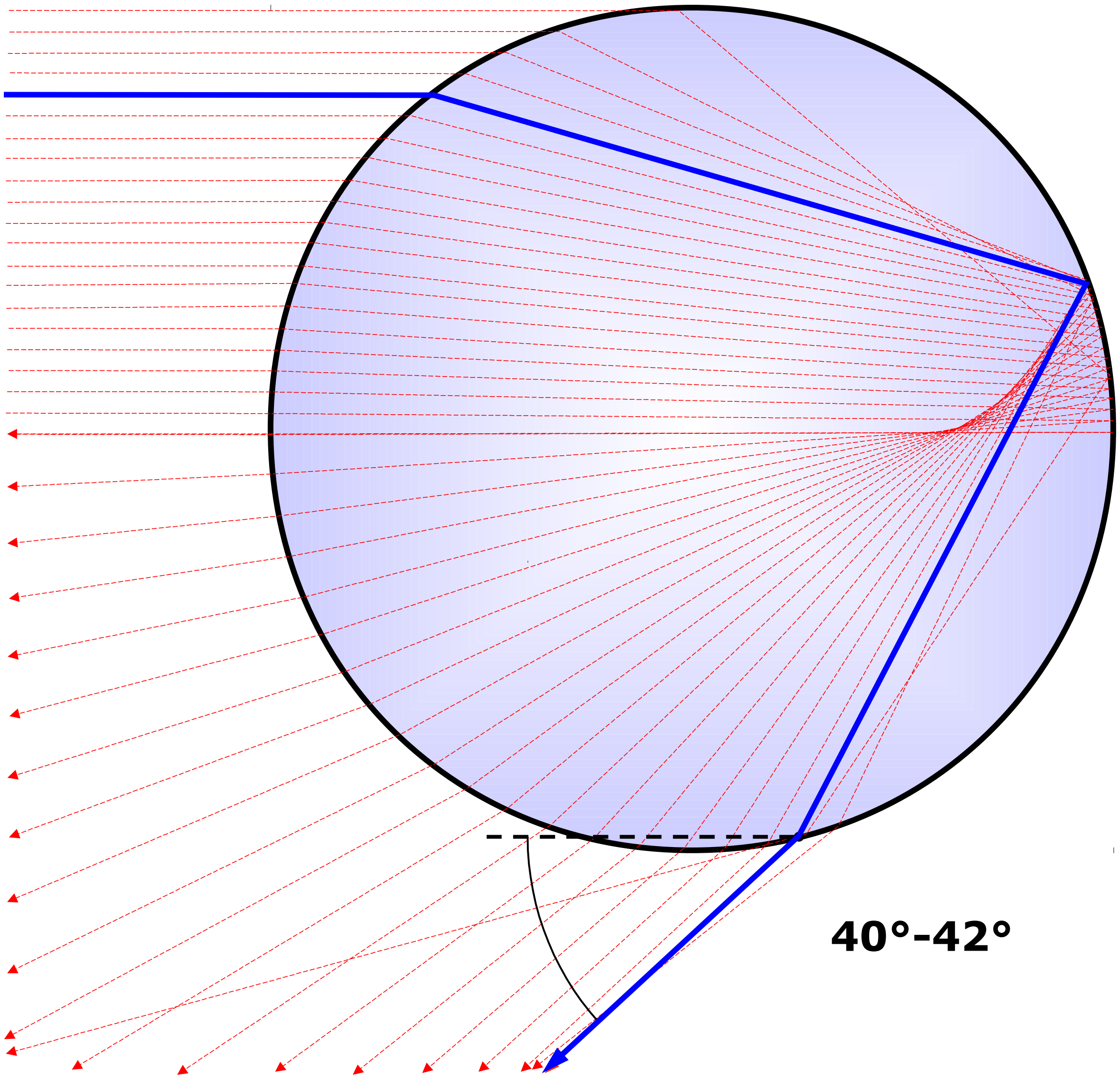
- The first explanation comes from the French mathematician *Henri Descartes.*

„Discours de la méthode"



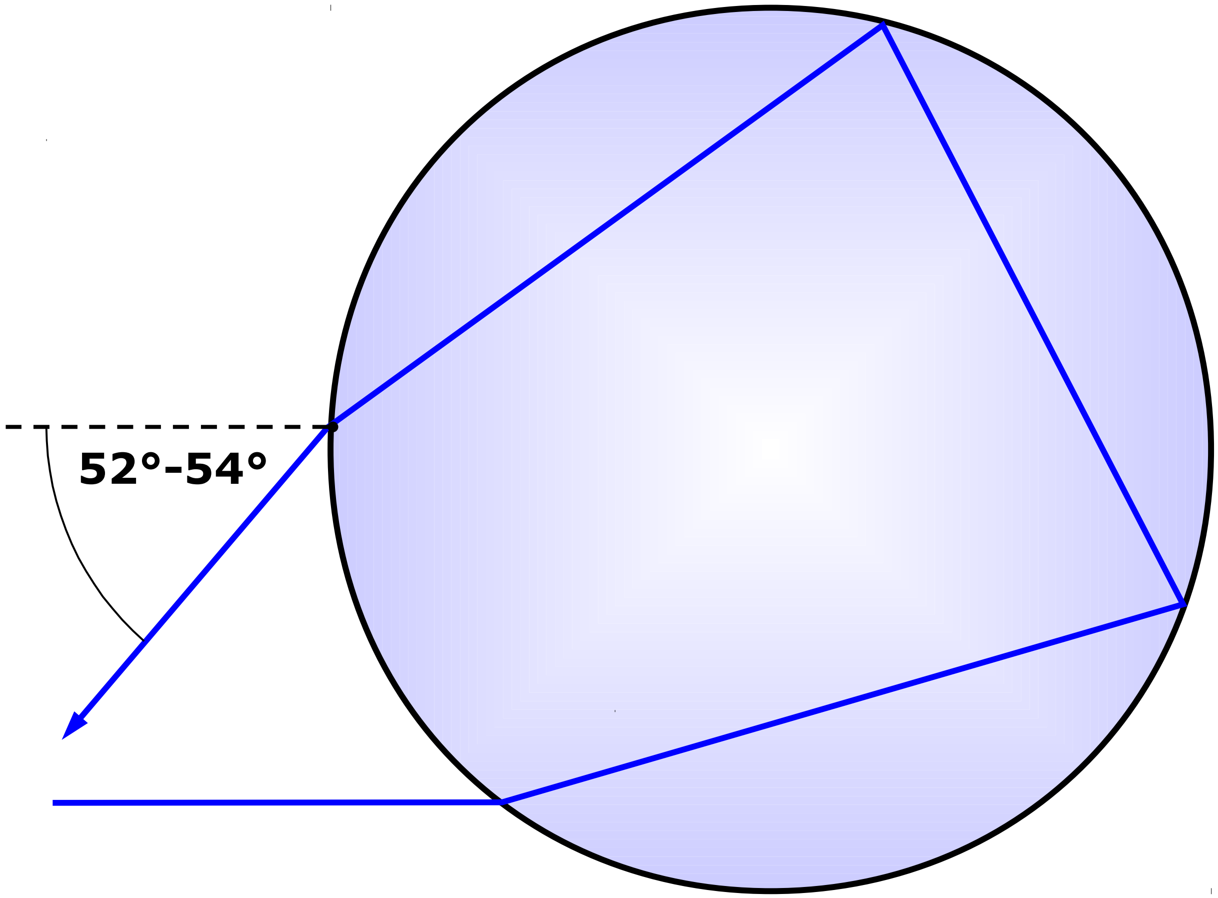
Light: Wave Model: What causes a rainbow?

- Reflections & refractions in the top hemisphere of a rain drop:



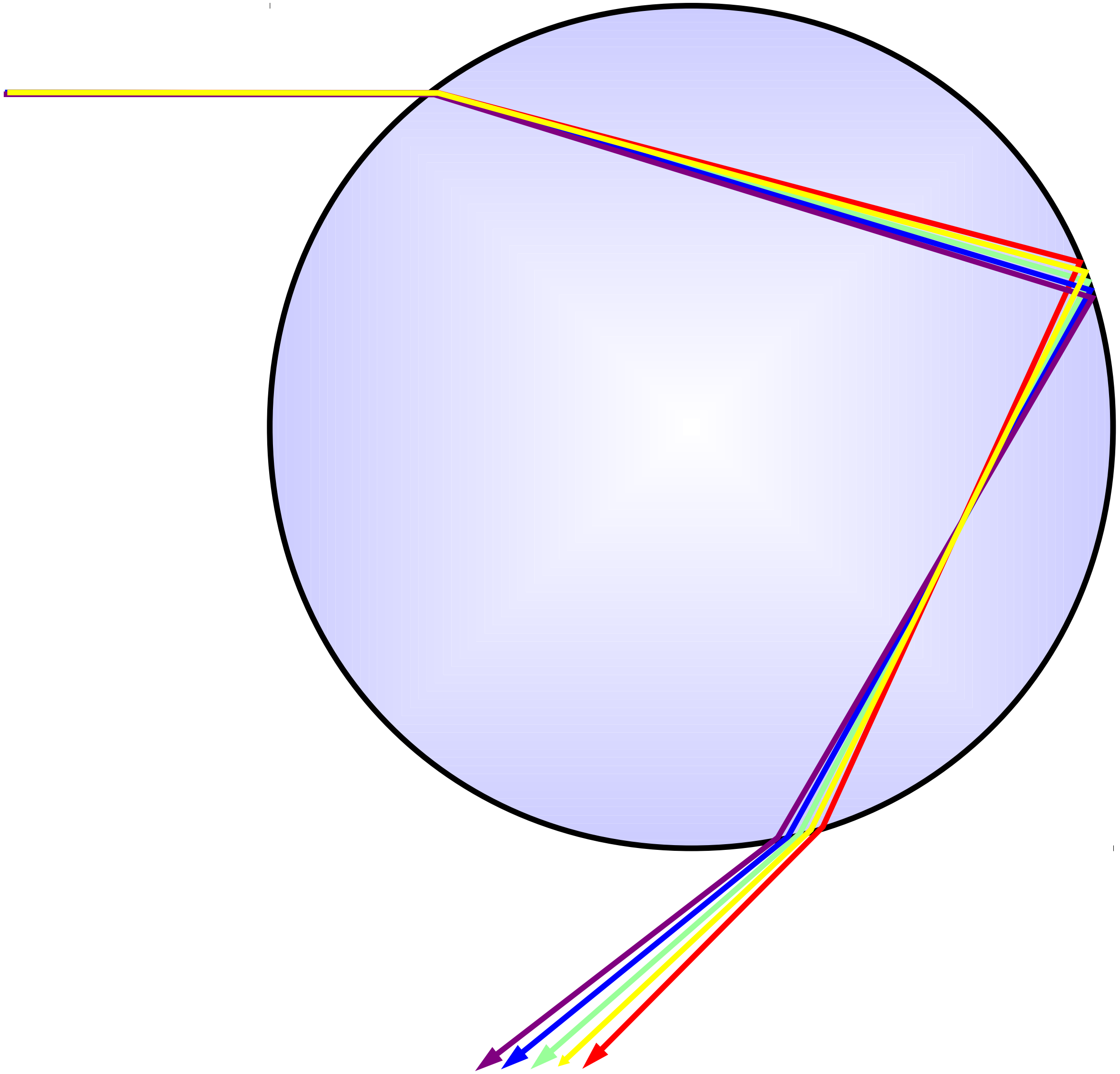
Light: Wave Model: What causes a rainbow?

- Reflections & refractions in the bottom hemisphere of a rain drop:



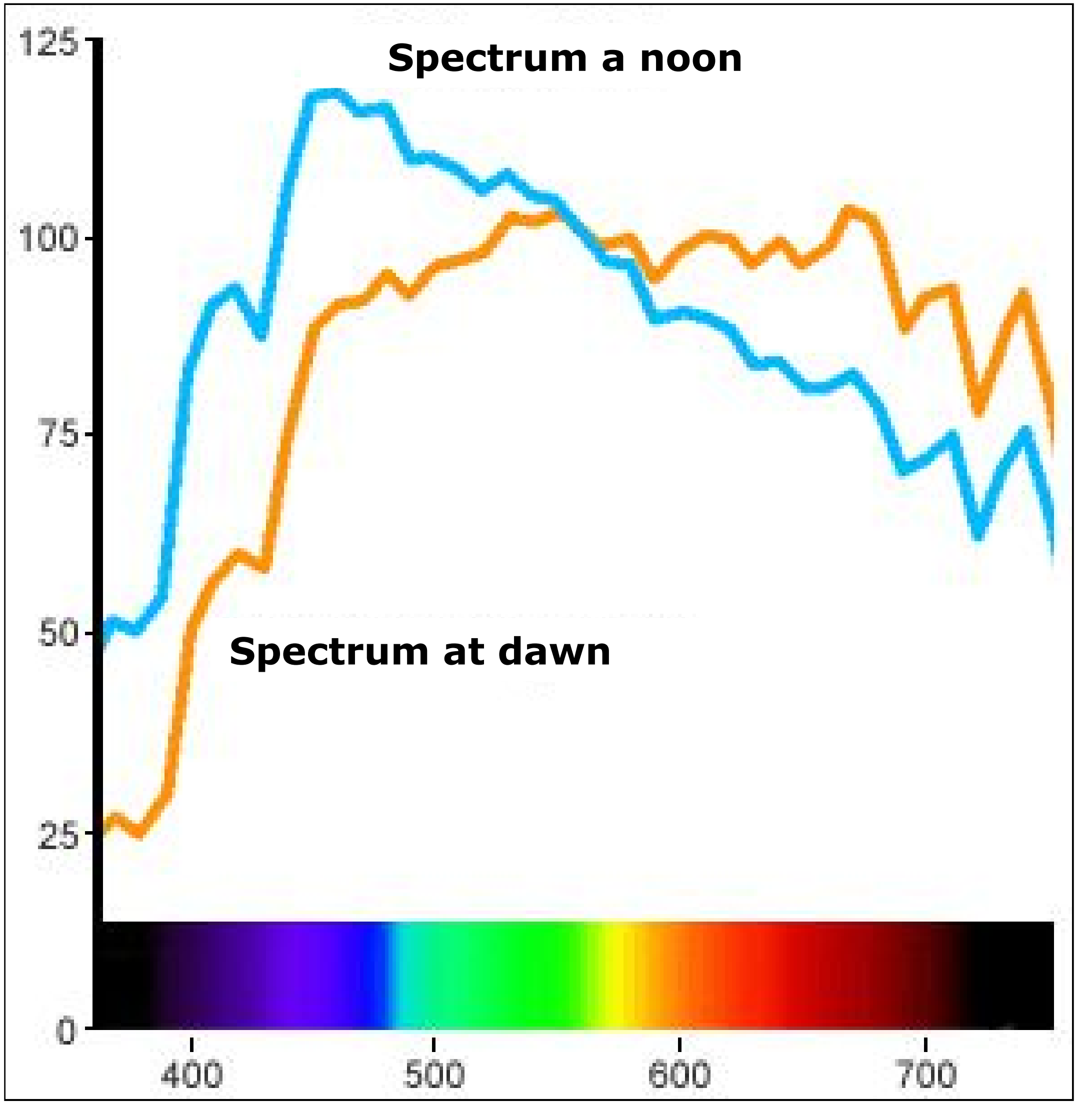
Light: Wave Model: What causes a rainbow?

Colors appear due to the different refraction angles:



Basics: Light: Wave Model

White Light can have very different spectras:



Basics: Light: Wave Model

- **Light rays propagate straight:**

  > Basis of geometric law of affinity

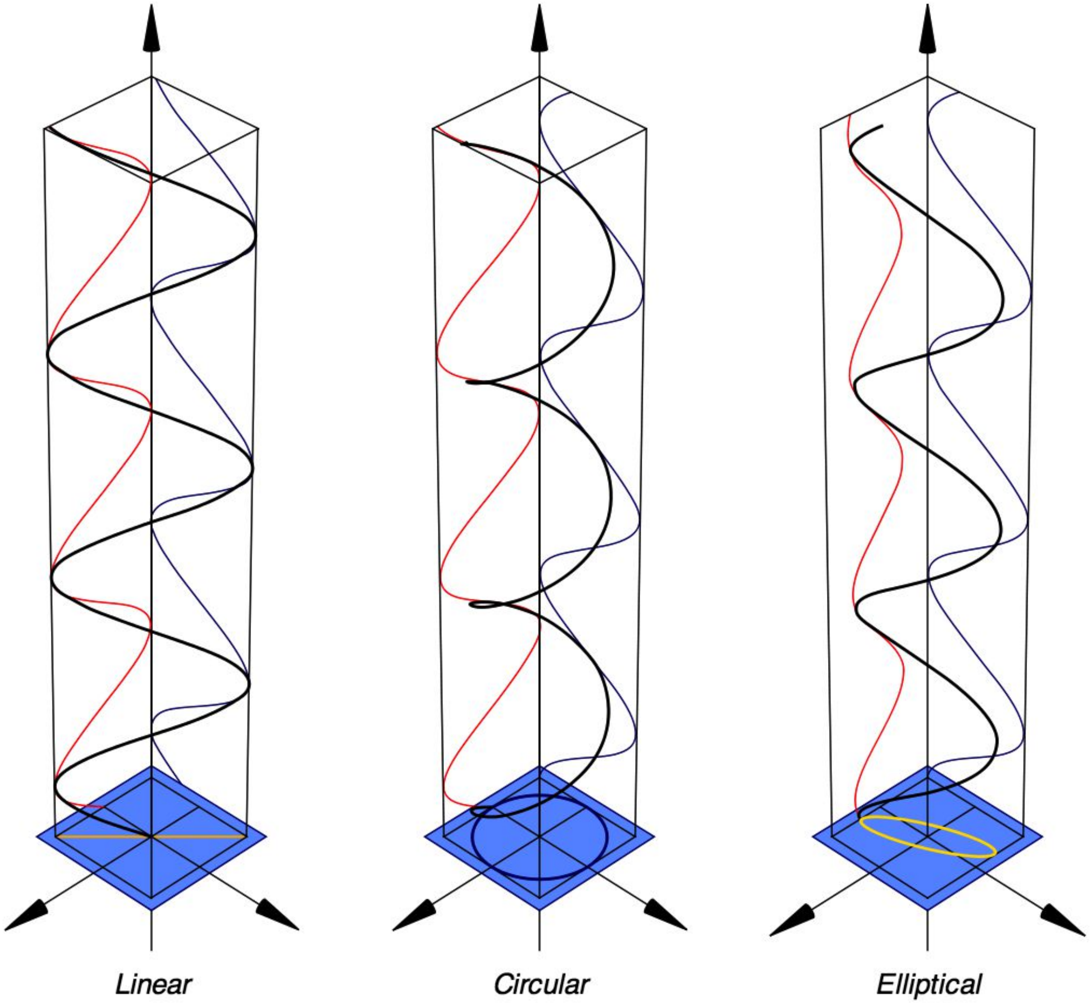
- **The wavelength of visible light is small (400 - 700 nm):**

  > We can see therefore small things sharp

Basics: Light: Wave Model:

Light Polarization

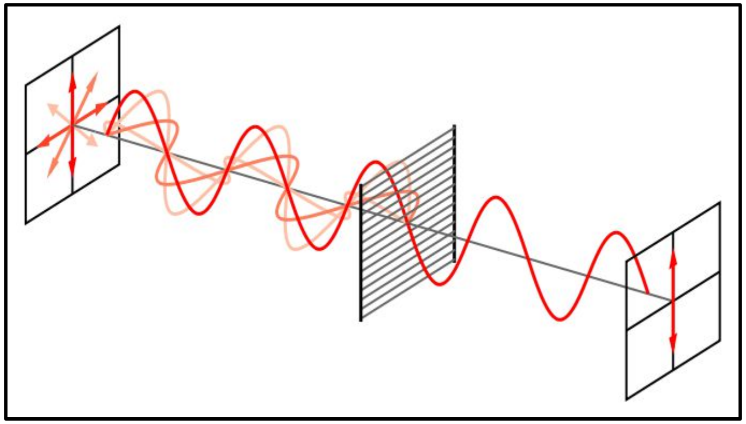
- The light doesn's swing necessarily in a plane. It can rotate around the propgation direction:

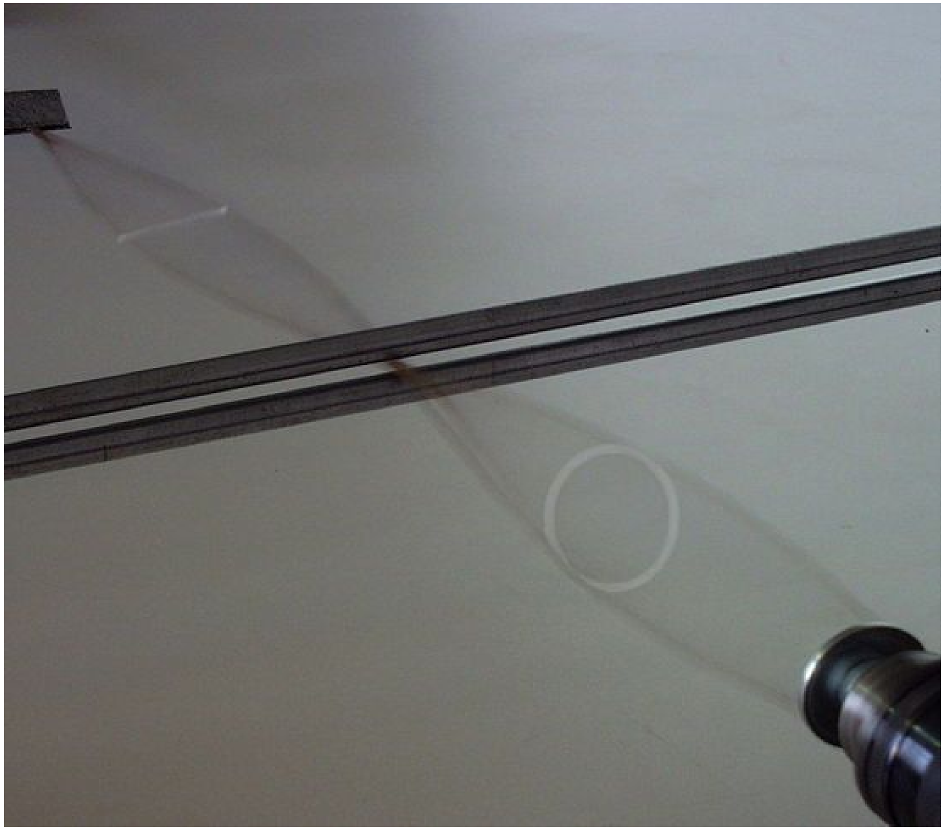


Basics: Light: Wave Model:

Light Polarization

- With a polarization filter it can be forced into a plane:





Basics: Light: Wave Model

Light Polarization

- In photography you can use a polarization filter to reduce reflections:

Basics: Light: Wave Model

Light Polarization

- In photography you can use a polarization filter to get a dark blue sky:

Basics: Light: Wave Model

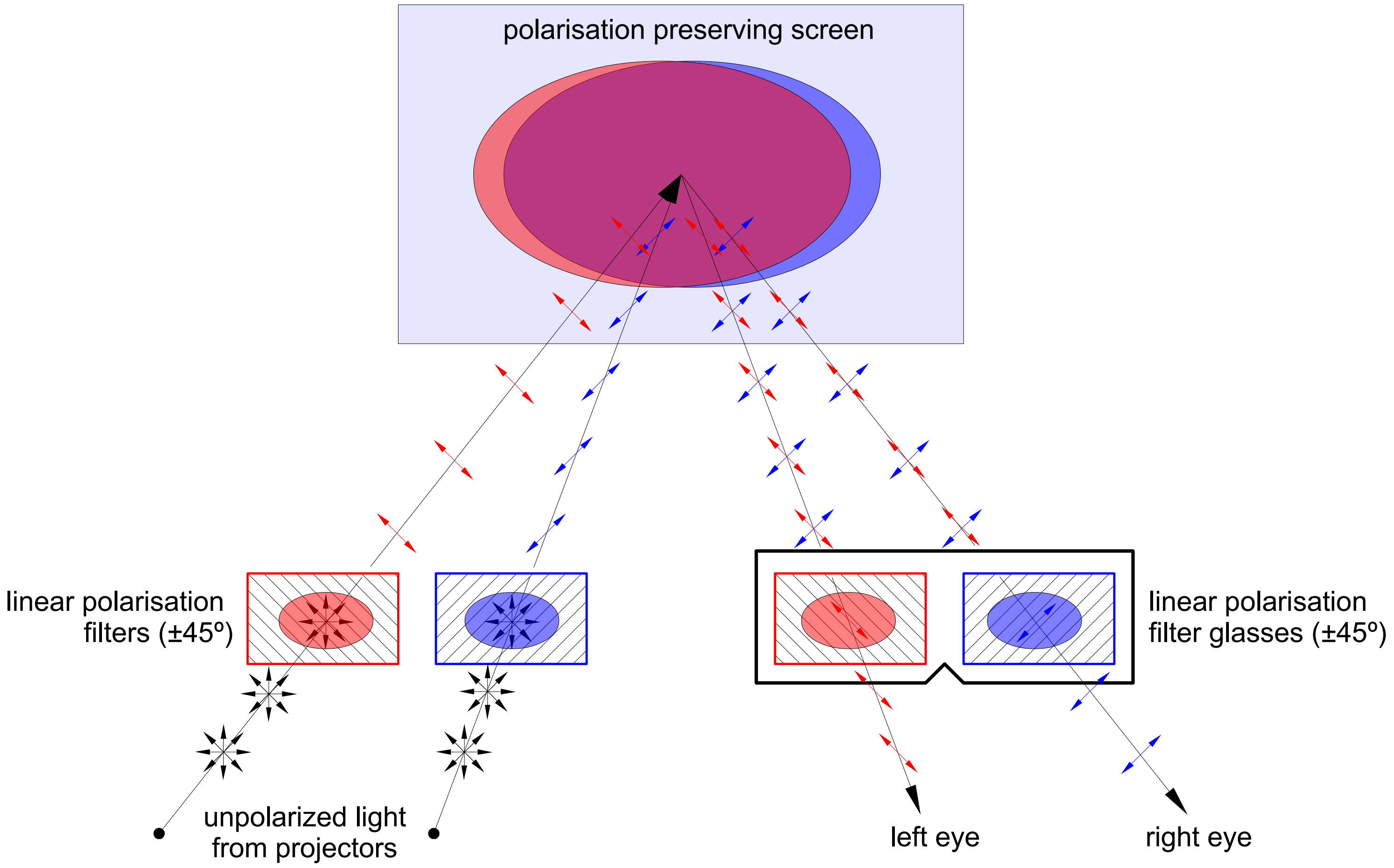
Light Polarization

- You can use polarization filter for stereo projection to separate the left and right image:

Basics: Light: Wave Model

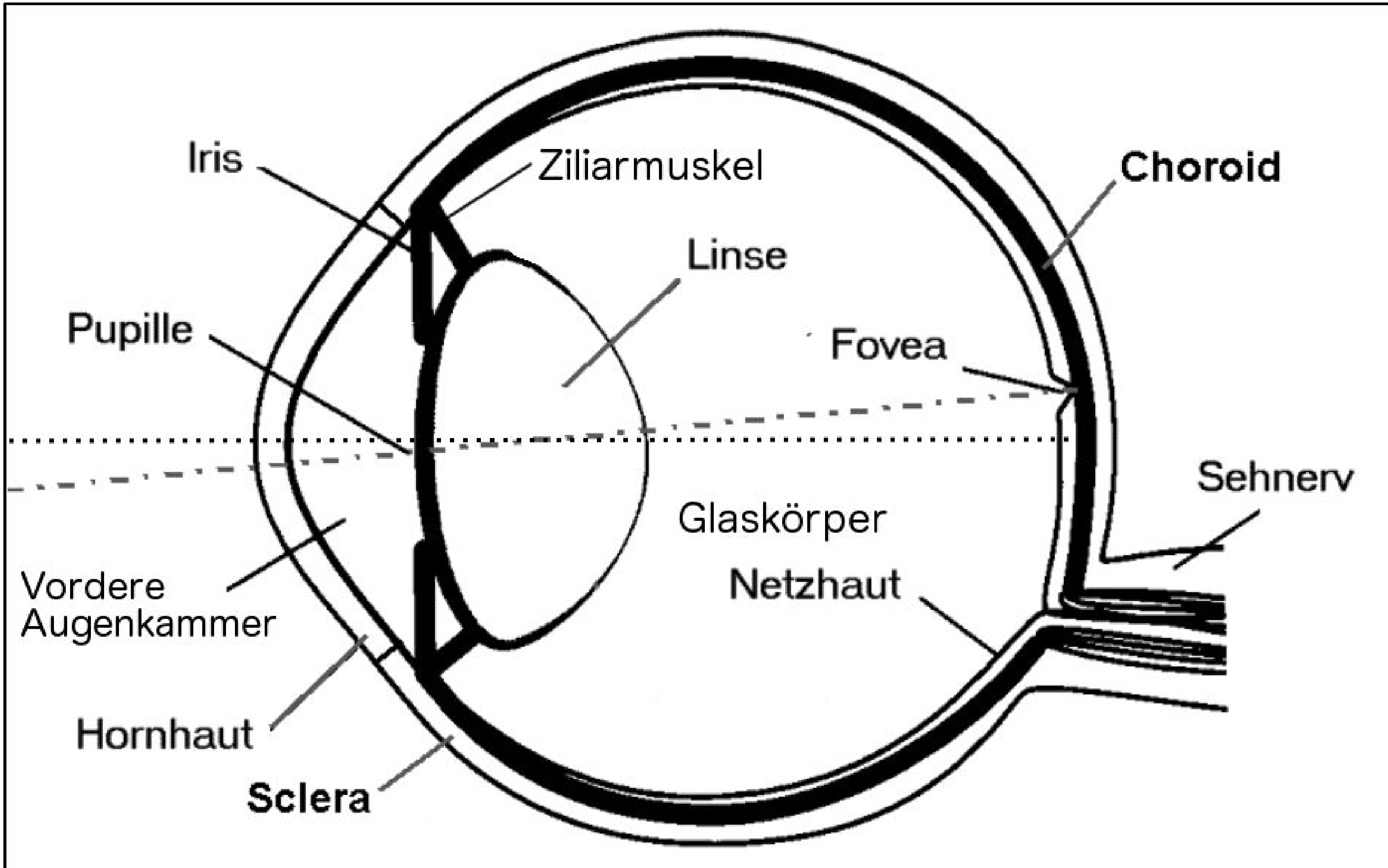
Light Polarization

- You can use polarization filter for stereo projection to separate the left and right image:



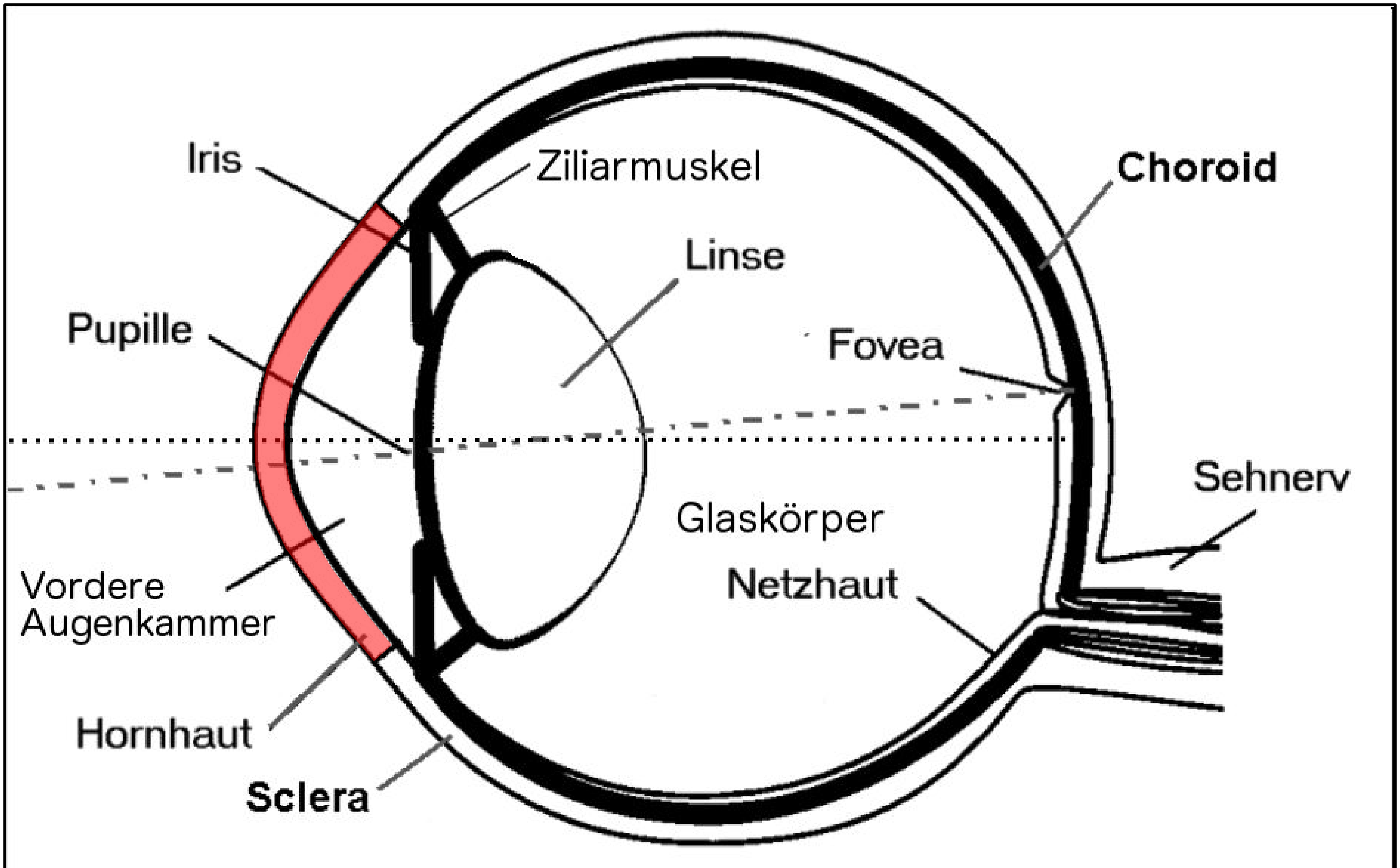
Basics: Eye

About spherical, ca. 22mm diameter



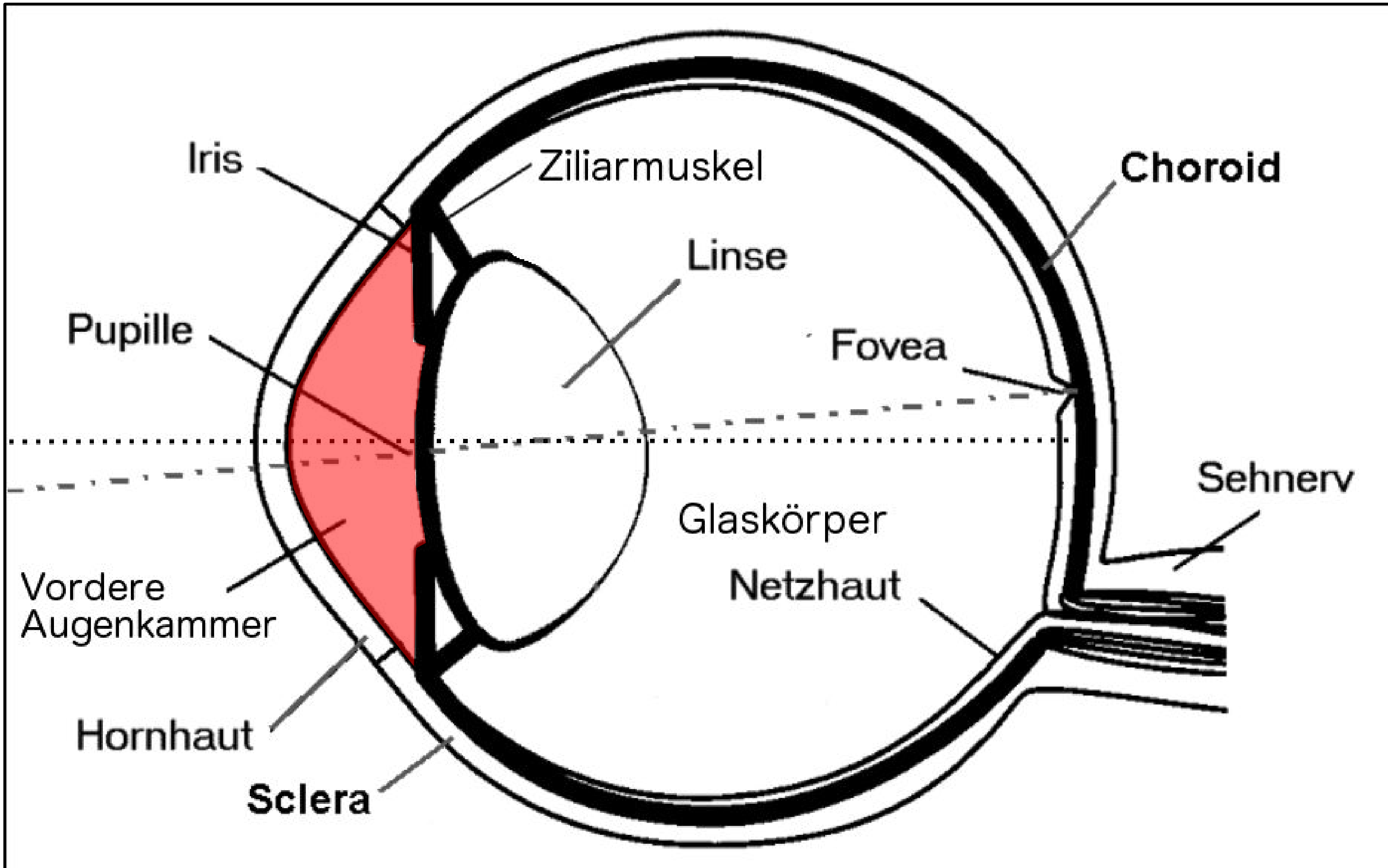
Basics: Eye: Cornea (Hornhaut)

Though, transparent, thickness only 0.5-0.7mm



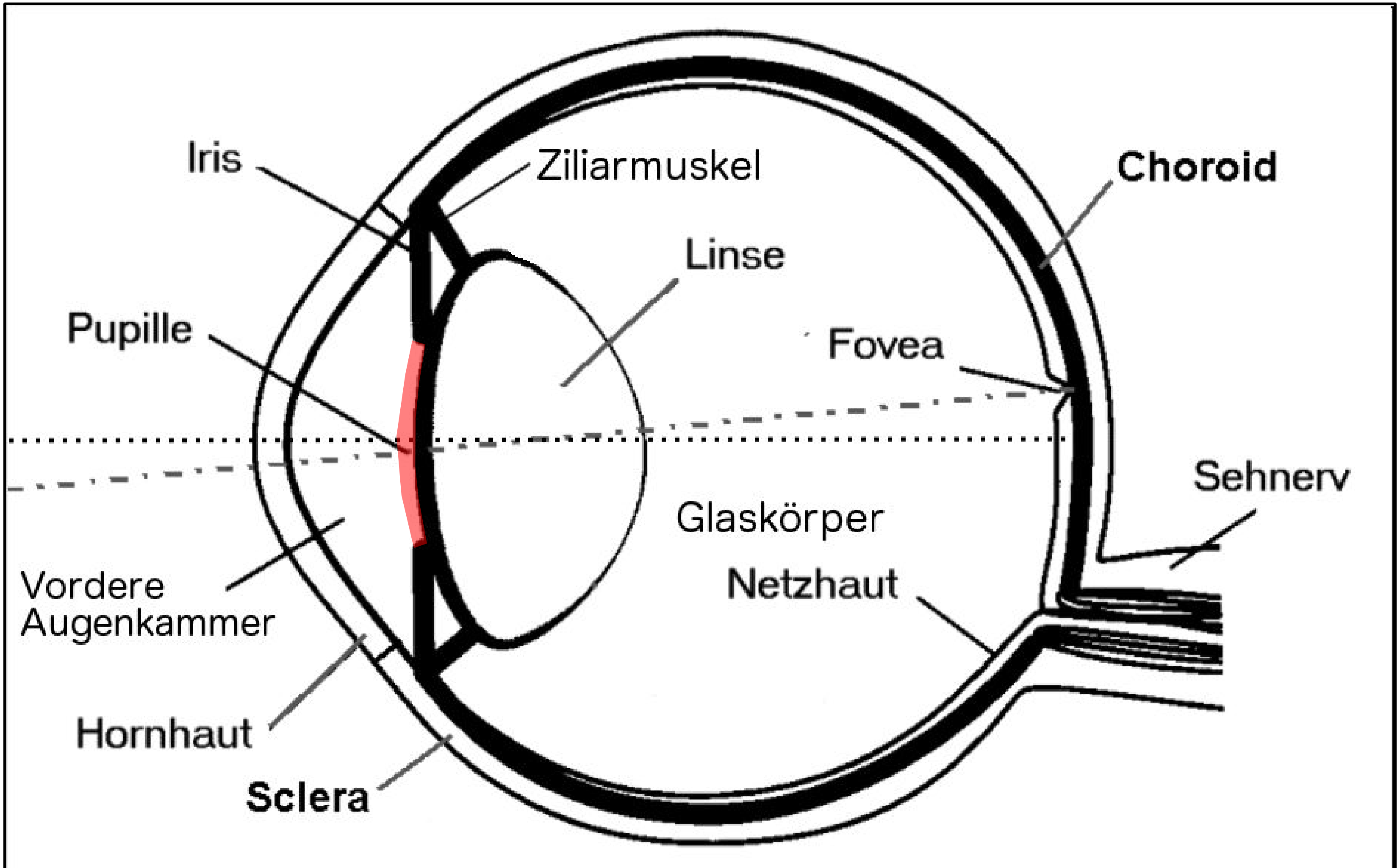
Eye: Anterior Chamber (Vordere Augenkammer)

Highly transparent liquid, constantly rebuilt.



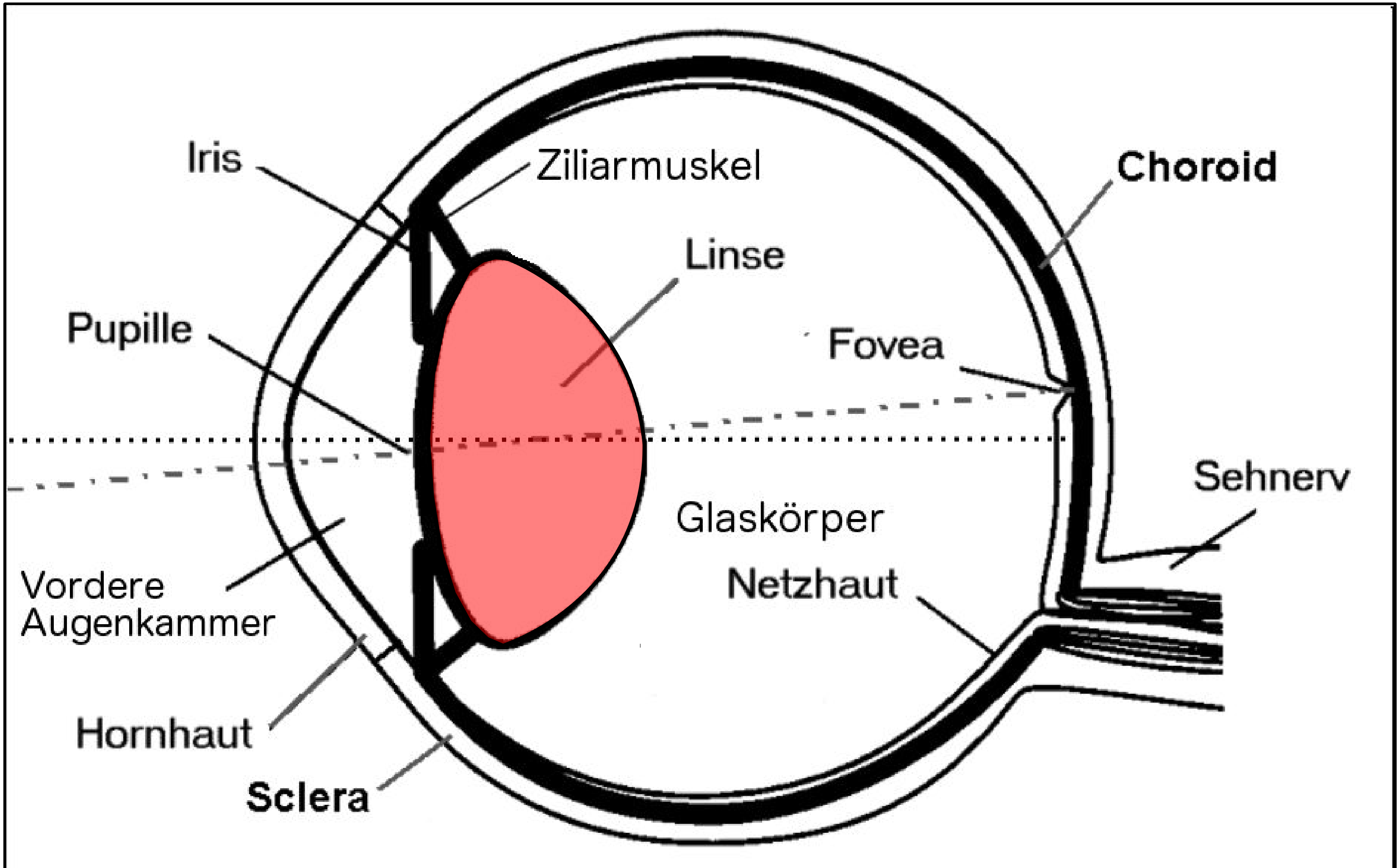
Basics: Eye: Pupil

Diaphragm of the eye, 2-8 mm diameter, controls the amount of light



Basics: Eye: Lens

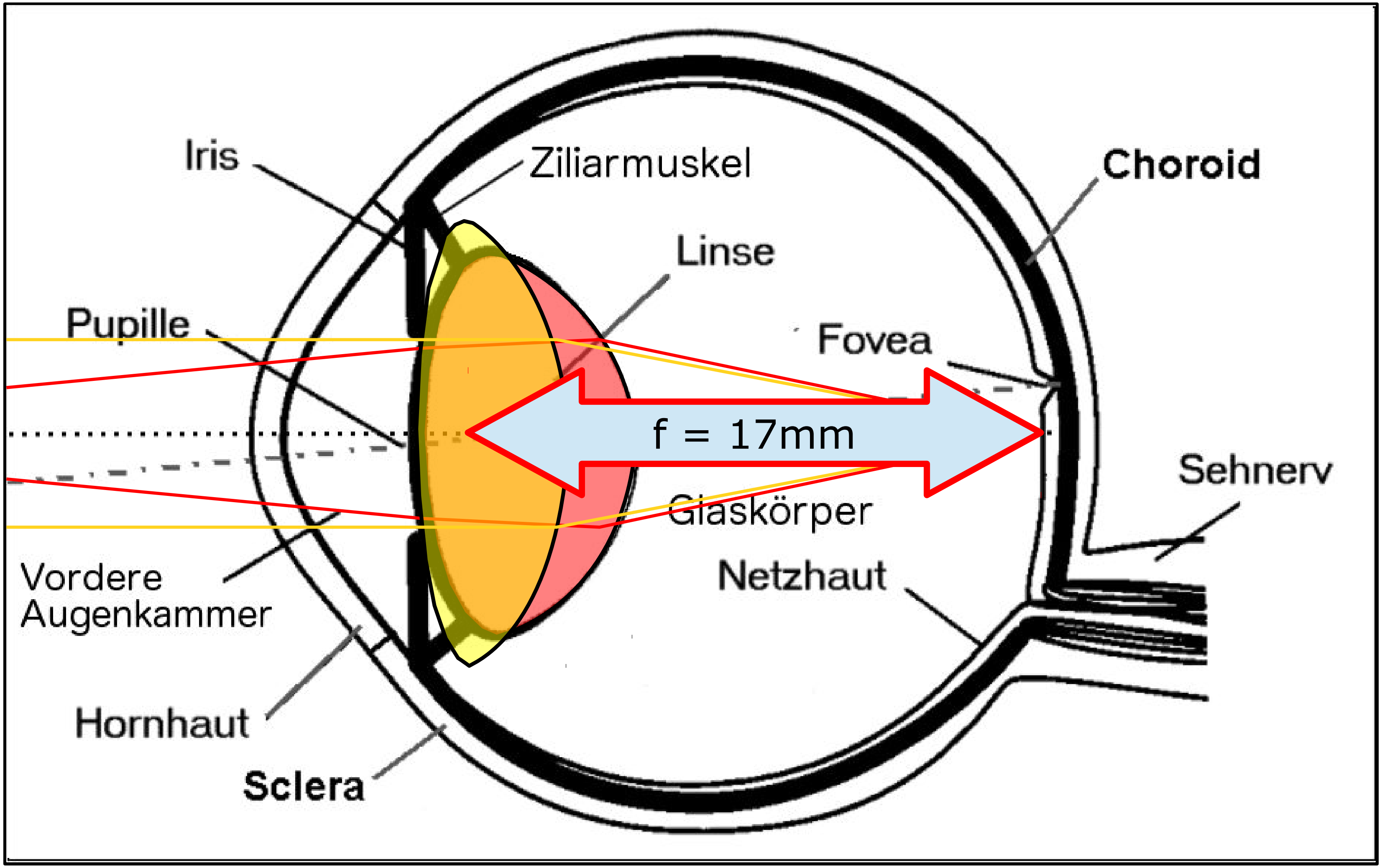
Contains 70% water, the rest (fat & proteines) absorbs infrared & UV light



Basics: Eye: Lens

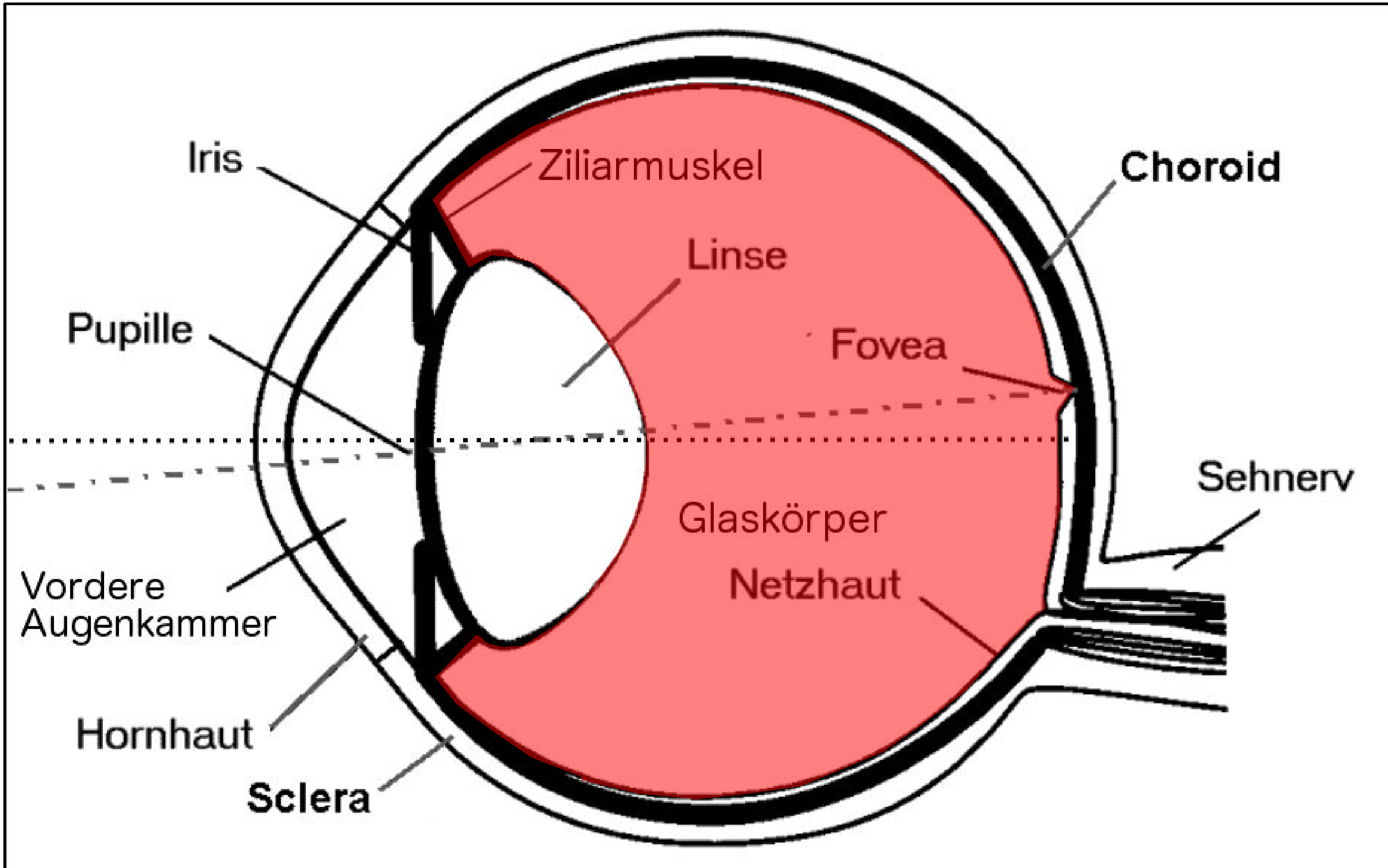
With relaxed ciliar muscles we focus to the near.

With tight ciliar muscles we flatten the lens and focus to the far.



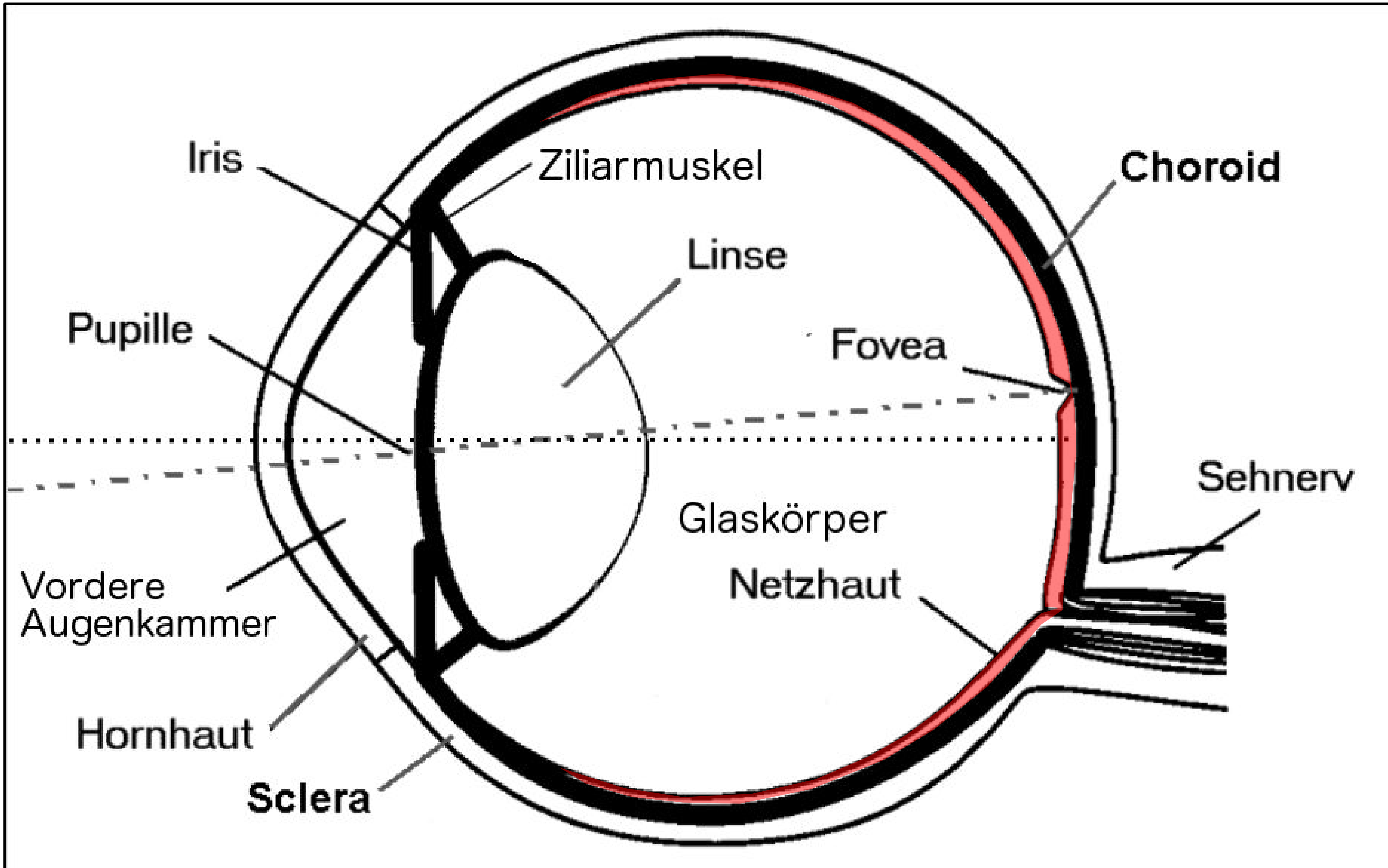
Basics: Eye: Vitreous Body (Glaskörper)

Highly transparent gelatinous mass fills the eye body



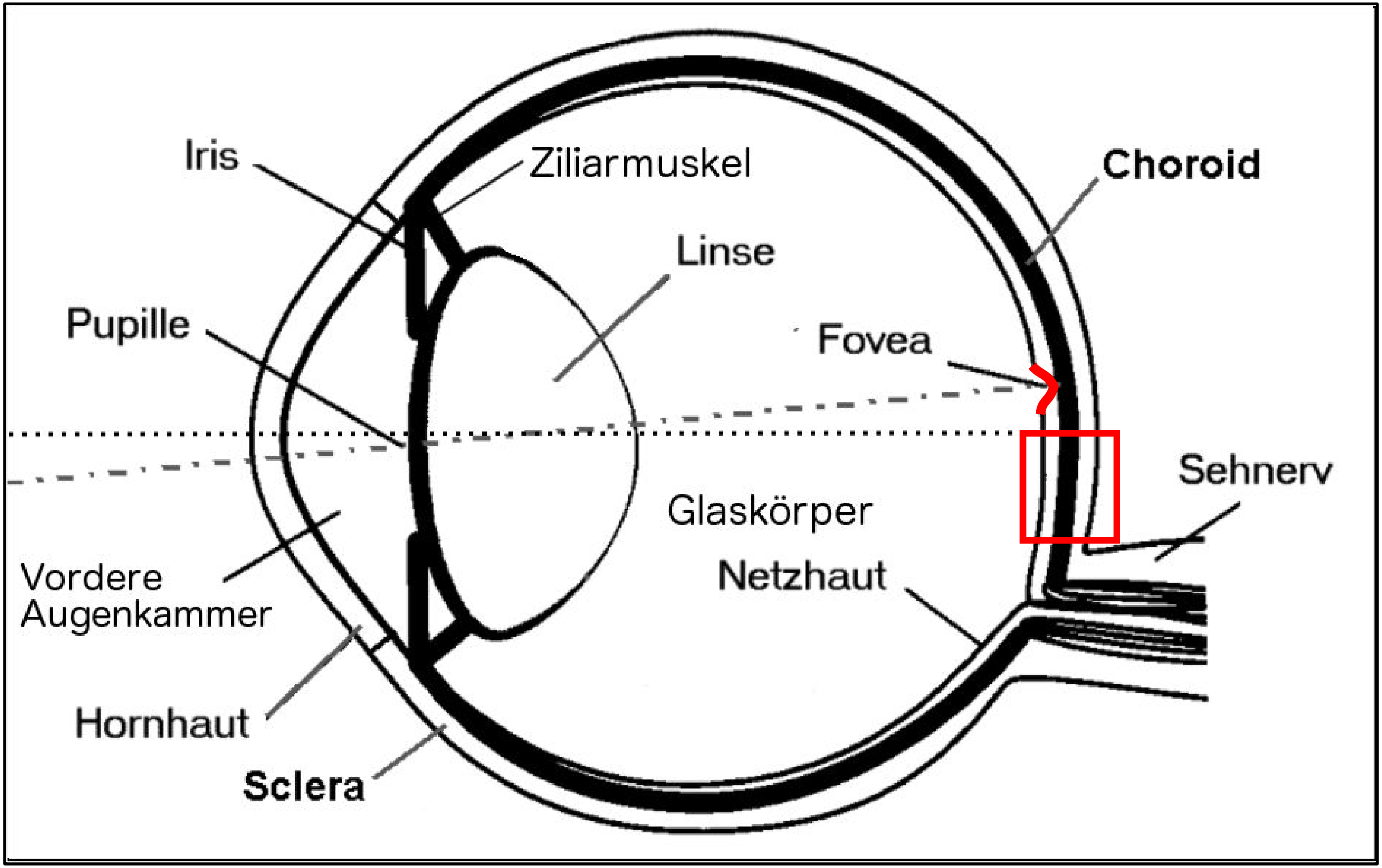
Basics: Eye: Retina (Netzhaut)

Contains the light sensitive cells, the blood vesels and nerves



Basics: Eye: Fovea Centralis

Where real perception happens, about 2mm diameter, mostly color perception



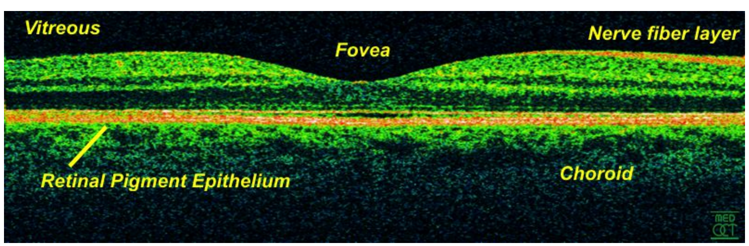
Basics: Eye: Retina

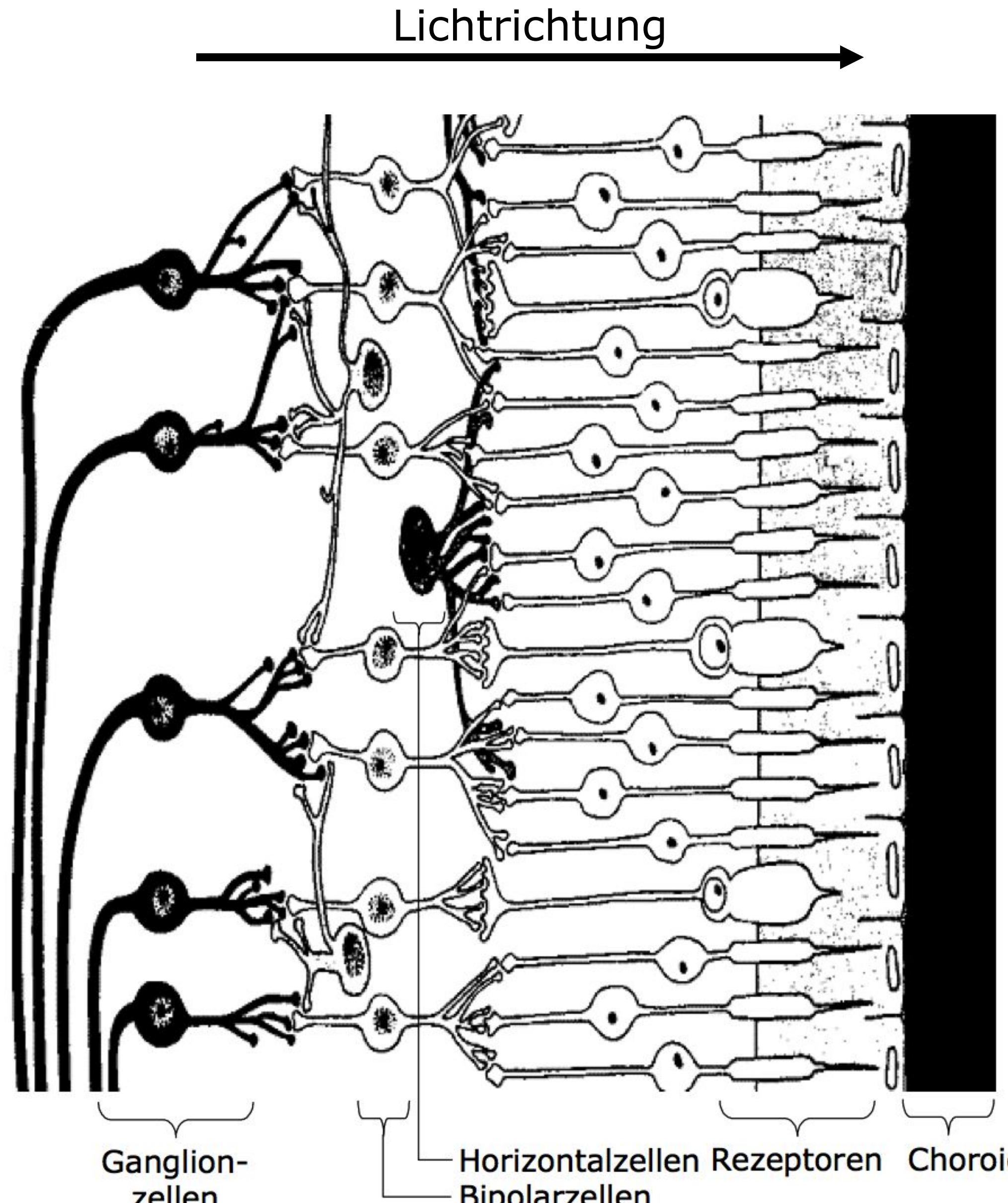
Ganglion cells lead about 1 mio. nervs to the blind spot.

Bipolar and horizontal cells create the differential signal for edge and contrast enhancement as well as for color encoding

Receptors transform the light intensity into nerve impulses.

OCT Scan of the retina:





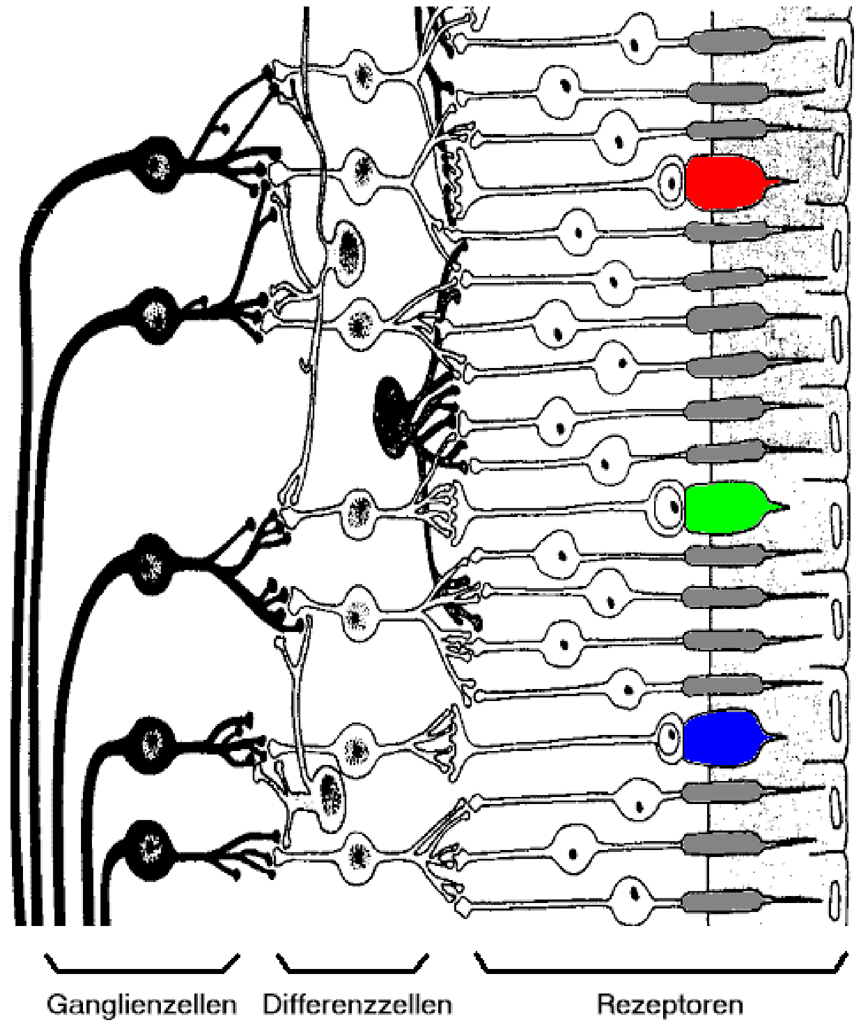
Basics: Eye: Retina

Receptors

- The receptors contain photopigment **Rhodopsin** as an active substance.
- Rhodopsin gets constantly rebuilt.

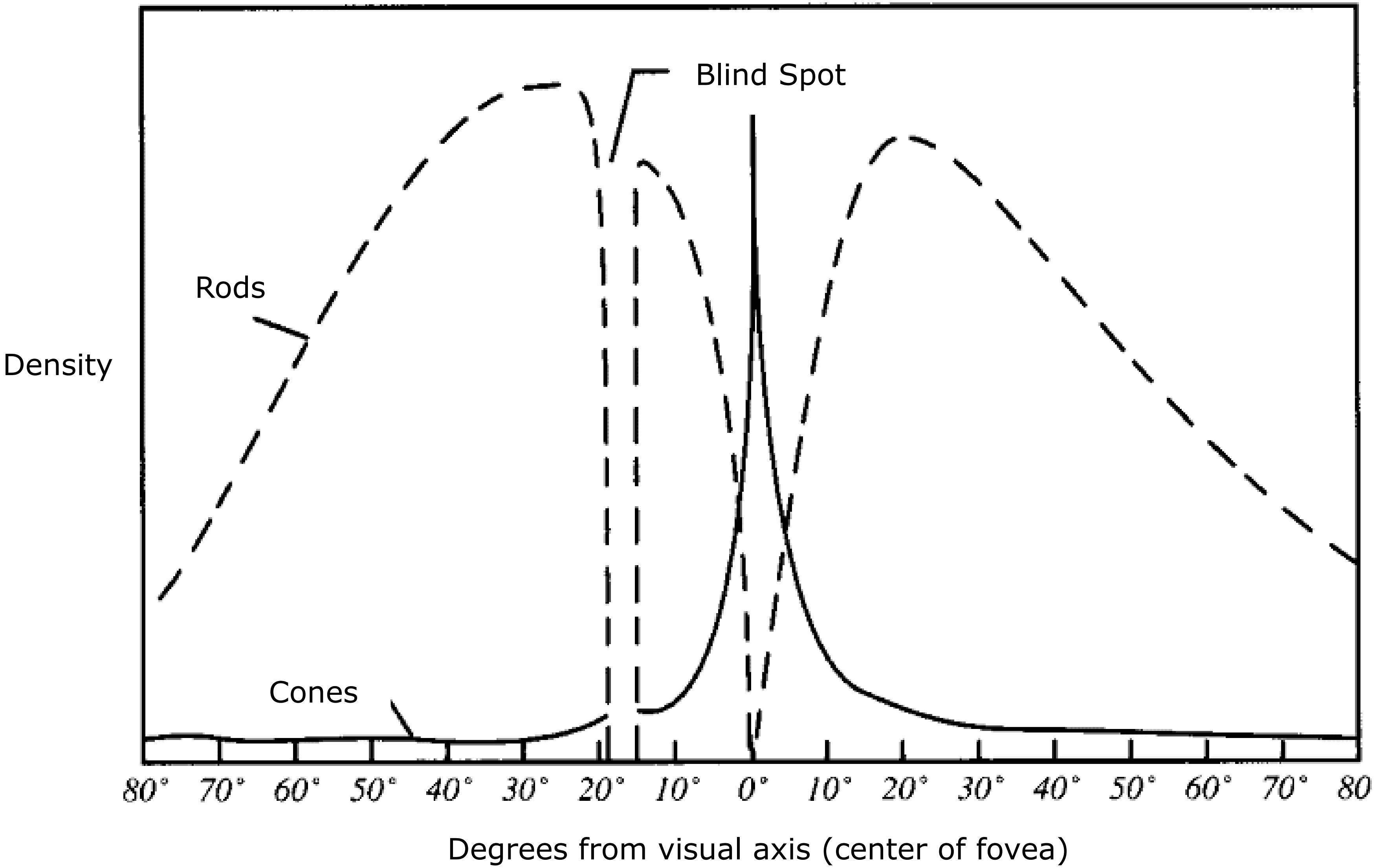
110-130 mio. rods (Stäbchen, bâtonnets) are sensitive to the full visible spectrum and therefore important for luminance sensitivity.

6-8 mio. cones (Zapfen, cônes) are sensitive in narrow spectras and therefore responsible for the color sensitivity.



Basics: Eye: Retina

Distribution of cones and rods over the retina:



Basics: Eye: Retina: Space Variant Vision

Louis Boilly (1761-1845) Thirty-Six Faces of Expression, Log-Polar Transform by R. A. Peters, Vanderbilt University

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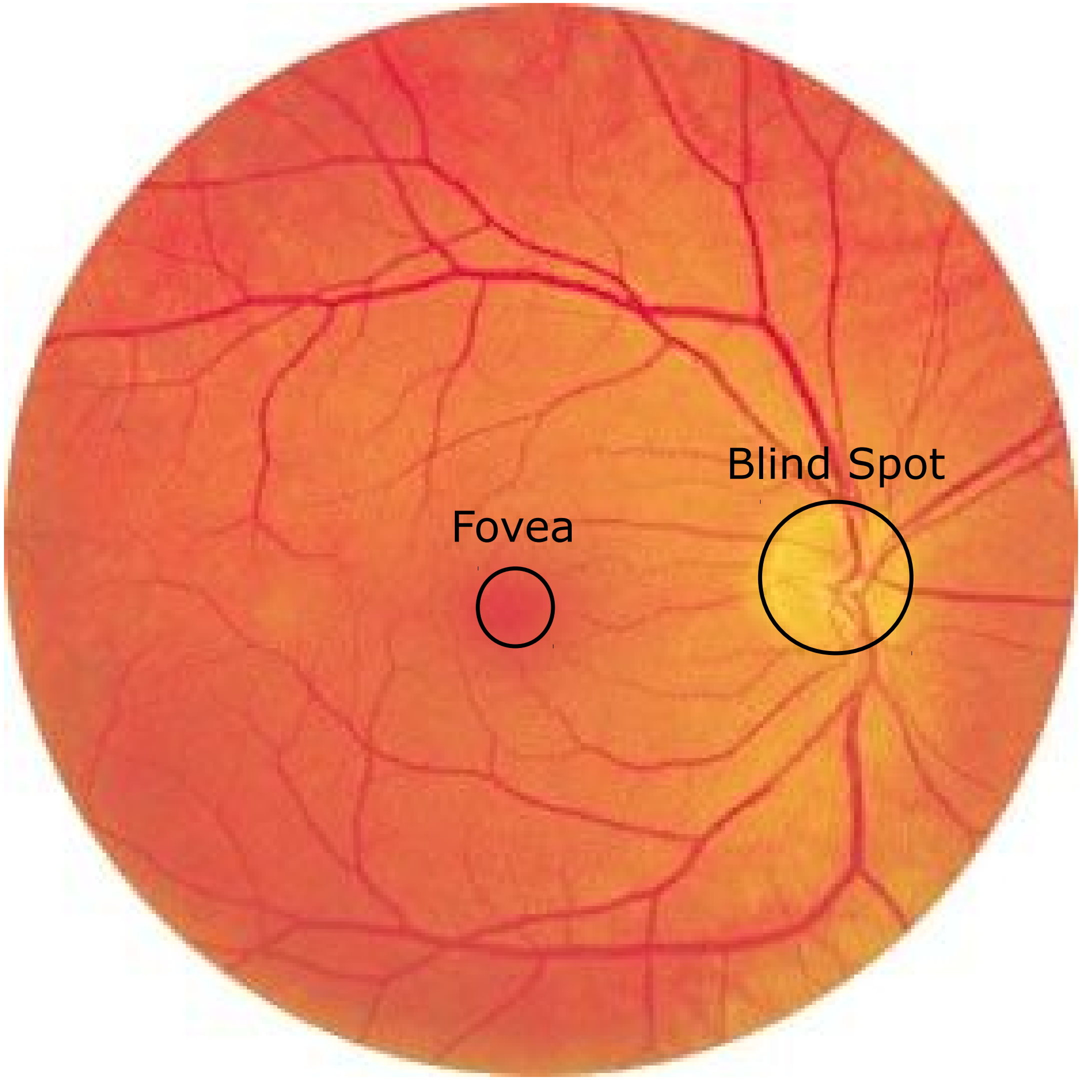


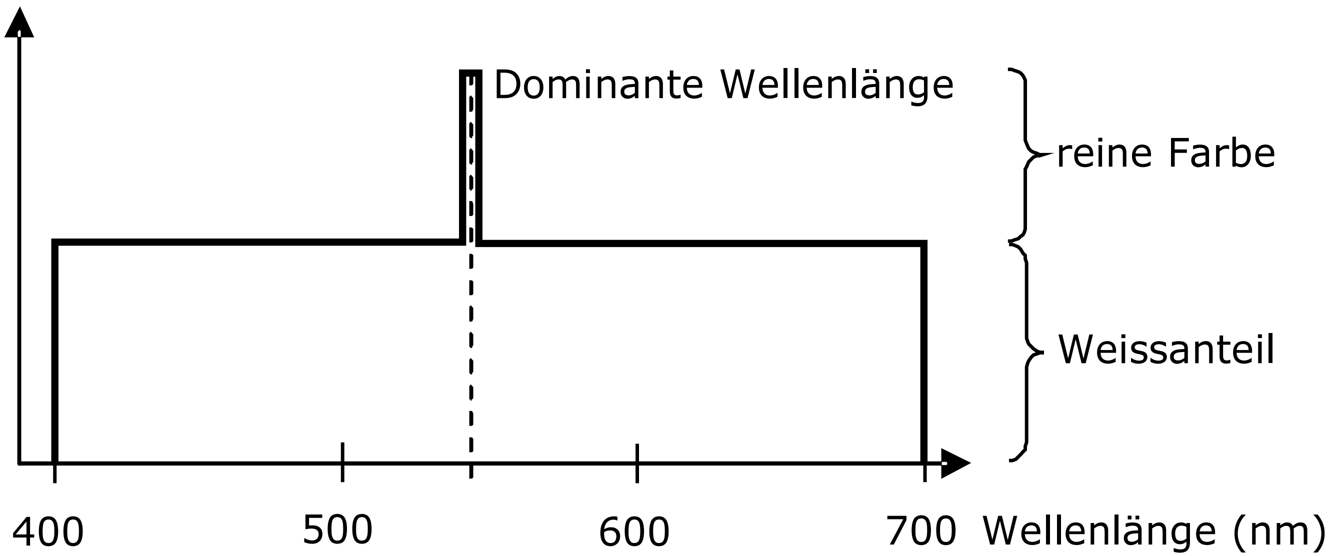
Basics: Eye: Color Sensitivity

- The **color perception** kept the science busy for centuries.
- **Milestone** of the color understanding:
  - **Newton 1666:** Separation of white light into the color spectrum
  - **Goethe 1808:** Natural order of colors
  - **Maxwell, Young, Helmholz 1800-1870:** Tristimulus theory
  - **Grassmann 1853:** Grassmann laws
  - **Hering 1895:** Opposite color theory

Basics: Eye: Color Sensitivity

Color Perception:

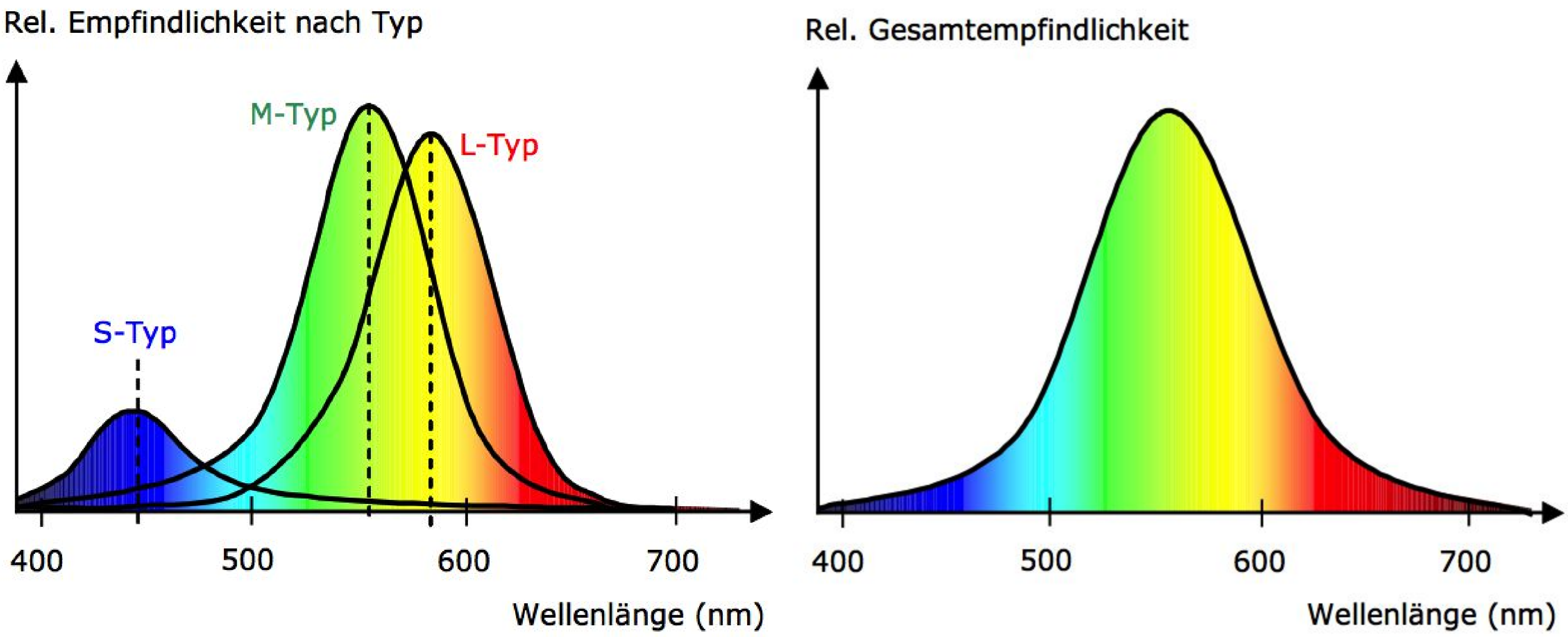
- **Hue (Farbton, teinte)** corresponds to the **dominant wavelength**
- **Luminosity (Helligkeit, luminosité)** corresponds to the **radiance energy**.
- **Saturation (Sättigung, saturation)** corresponds to the **purity of stimulus**.



Basics: Eye: Color Sensitivity

Tristimulus Theory

- The 3 cone types have different sensitivities
- The L-Typ responds to *long waves*
- The M-Typ responds to *medium wavses*
- The S-Typ responds to *short wave*

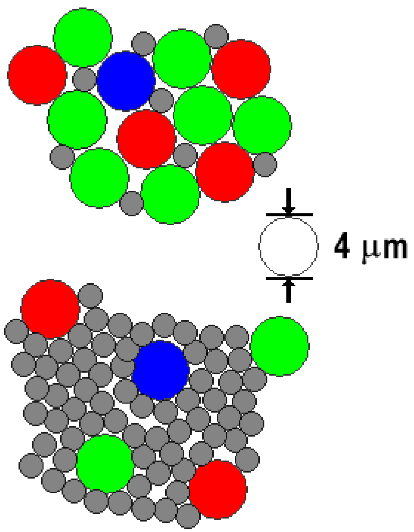


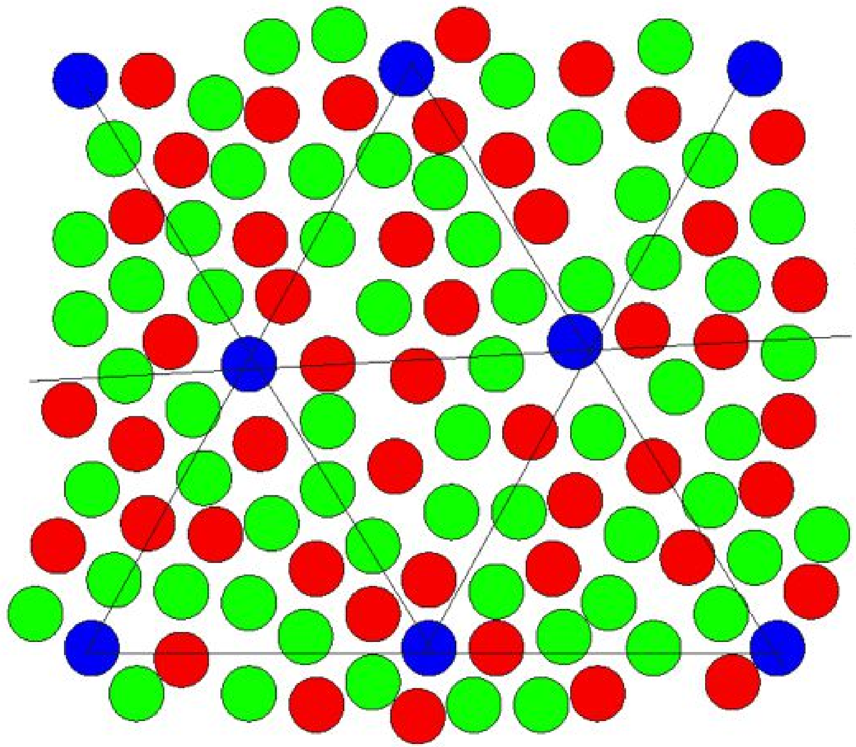
Basics: Eye: Color Sensitivity

Cone distribution in the fovea:

- 10% S-Typ (Blue)
- 48% M-Typ (Green)
- 42% L-Typ (Red)
- The iregular poisson distribution reduces aliasing effects

- Cone/Rod distribution in the fovea and 5mm away from the fovea:





Basics: Eye: Color Sensitivity

Cone distribution in the fovea:

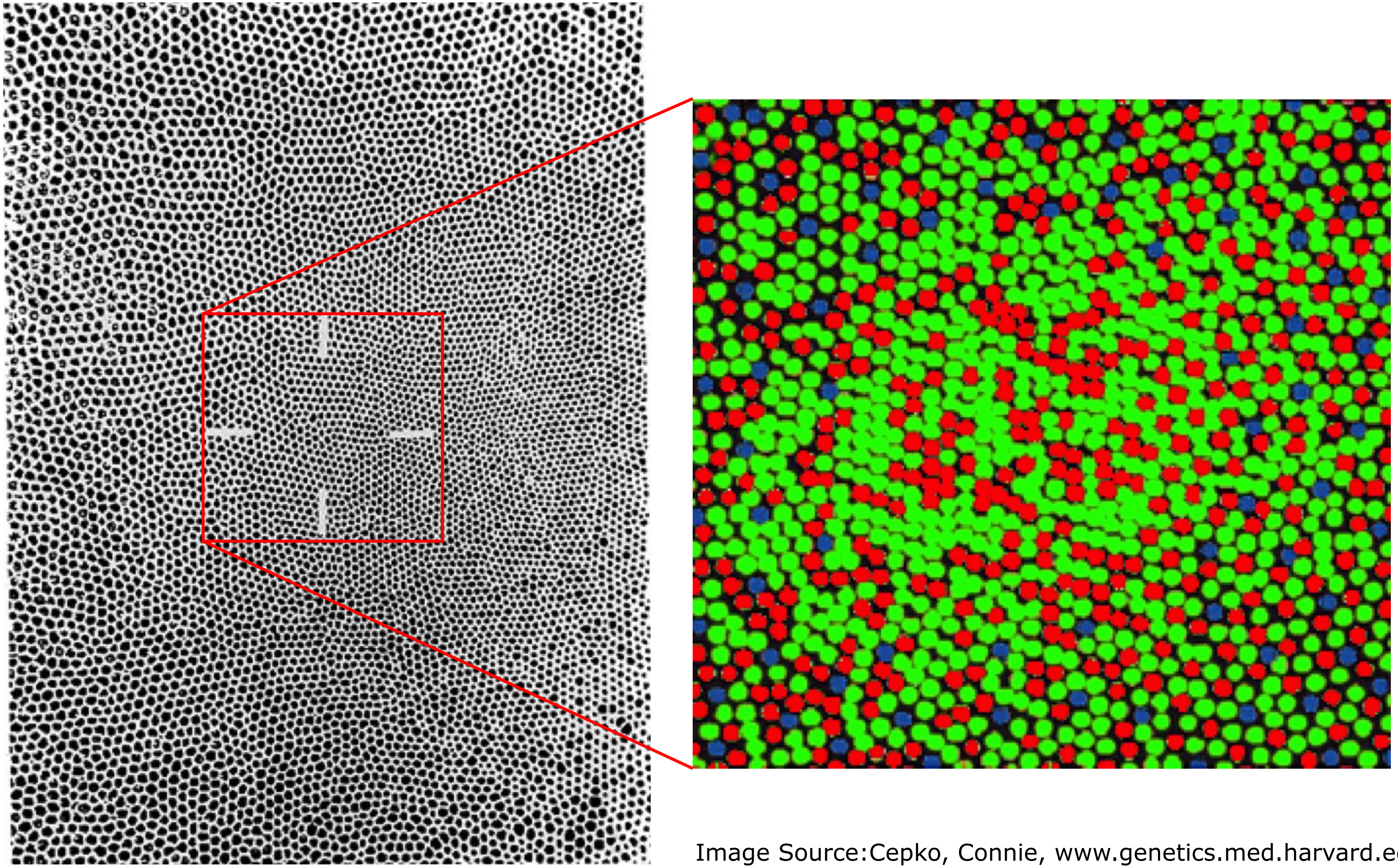
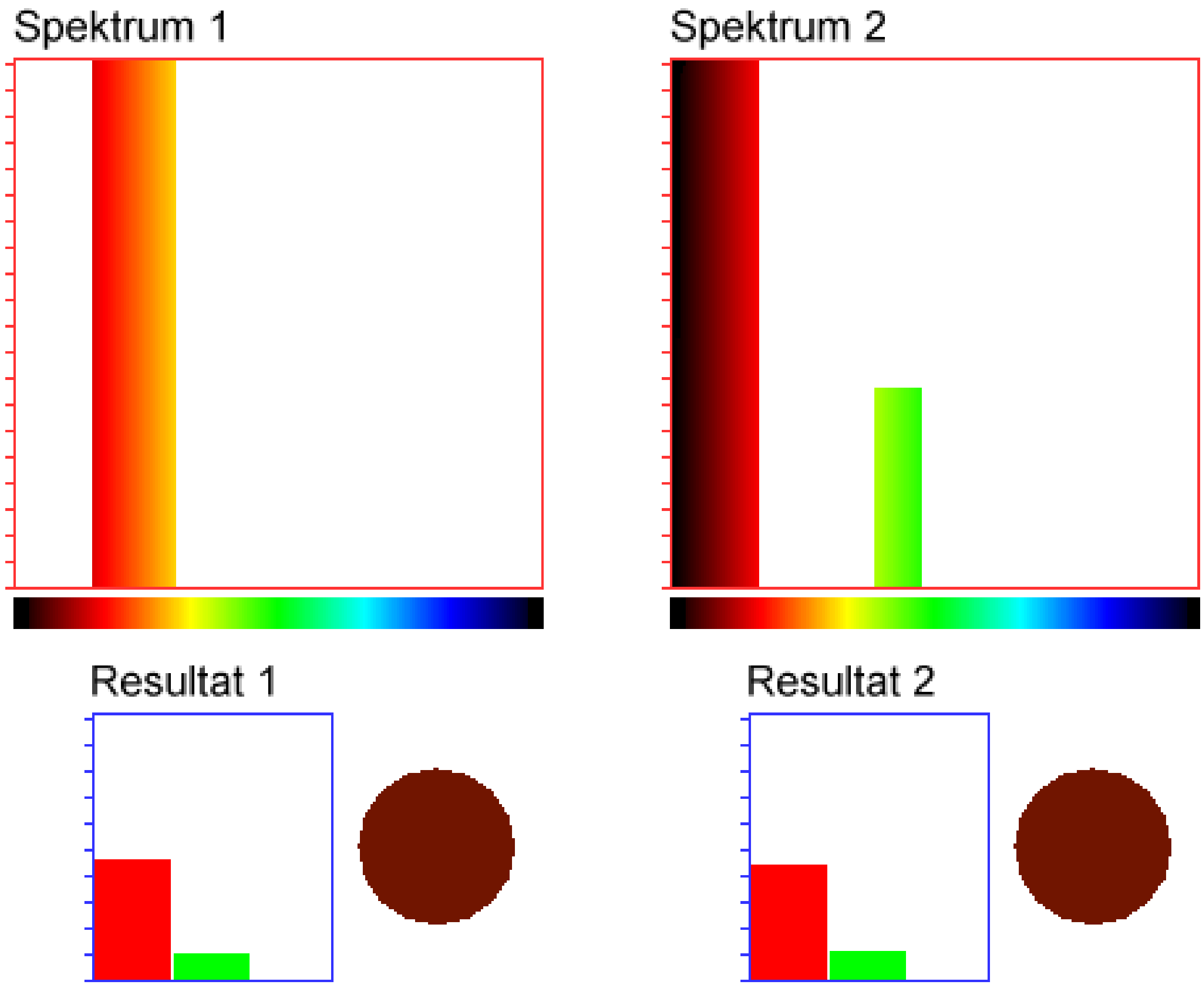


Image Source:Cepko, Connie, www.genetics.med.harvard.edu

Basics: Eye: Color Sensitivity

Metamerism is the matching of apparent color of objects with different spectral power distributions:



Basics: Eye: Color Sensitivity

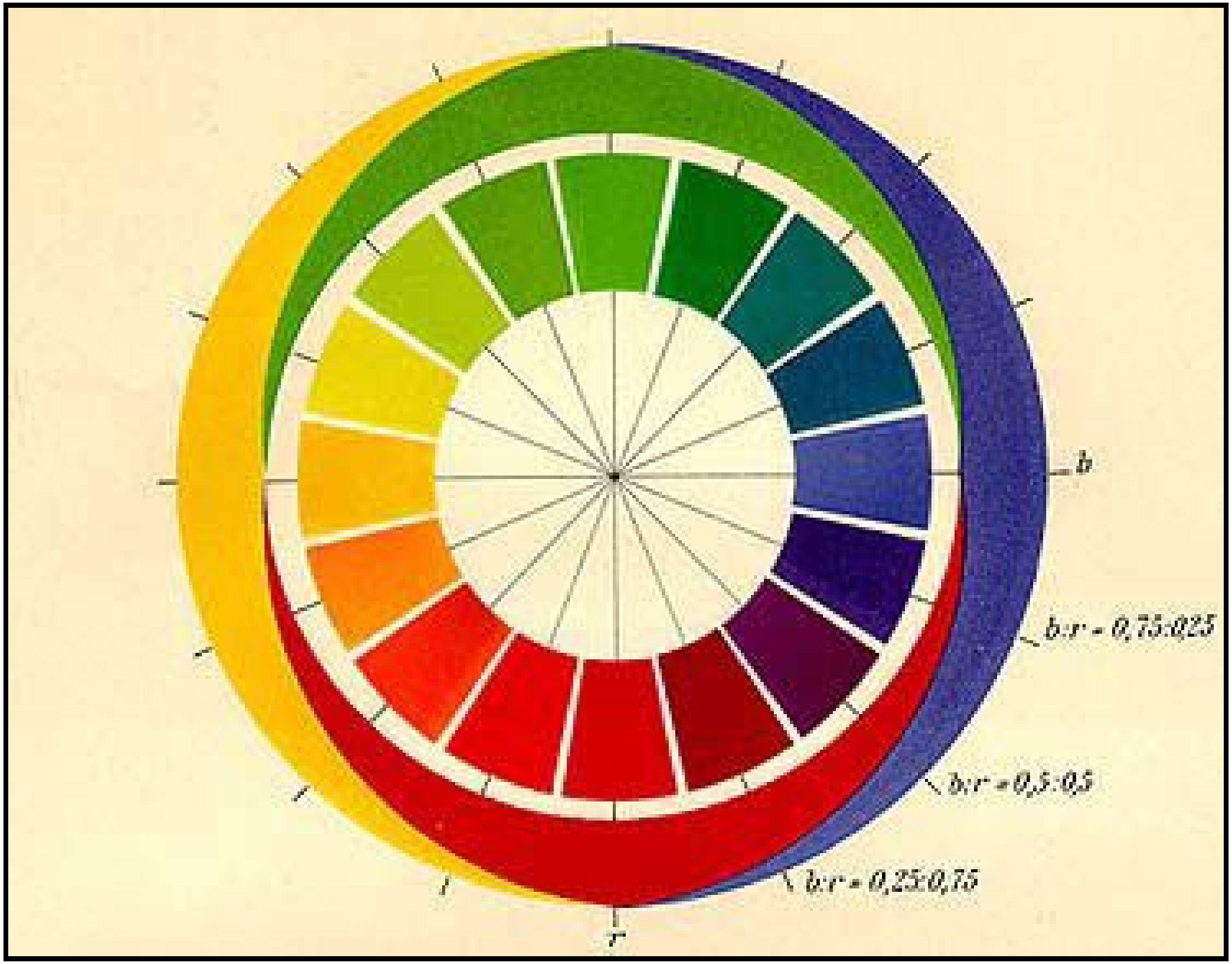
Opposite Color Theory

- If you are asked about the most important color yellow is the most important after red, green and blue.
- Yellow seems to be an independant color.
- We can easily imagine color mixtures for yellow-red, yellow-green, blue-green and red-blue.
- But yellow-blue and red-green are hard to imagine.

- **Ewald Hering** developed from that fact the **Opposite Color Theory** 1895.
- He assumed that the eye produces a signal for yellow-blue, red-green and for the luminosity.

Basics: Eye: Color Sensitivity

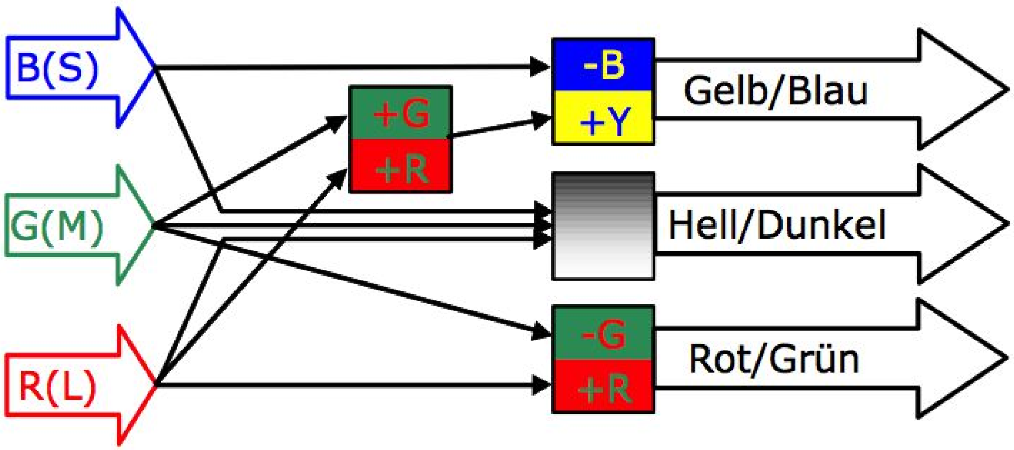
Opposite Color Theory: Opposite Color Circle

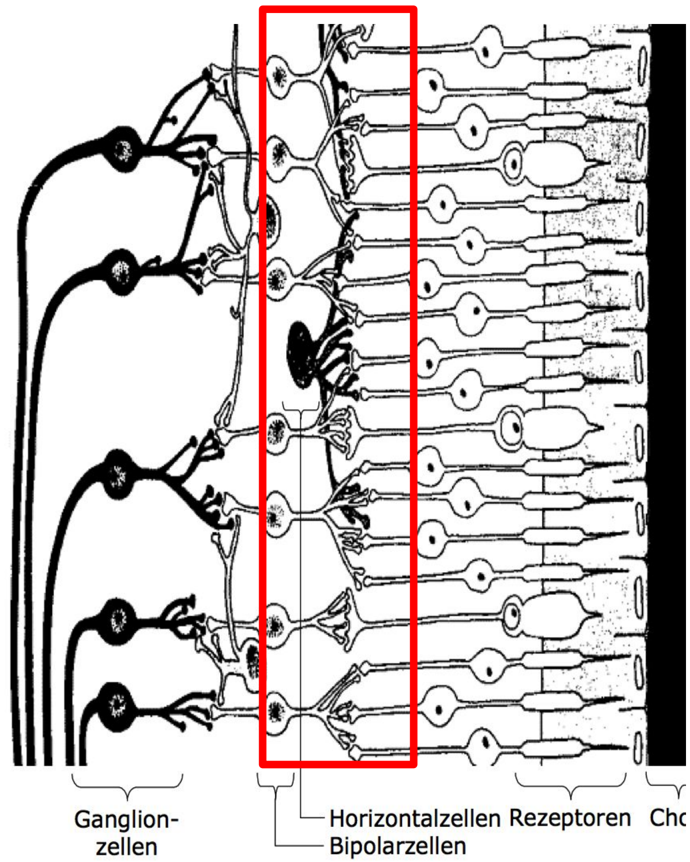


Basics: Eye: Color Sensitivity

Opposite Color Theory:

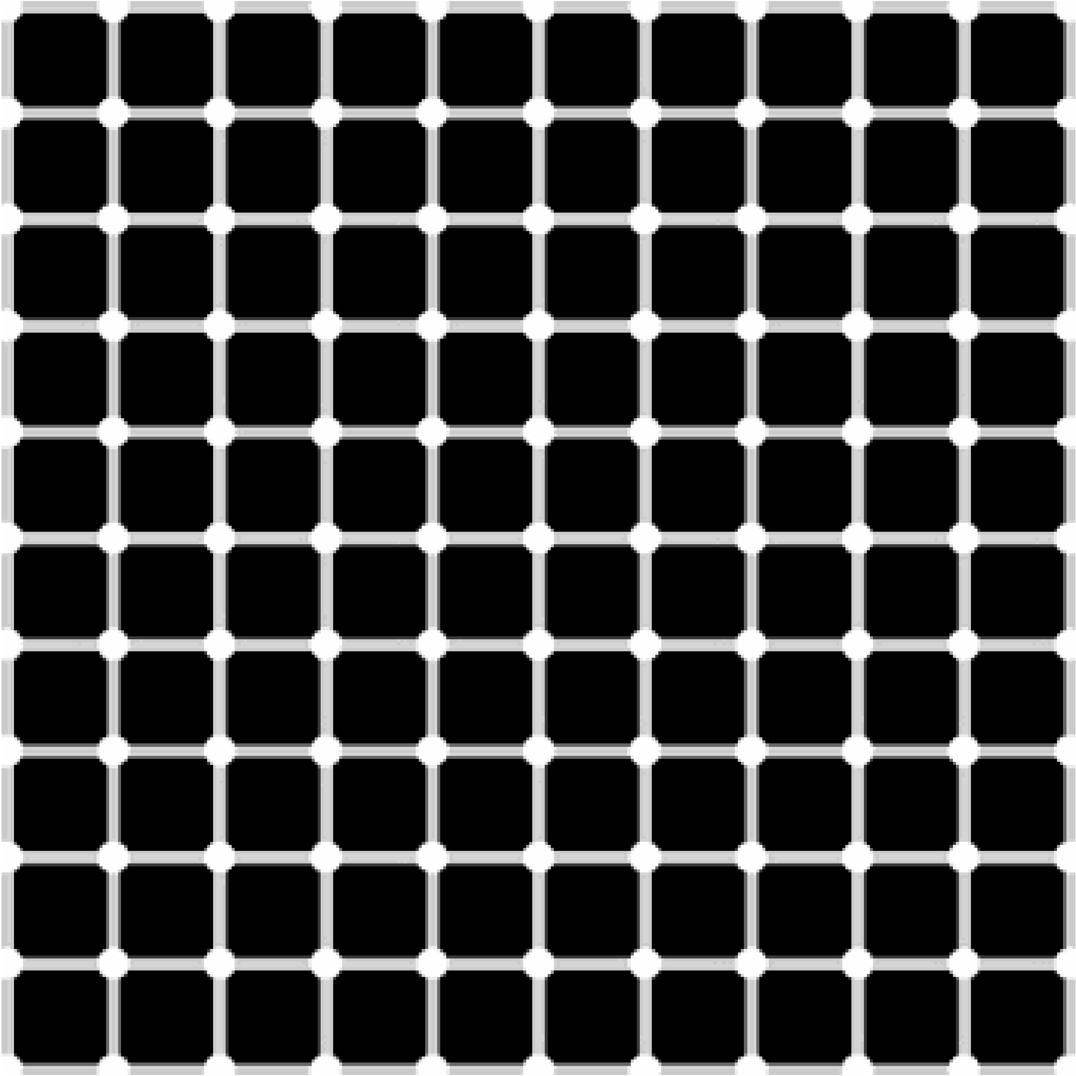
- In the mid 80'ies researchers found that this color encoding happens in the horizontal and bipolar cells of the retina:





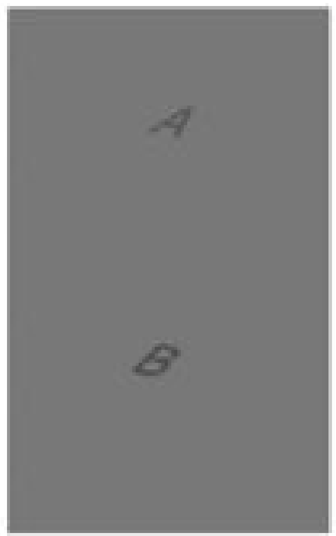
Basics: Eye: Contrast Sensitivity

The percepted brightness depends on neighbourhood:



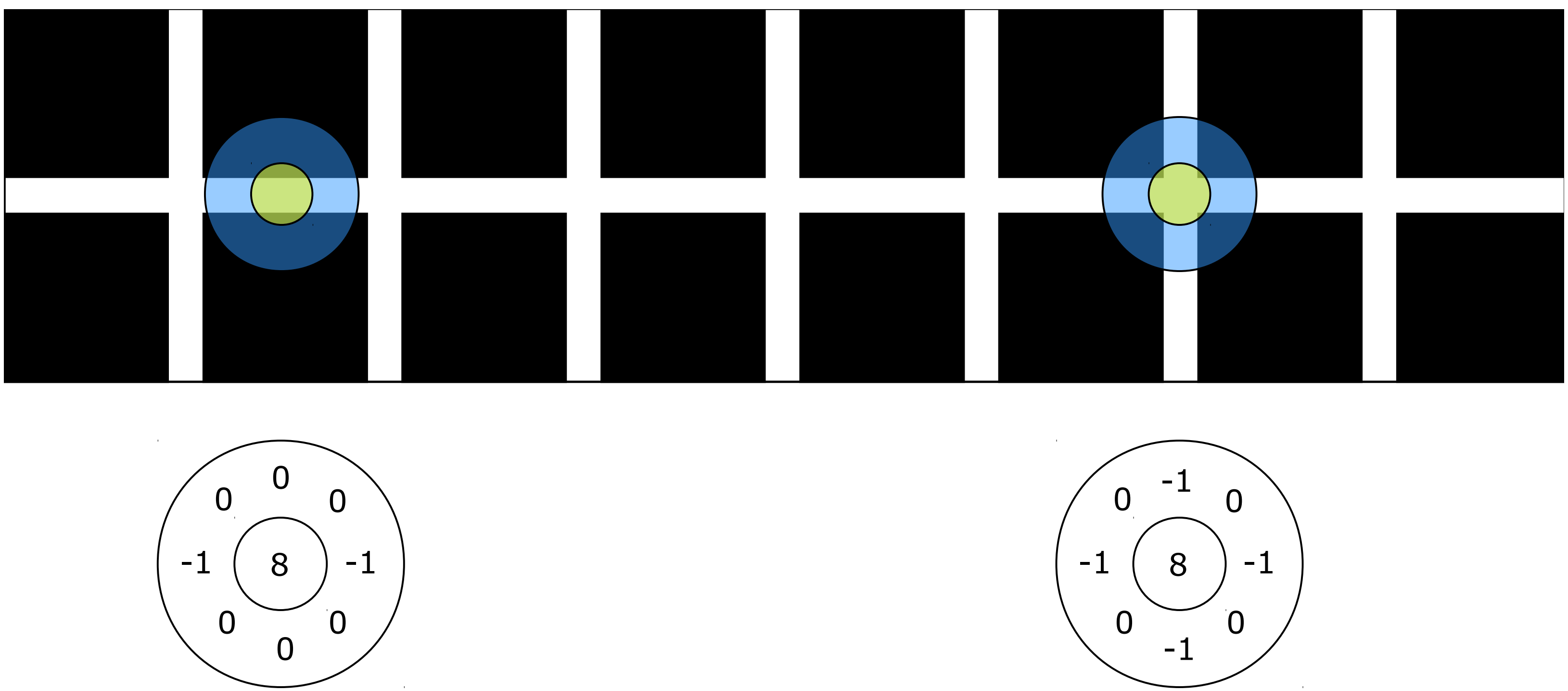
Basics: Eye: Contrast Sensitivity

The percepted brightness depends on neighbourhood:



Basics: Eye: Contrast Sensitivity

- The **ganglion** and **bipolar** cells define **receptive fields**.
- The signale is a weighted sum of the center and neighbourhood.
- The center has the weight 8.
- The neighbourhood has the summed up weight -8

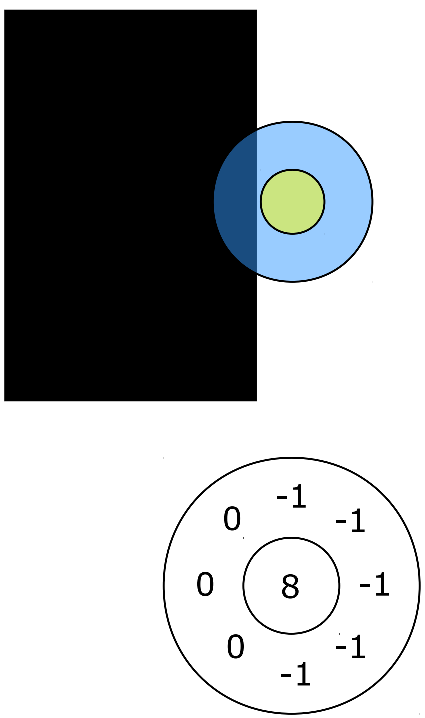


Sum 6

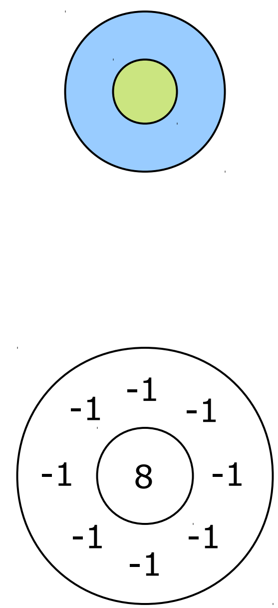
Sum 4

Basics: Eye: Contrast Sensitivity

- The **ganglion** and **bipolar** cells define **receptive fields**.
- The signale is a weighted sum of the center and neighbourhood.
- Homogenous regions produce no signal.
- Edges produce signals.



Sum 3



Sum 0

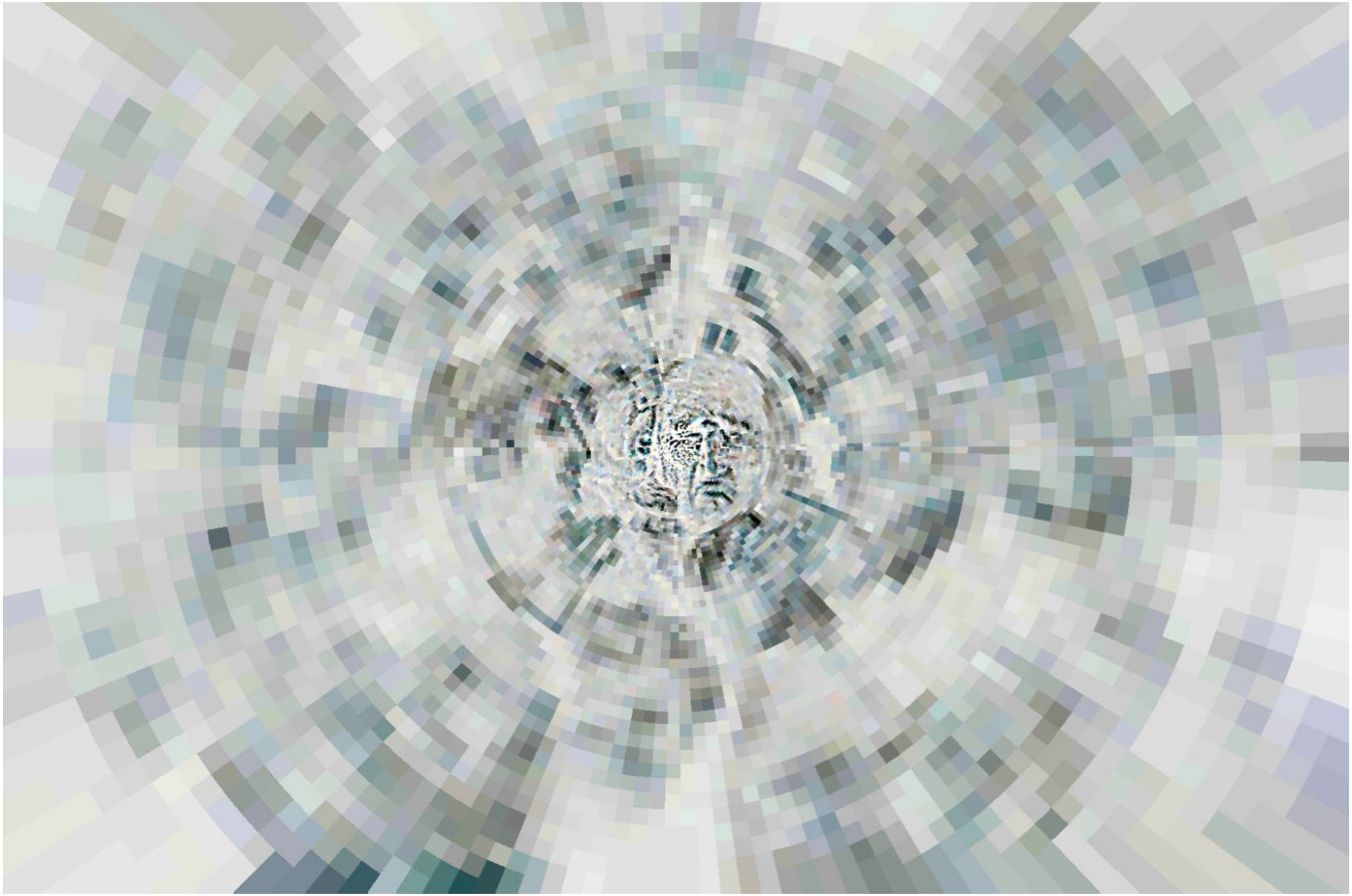
Basics: Eye: Contrast Sensitivity

• The eye transfers an edge signal to the brain:

Edges from Louis Boilly (1761-1845) Thirty-Six Faces of Expression, Source: R. A. Peters, Vanderbilt University

Basics: Eye: Contrast Sensitivity

- The eye transfers an edge signal to the brain:



Louis Boilly (1761-1845) Thirty-Six Faces of Expression, Log-Polar Transform by R. A. Peters, Vanderbilt University

Basics: Eye: Contrast Sensitivity

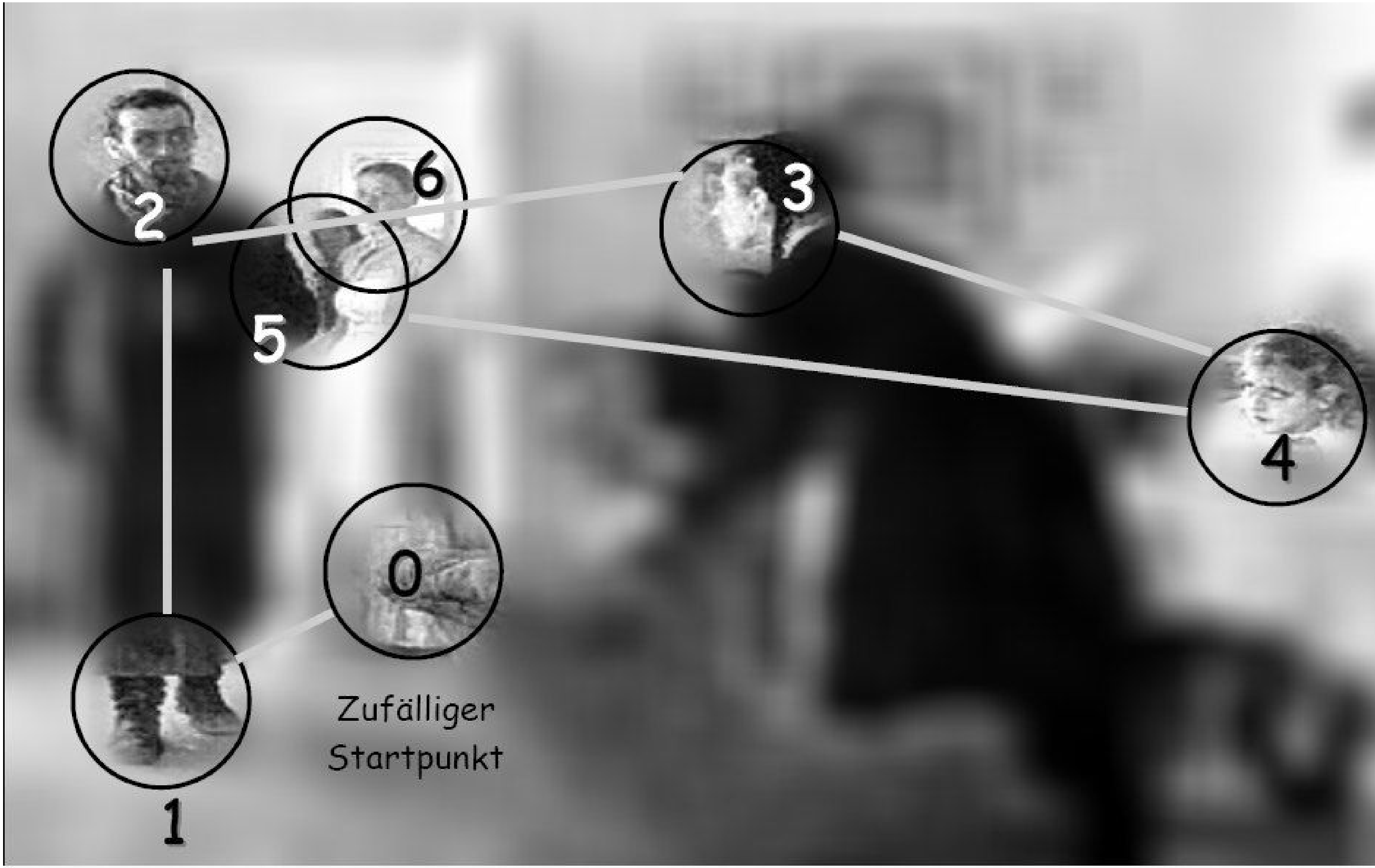
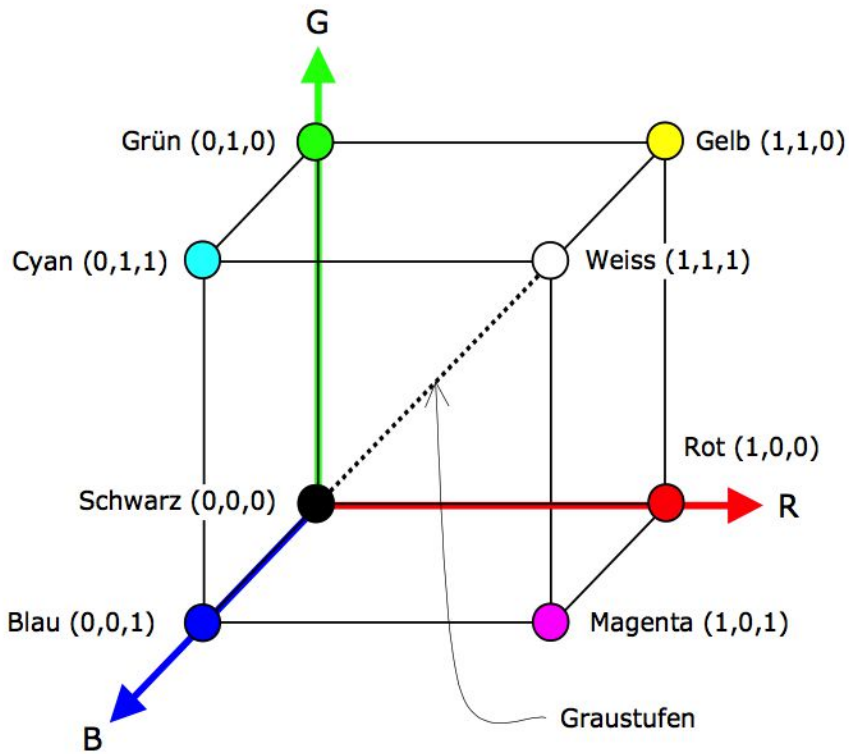


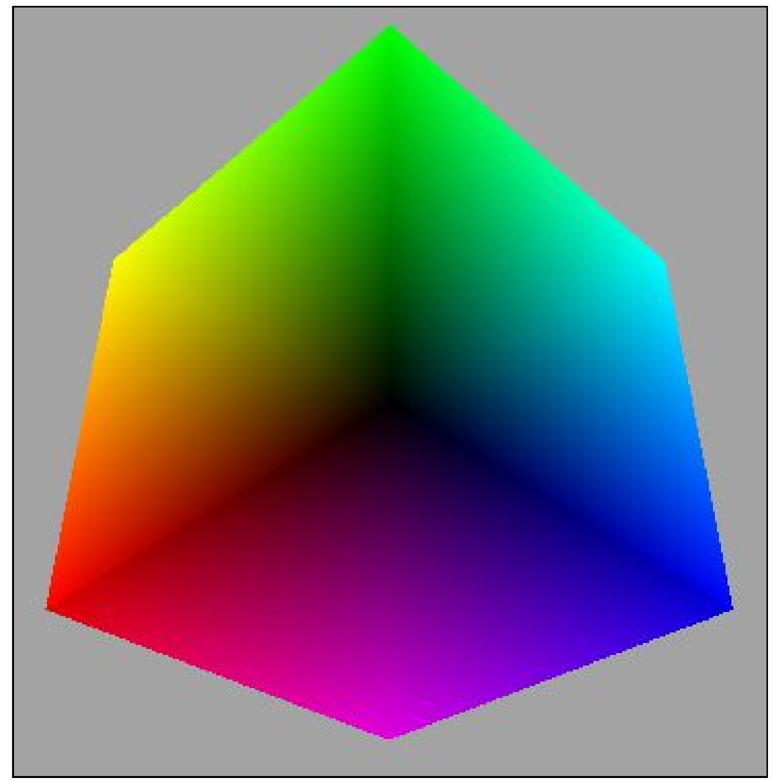
Bild 11: Foveale Ergänzung durch die ersten 6 Fixationen (nach Daten von *Yarbus,1967*)

Color Models

Basics: Color Models: RGB

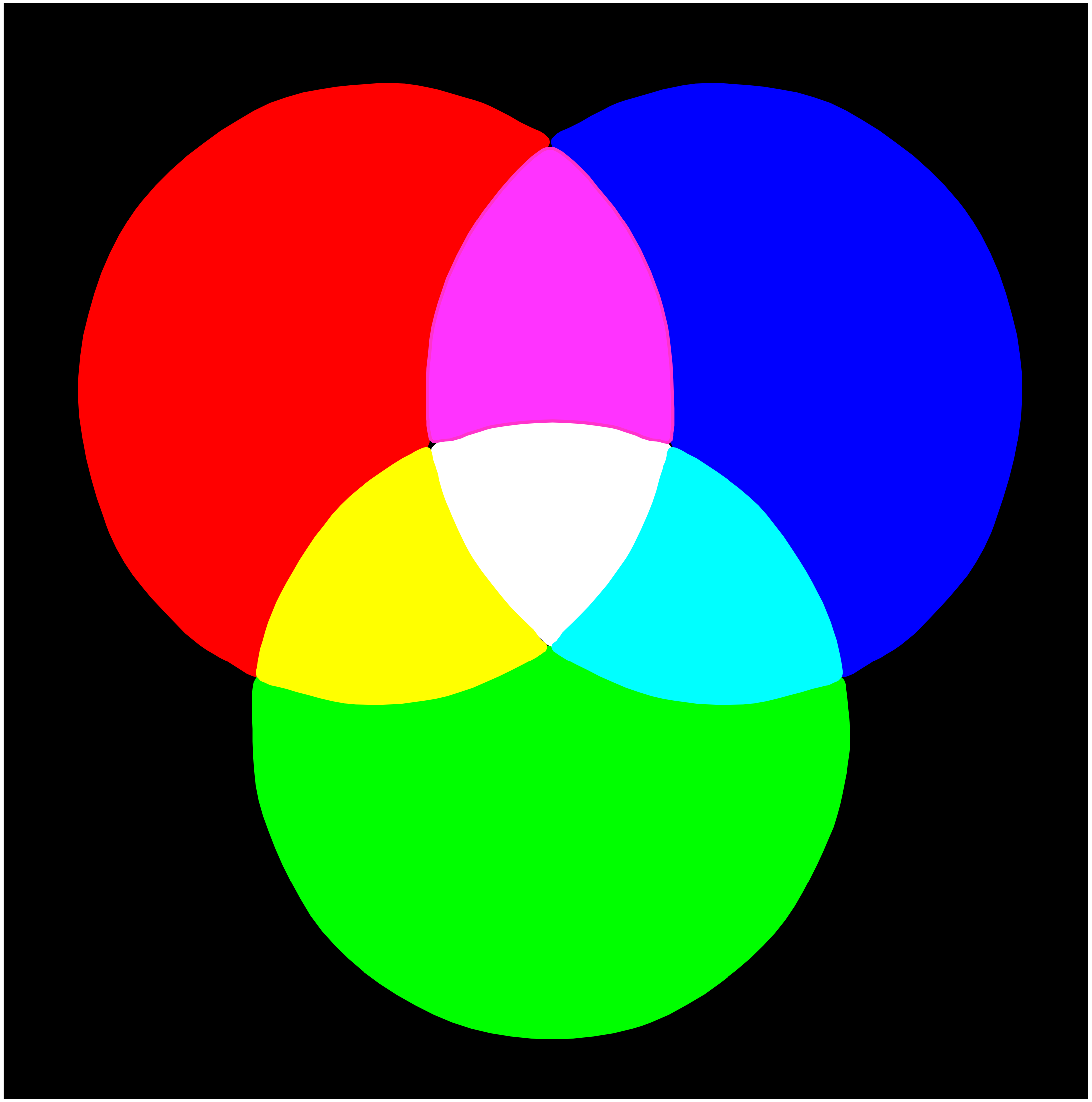
- The RGB color system can be imagined as a 3D coordinate system.
- Every point in the unit cube is a mix of RGB colors
- Colors can be combined with vector algebra.





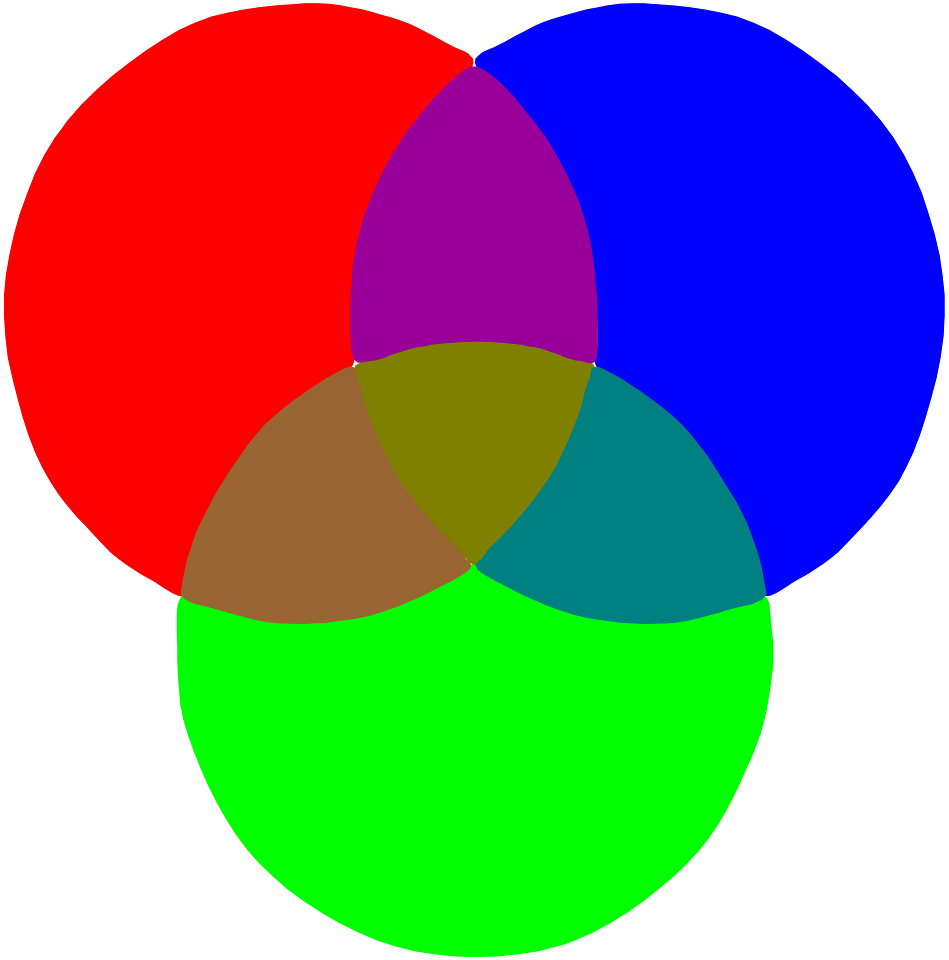
Basics: Color Models: RGB

- We see here 7 colors:
- the 3 base colors **red**, **green** and **blue**,
- the combinations **cyan**, **magenta** and **yellow**
- and **white** as the combination of all base colors.
- **Black** is the absence of light
- Colors are combined by **adding** light colors



Basics: Color Models: RGB

- The RGB system is not suitable for printing
- If you mix red, green and blue with painting colors you will get not the desired result.



Basics: Color Models: CMY

- The **CMY** color system controls the **reflected colors from white paper**.
- The CMY color system is said to be **subtractive** because the print colors CMY subtract the opposite colors that are absorped:

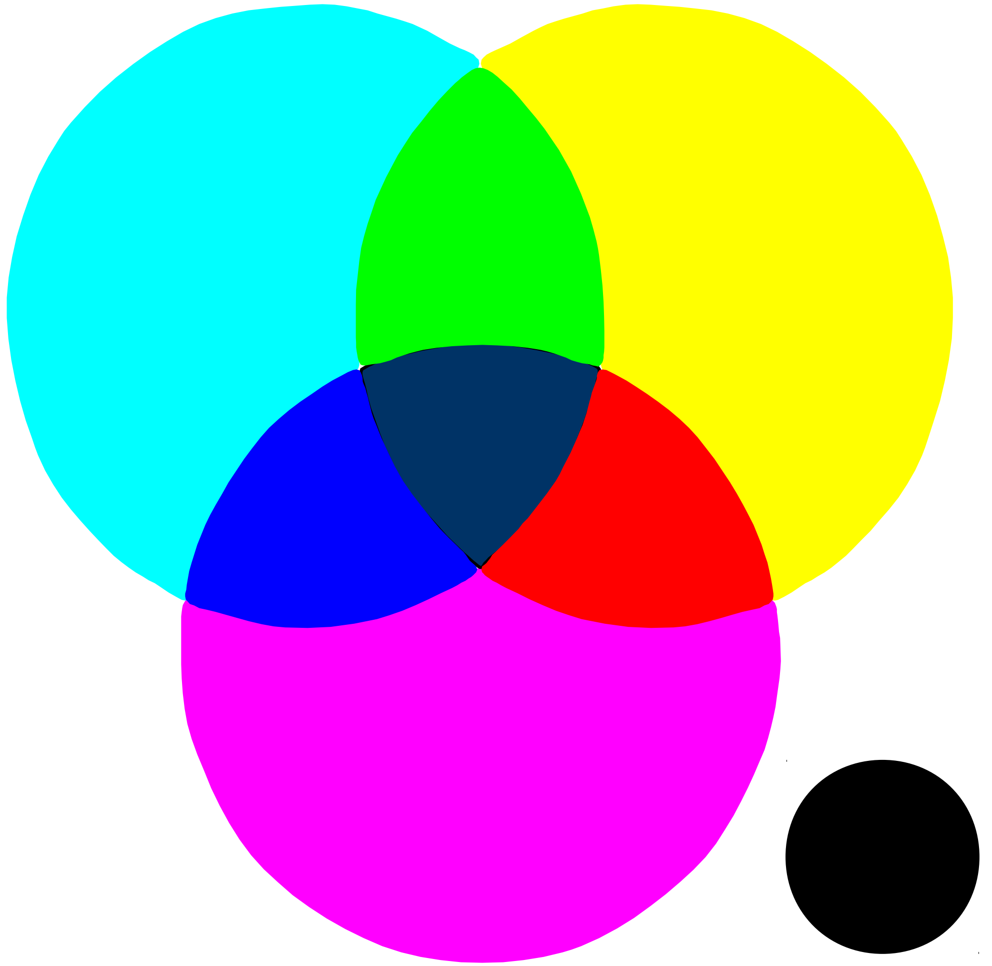
Print Color	absorbed	reflected
Cyan	Red	Blue, Green
Magenta	Green	Blue, Red
Yellow	Blue	Red, Green
All	All	nothing

- The transform from the RGB to the CMY system is simple:

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Basics: Color Models: CMYK

- It is difficult to create CMY printing colors that all together absorb all light.
- It it also a waste of ink.
- Therefore most color print systems have the forth print color black
- K stands for key

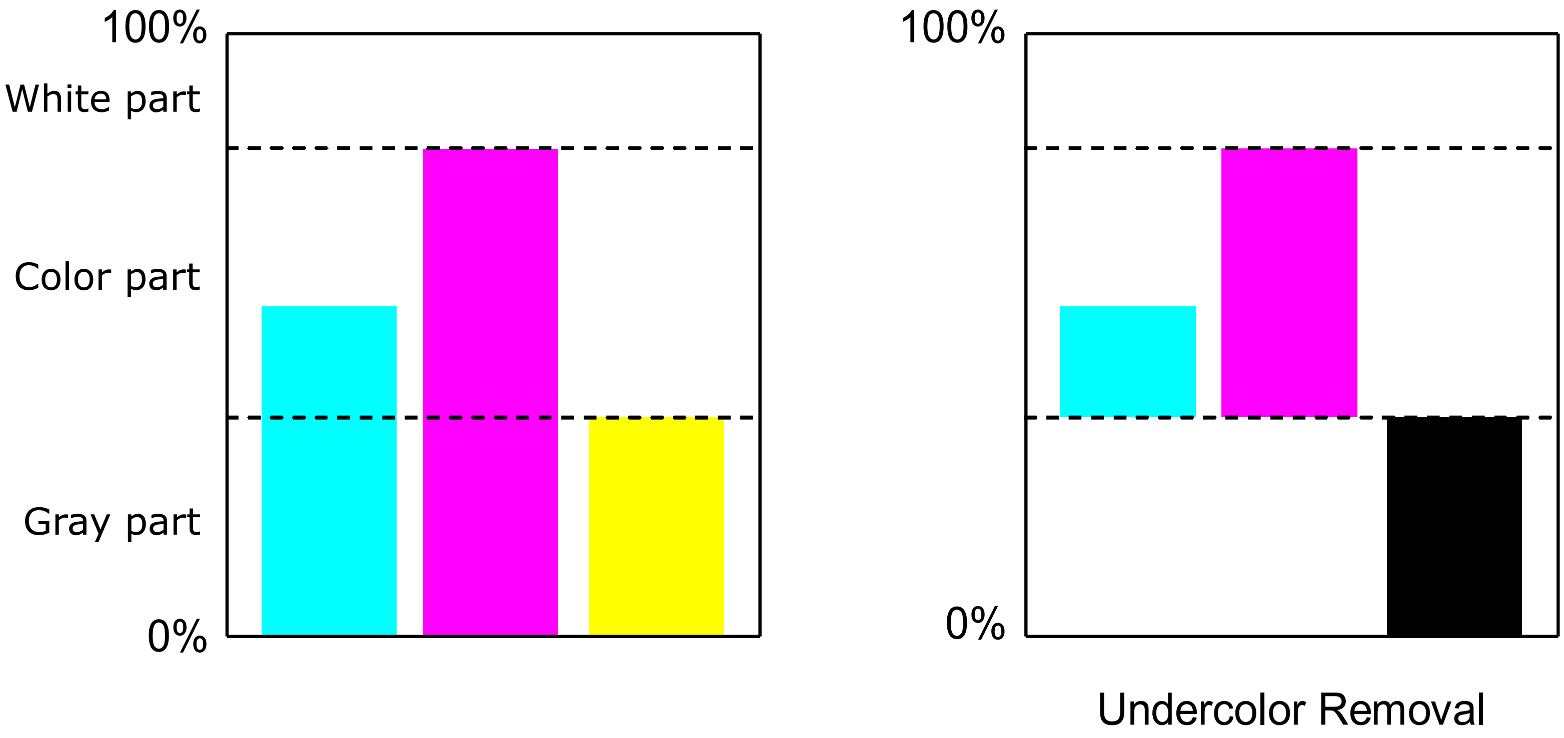


$$\begin{bmatrix} C_K \\ M_K \\ Y_K \\ K \end{bmatrix} = \begin{bmatrix} C \\ M \\ Y \\ 0 \end{bmatrix} + \begin{bmatrix} -\min(C, M, Y) \\ -\min(C, M, Y) \\ -\min(C, M, Y) \\ \min(C, M, Y) \end{bmatrix}$$

Basics: Color Models: CMYK

Undercolour Removal

The fourth color saves color ink:



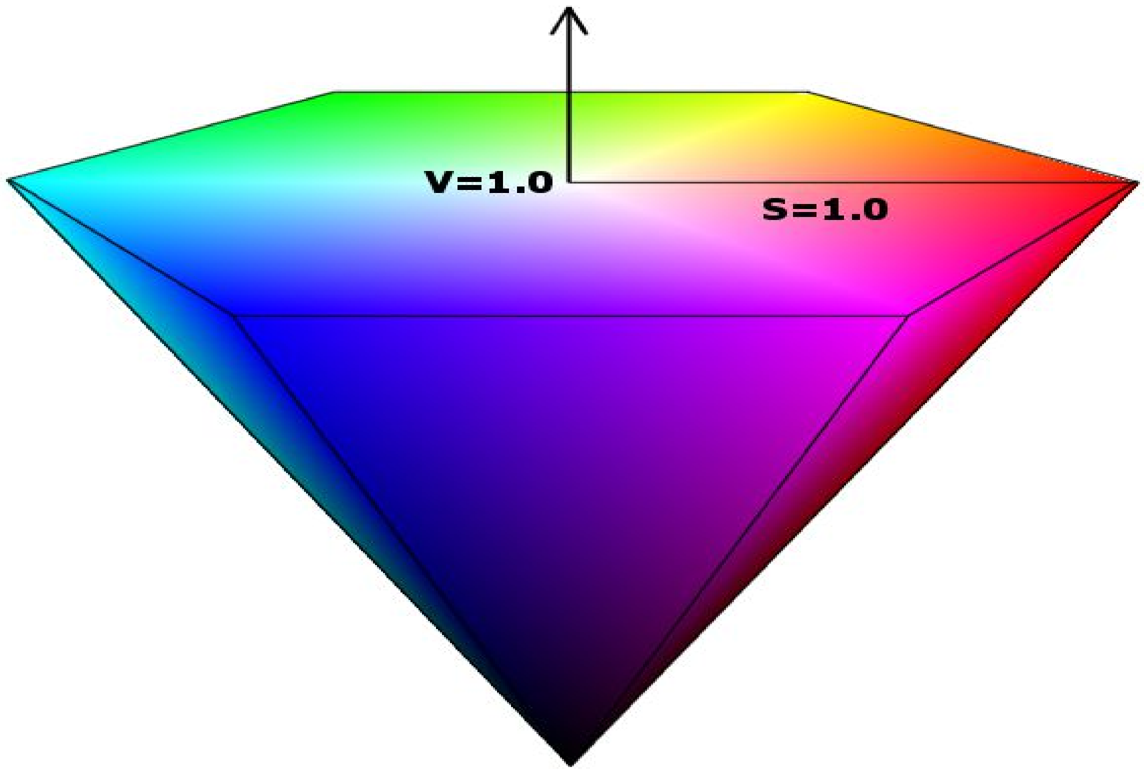
Basics: Color Models: CMYK

Basics: Color Models: HSV

The RGB and CMY color models are **technical models** and **not intuitive.**

The **HSV** color model defines the color space with:

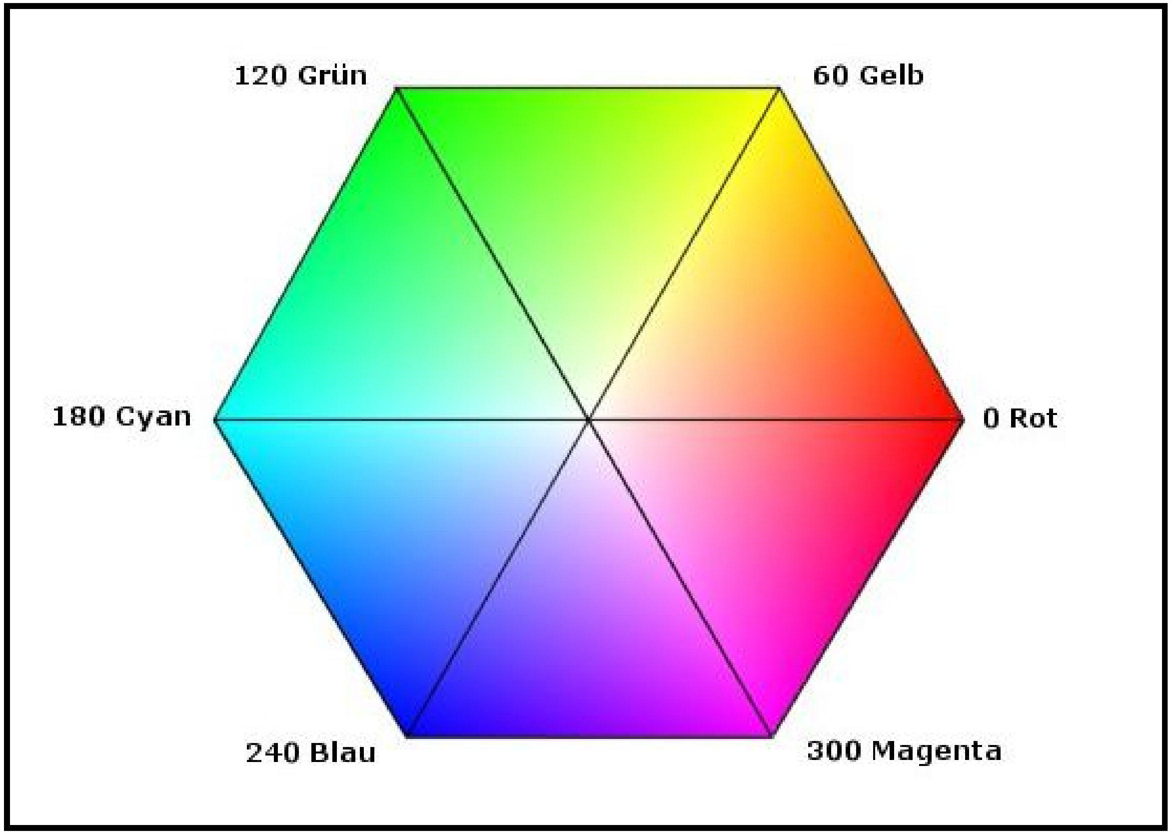
- **Hue**
- **Saturation**
- **Value (Luminosity)**



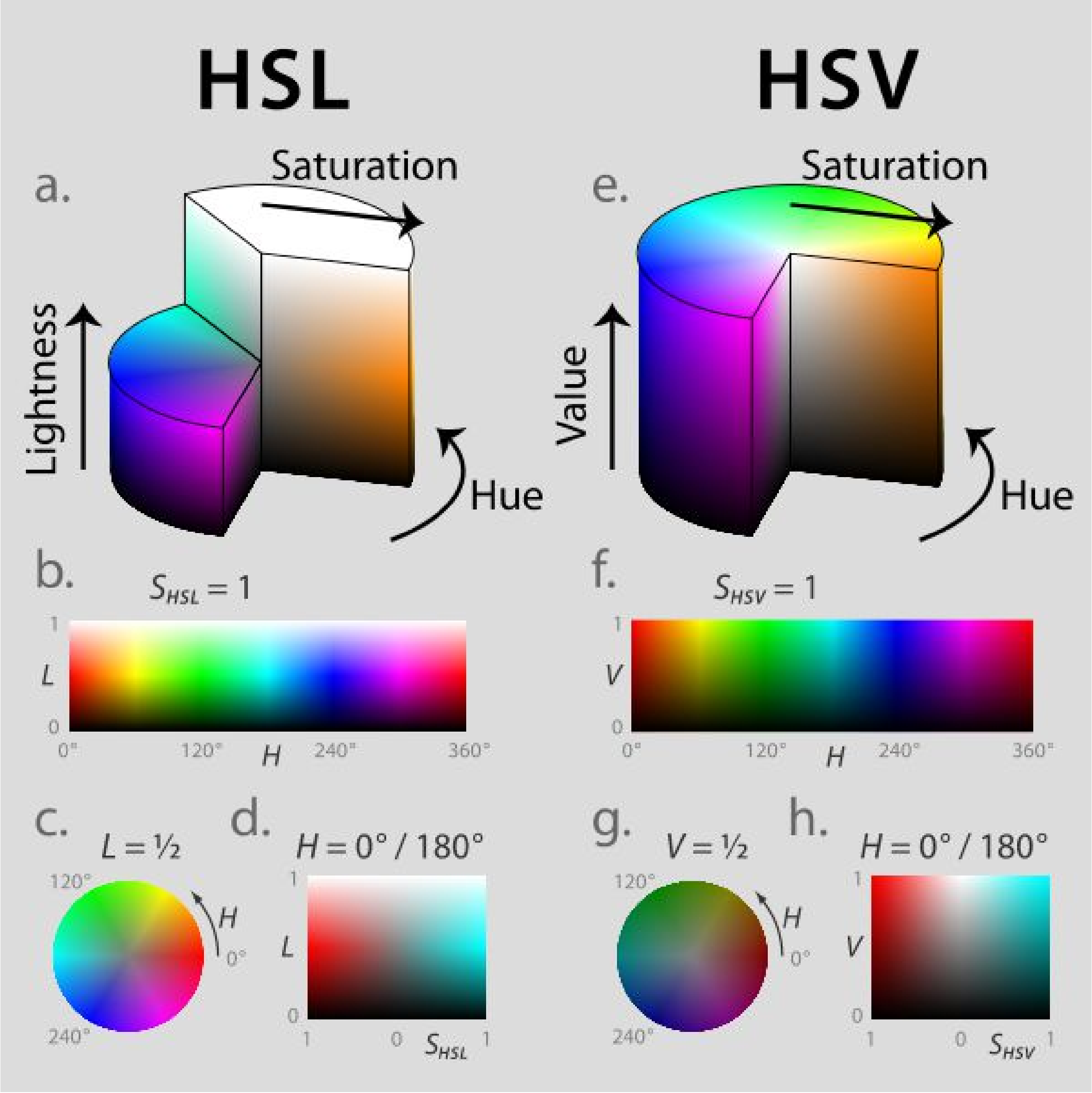
Basics: Color Models: HSV

The hue value is within a **hexagone plane**:

V = max(R,G,B)
S = V - min(R,G,B) / V
H= (G - min(RGB) / (max(RGB) - min(RGB)) * 60°
in case R=Max(R,G,B) and B=Min(R,G,B)



Basics: Color Models: HSL



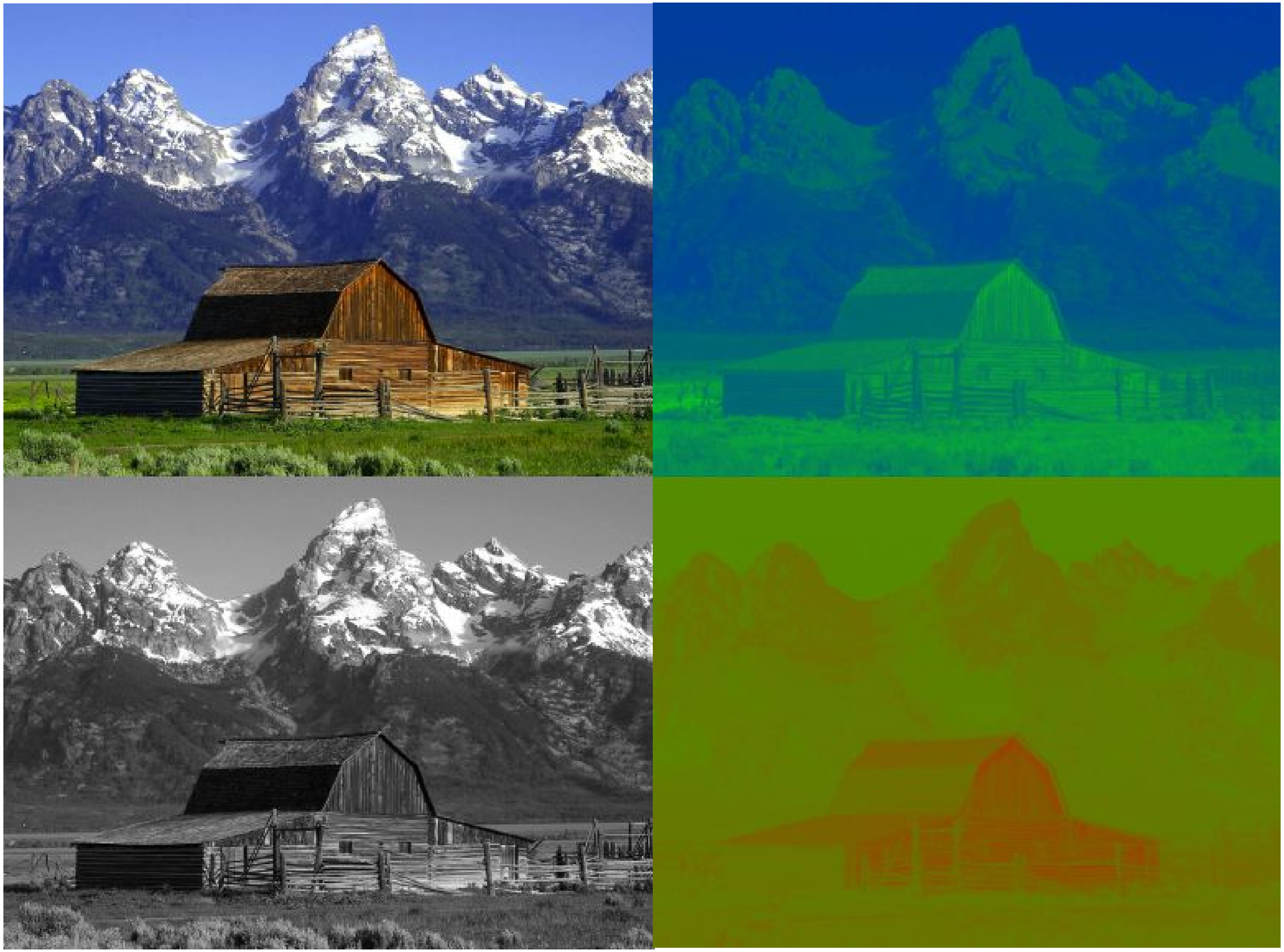
Basics: Color Models: YUV

- The **YUV** color model was developed with the european TV standard PAL.
- The american TV standard NTSC used a similar color model YIQ.
- They where design for B/W TV compatibility.
- Both systems transfer the luminosity in the Y channel and the color in 2 separate channels.

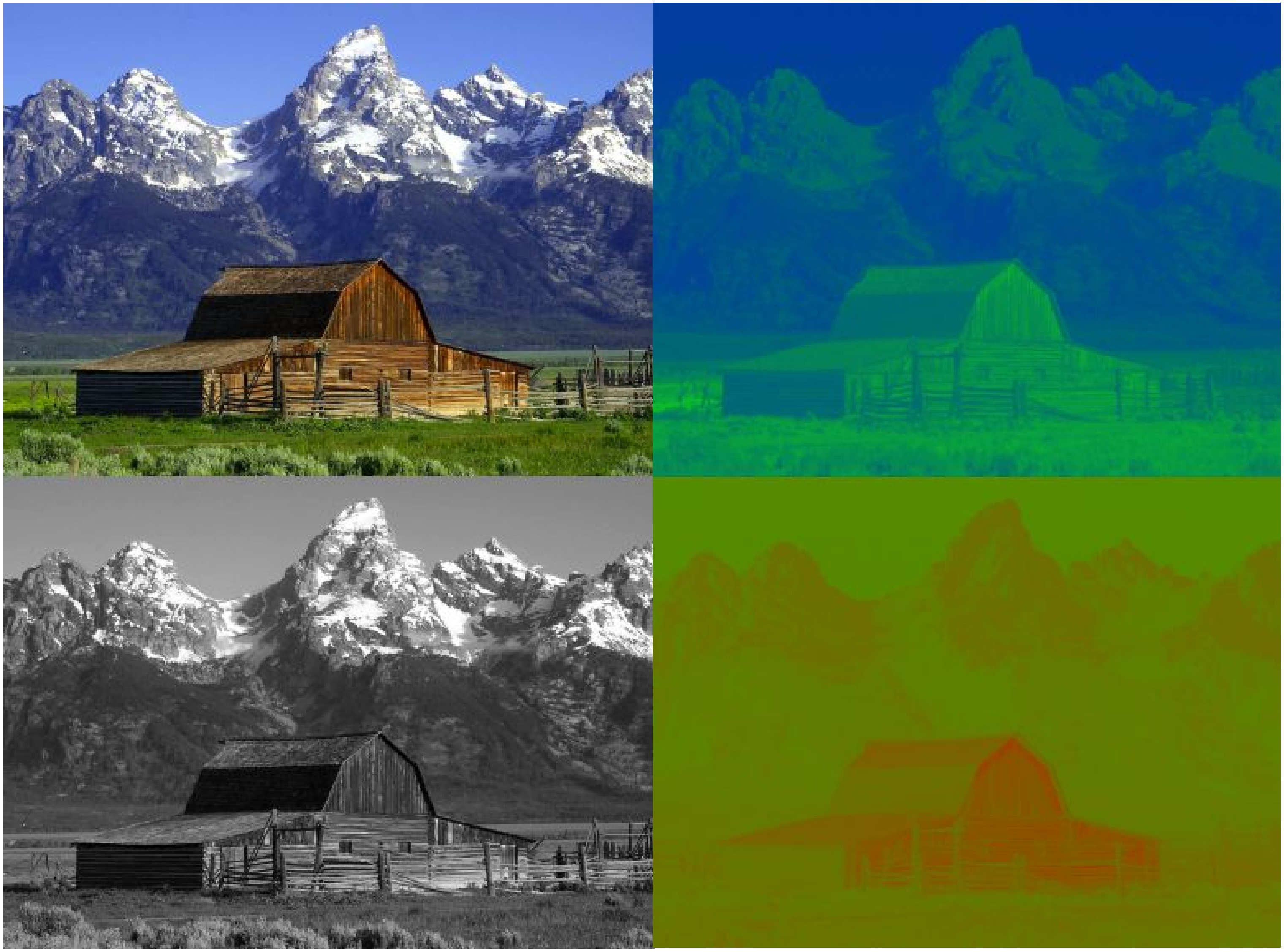
```
Y = round( 0.257*R + 0.504*G + 0.098*B) + 16
U = round(-0.148*R - 0.291*G + 0.439*B) + 128
V = round( 0.439*R - 0.368*G - 0.071*B) + 128
```

```
C = 1.164*(Y-16); D = U-128; E = V-128
R = clip(round(C           + 1.596*E))
G = clip(round(C - 0.391*D - 0.813*E))
B = clip(round(C + 2.018*D          ))
```

Basics: Color Models: YUV

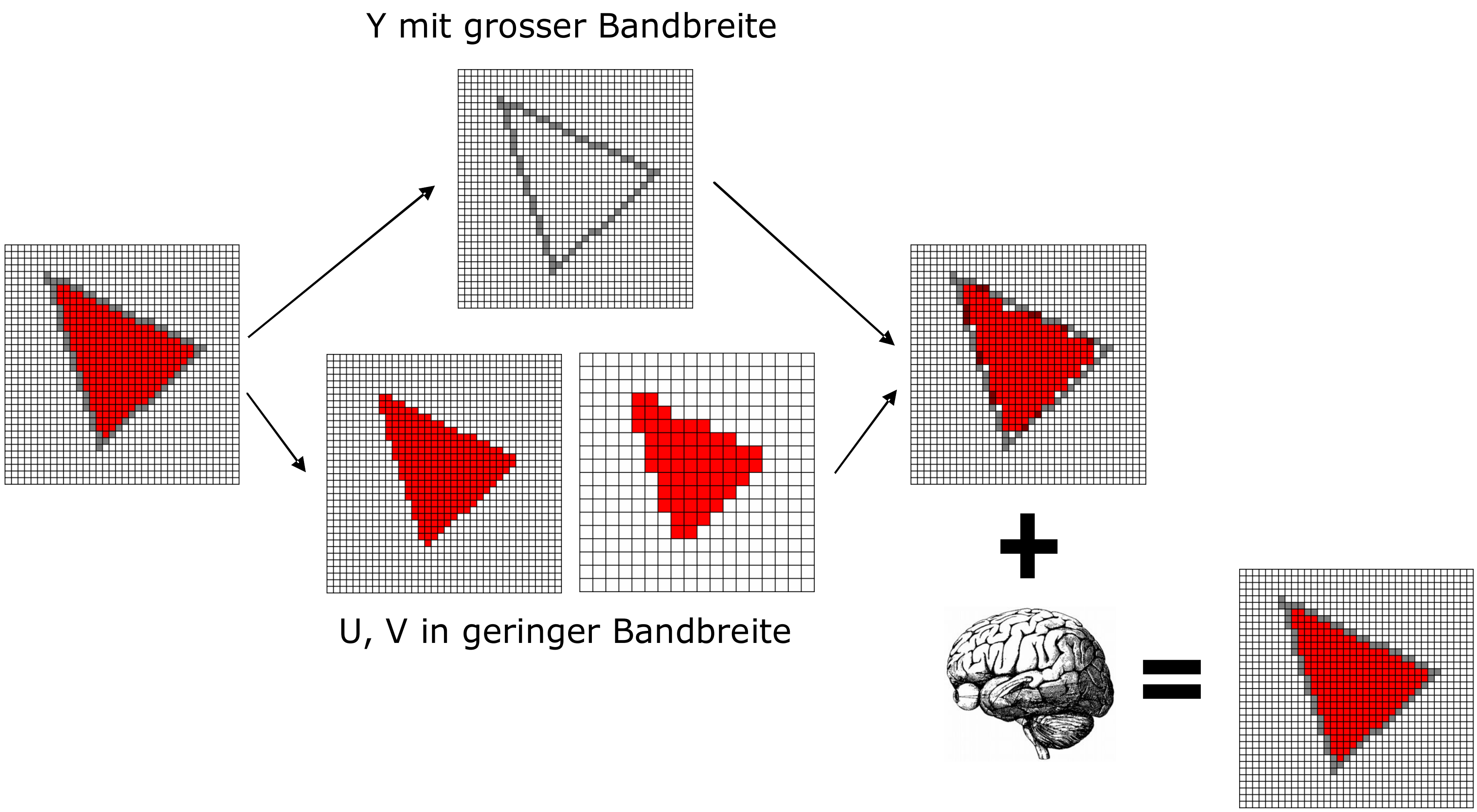


Basics: Color Models: YUV



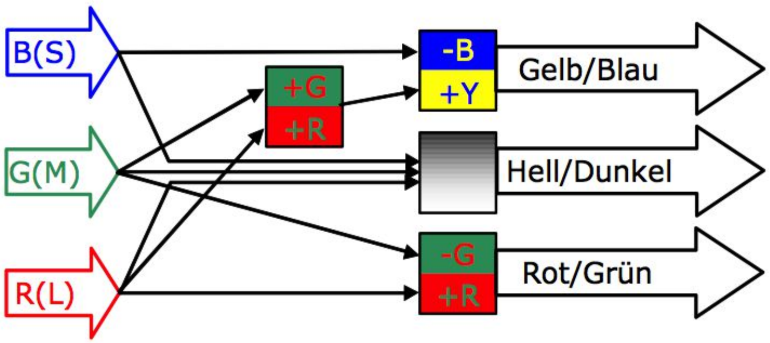
Basics: Color Models: YUV

- The color channels are transmitted with half of the resolution:



Basics: Color Models: YCbCr

- The **YCbCr** format is the **digital version of YUV.**
  - Y: Luminance
  - Cb: Blue-Yellow Chrominance
  - Cr: Red-Green Chriminance
- It is used in most digital formats such as JPEG and all MPEG standards.
- The transform to YCbCr is close to the opposite color transform in the retina:



- It has slightly different weights:

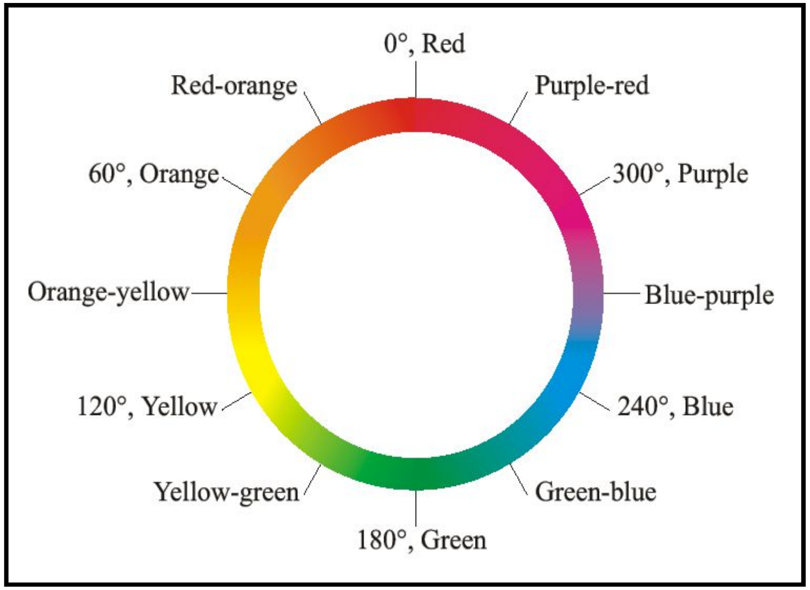
```
Y  = round( 0.299*R + 0.587*G + 0.114*B)
Cb = round(-0.169*R - 0.331*G + 0.500*B) + 128
Cr = round( 0.500*R - 0.419*G - 0.081*B) + 128
```

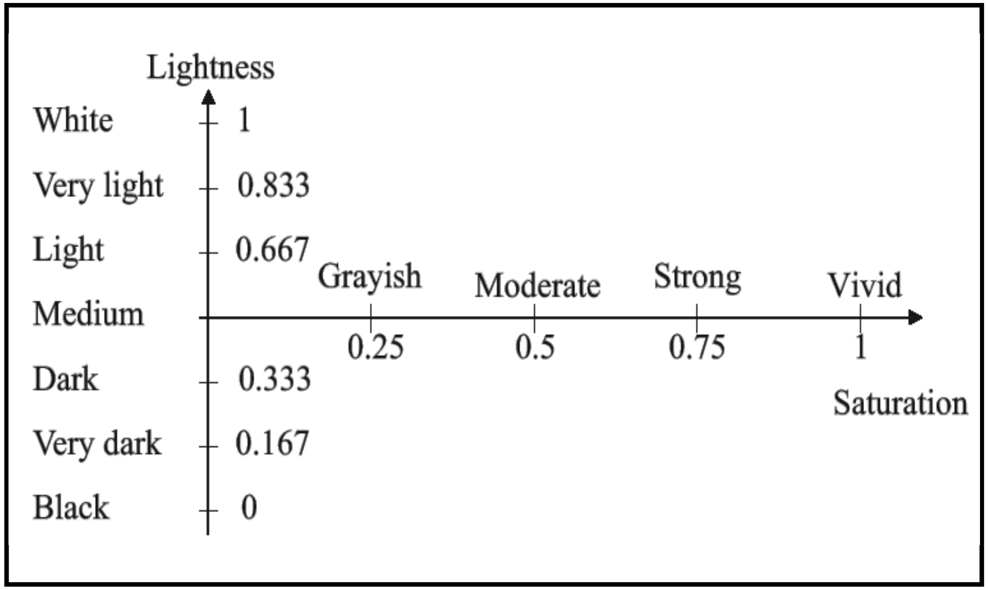
Basics: Color Models: YCbCr

Basics: Color Models: CNS

The **CNS model** (Color Name System) was design to describe colors with words:

- Hue: **red, orange, yellow, green, blue, purple**
- Saturation: **grayish, moderate, strong, vivid**
- Luminosity: **very dark, dark, medium, light, very light**
- The achromatic scale consists of seven grayscales:
  black, very dark gray, dark gray, gray, light gray, very light gray, white

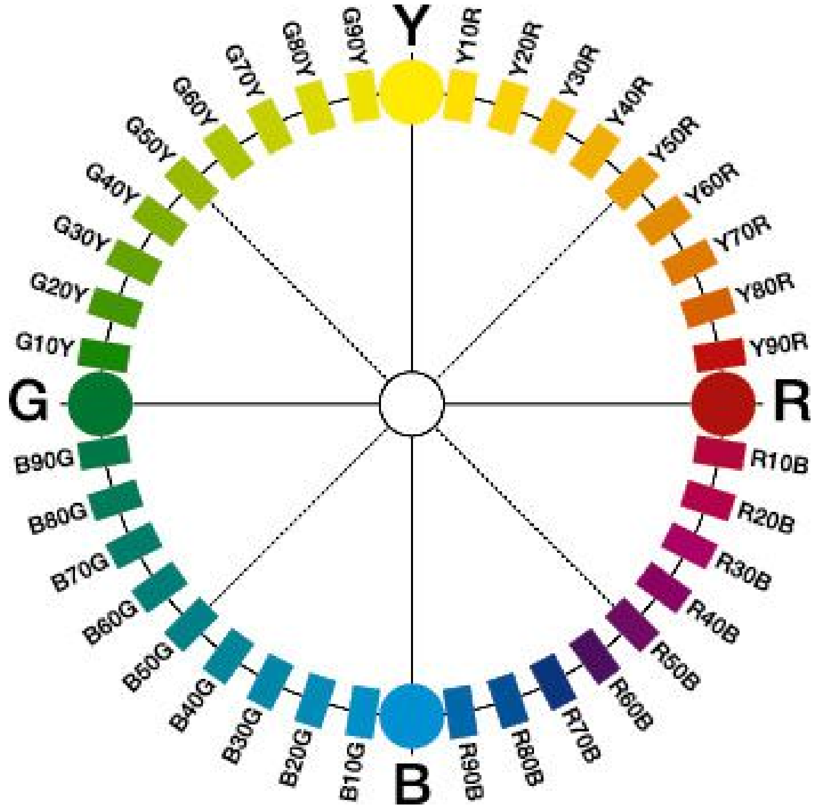


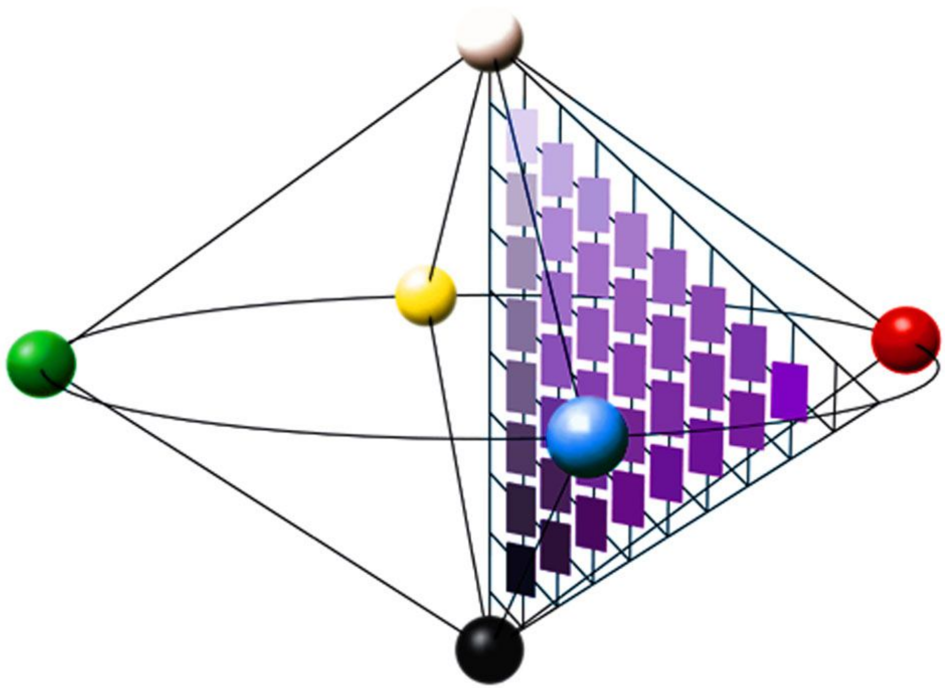


Basics: Commercial Color Systems: NCS

NCS: Natural Color System (Scandinavian Color Institute)

http://www.ncscolour.com/ncs_int.asp





Basics: Commercial Color Systems: RAL

RAL: Reichsausschuss für Lieferbedingungen