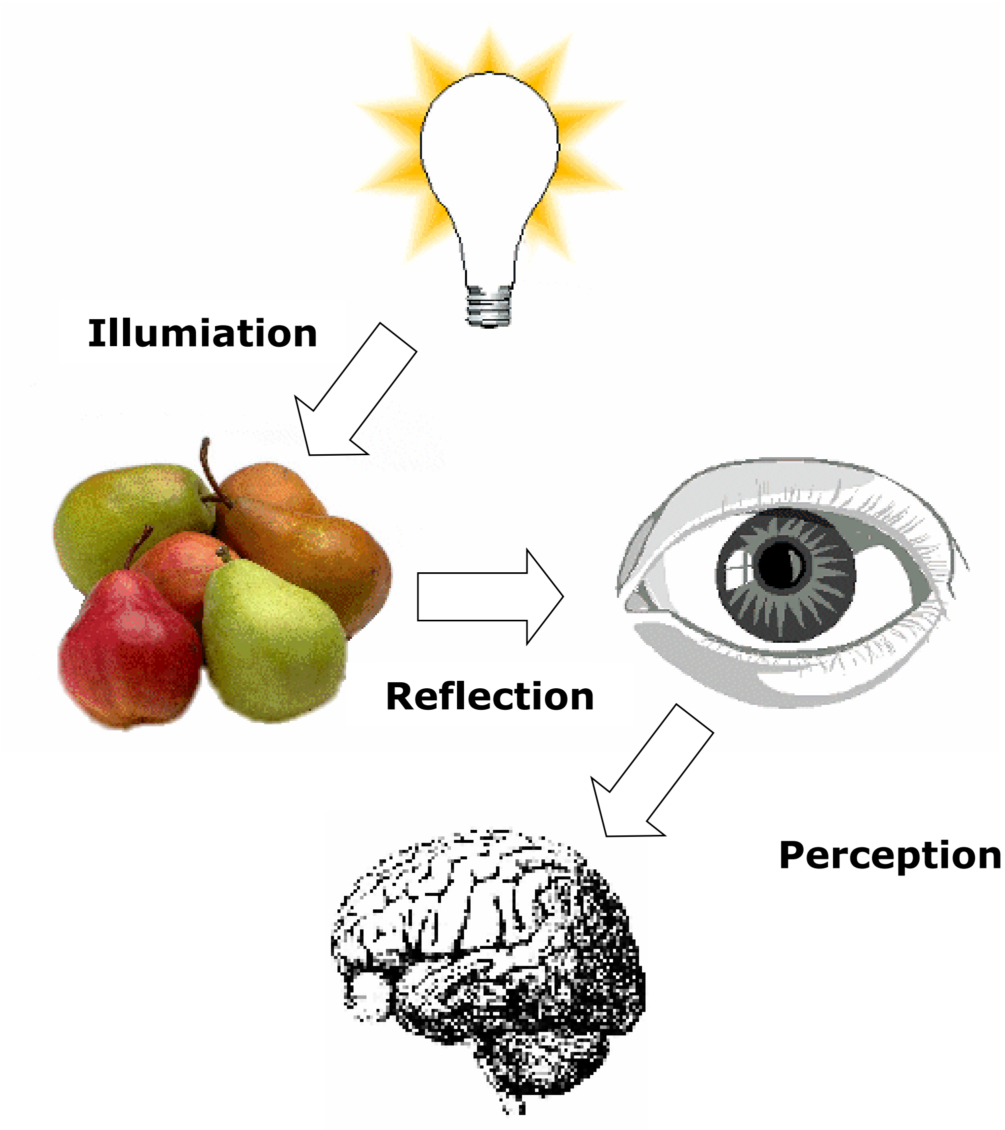
Berner Fachhochschule
Haute école spécialisée bernoise
Bern University of Applied Sciences

Introduction to Image Processing

# 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

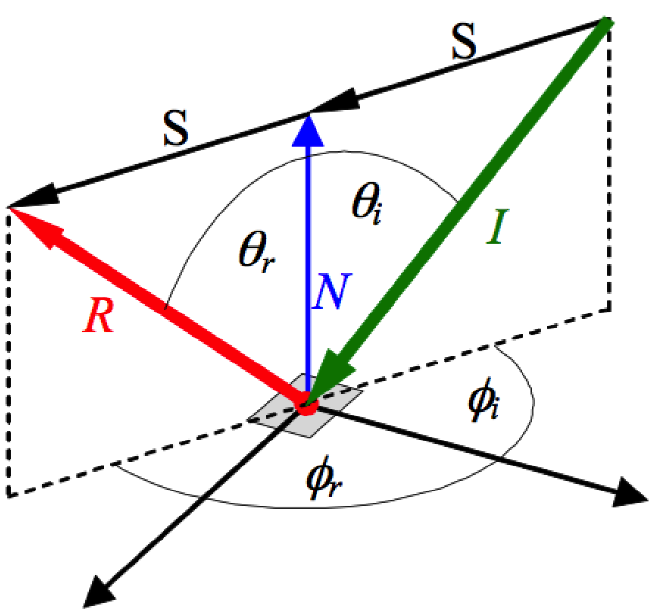
# Basics: Light: Ray Model

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




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

# 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

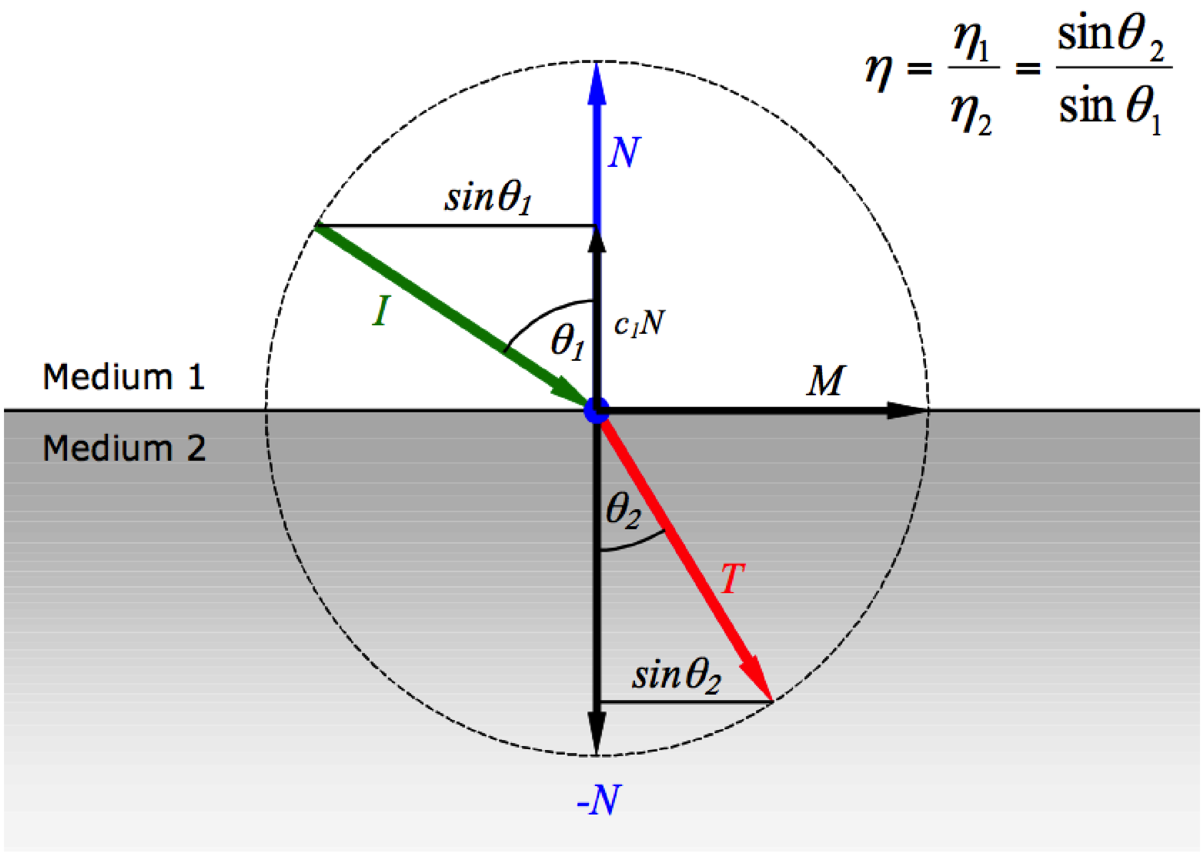
- The calculation of a refracted vector is based on the law of Snell (1621)

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

$mit$

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

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



# Basics: Light: Ray Model

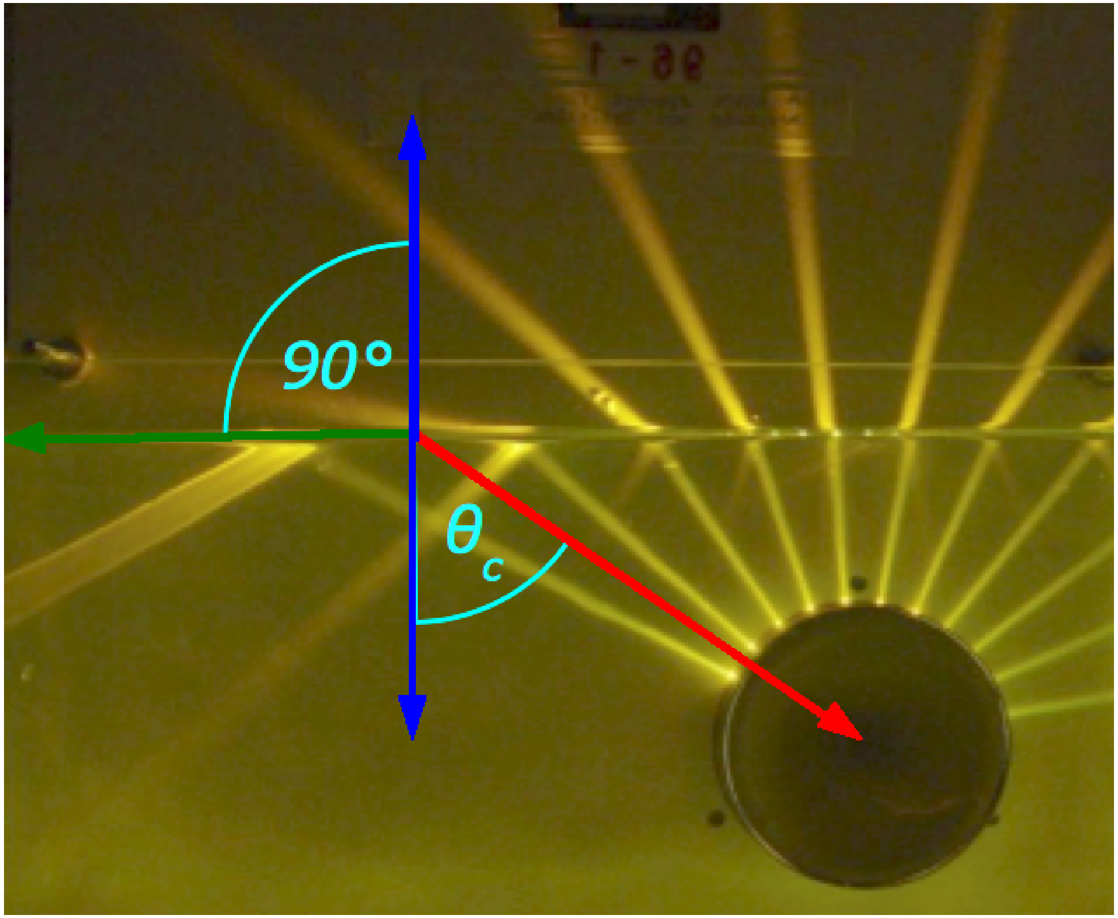
**Total Internal Reflection (TIR)**

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

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

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

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



# Basics: Light: Photon Model

**Photon Model:**

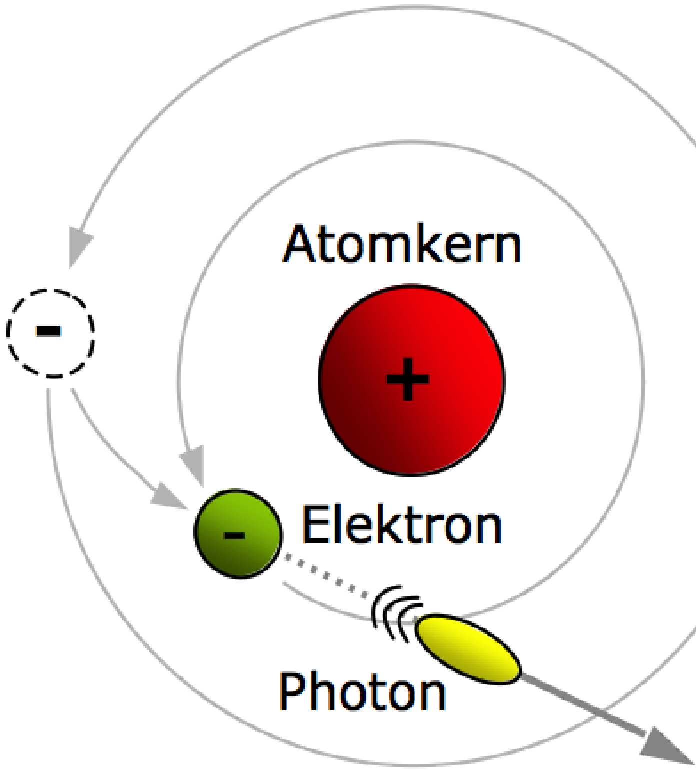
- Light is also an **energy transport** phenomena.
- It look as light comes in **packets of energy**.
- Such a packet is called **light particle** or **photon** (Greek for light quantum).
- The photon model was invented by **Albert Einstein**.

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

# Basics: Light: Photon Model

## Light Emission

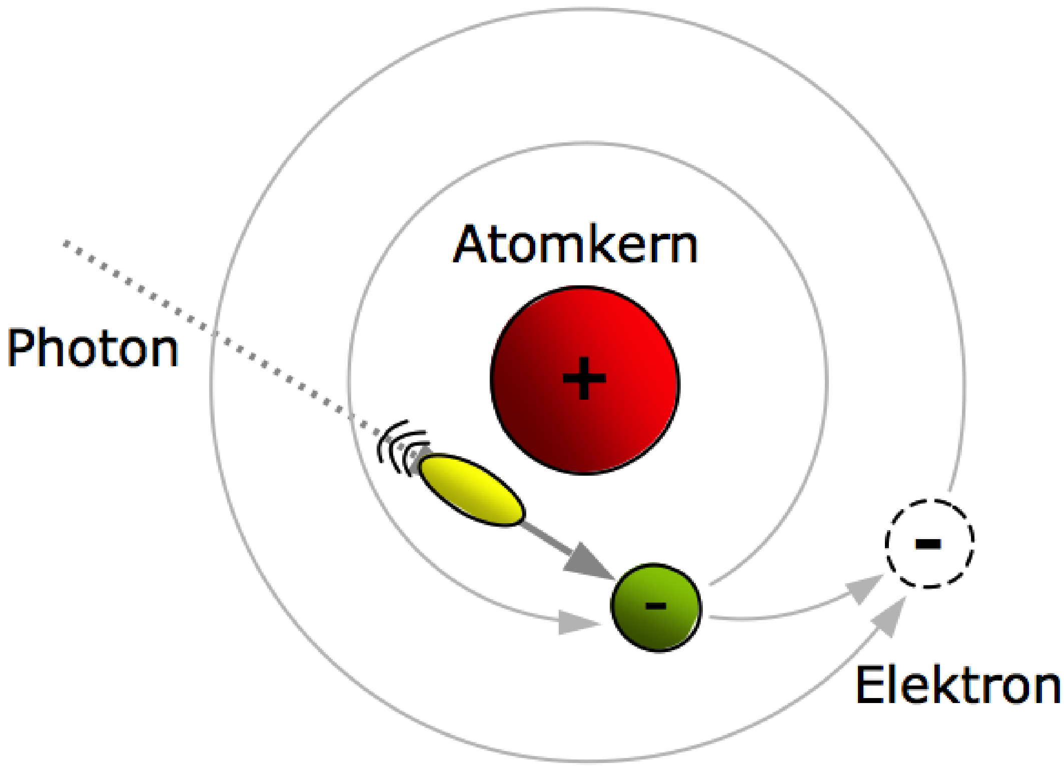
- When an electron change its orbit to a lower energy orbit it releases the energy in form of a photon.
- Because photons have no electric charge they can not be distracted by electromagnetic fields.



# Basics: Light: Photon Model

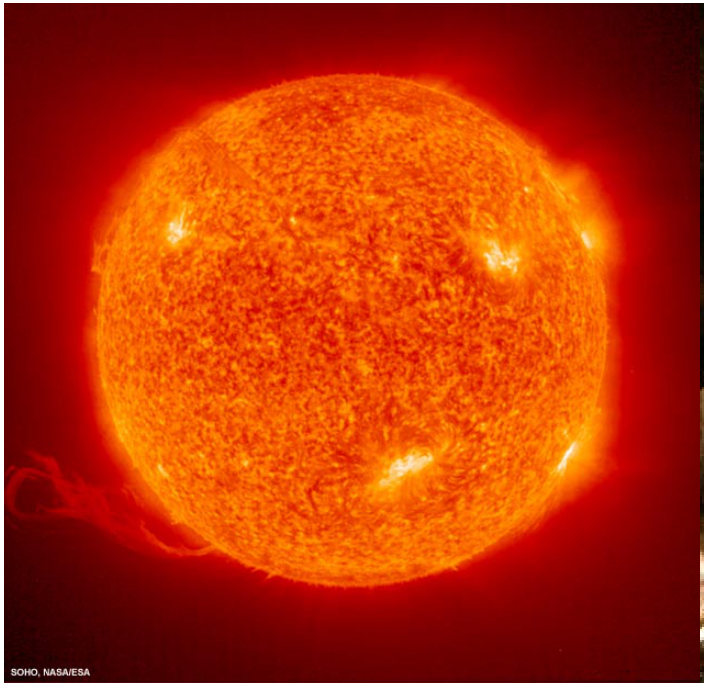
## Light Absorption

- 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:

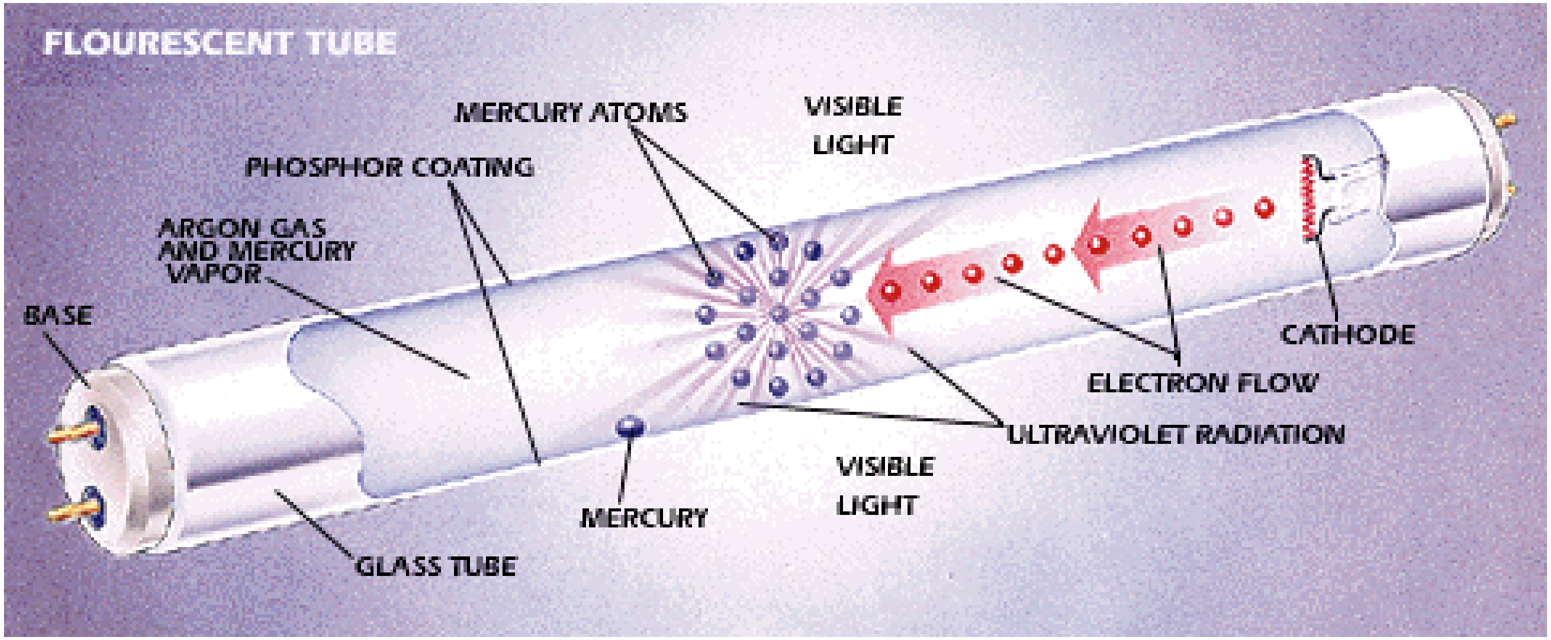



# Basics: Light: Photon Model: Light Sources

- **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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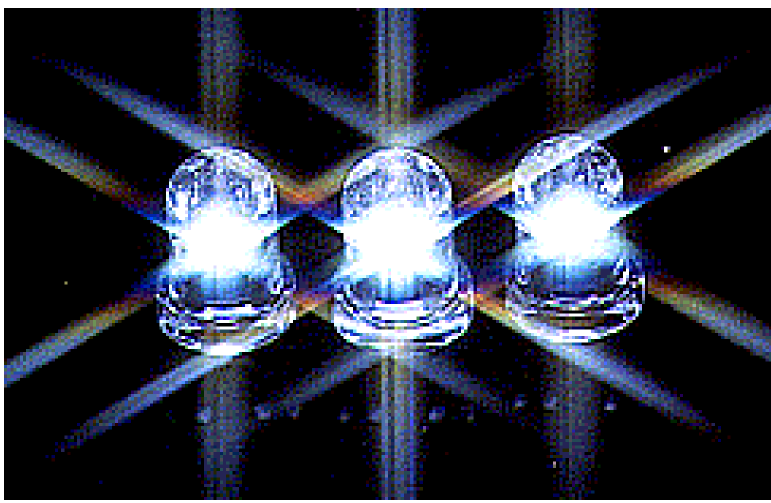
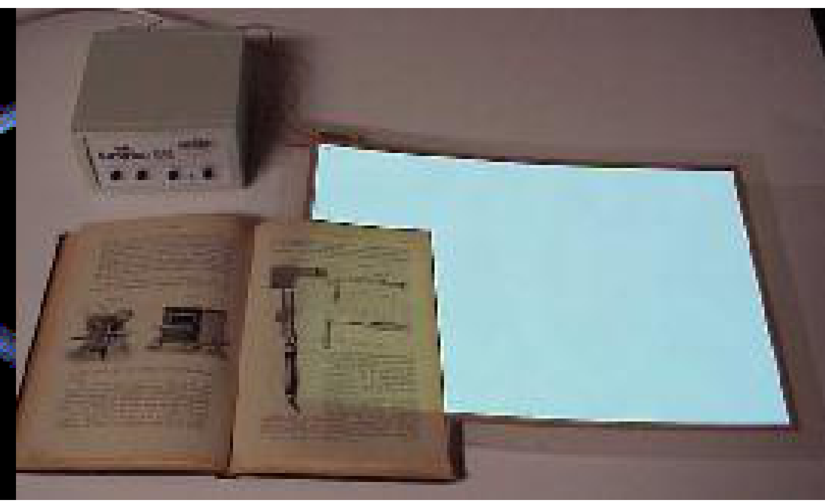
    - Light emitting diods (LED)
    - Light emitting condensators (LEC)





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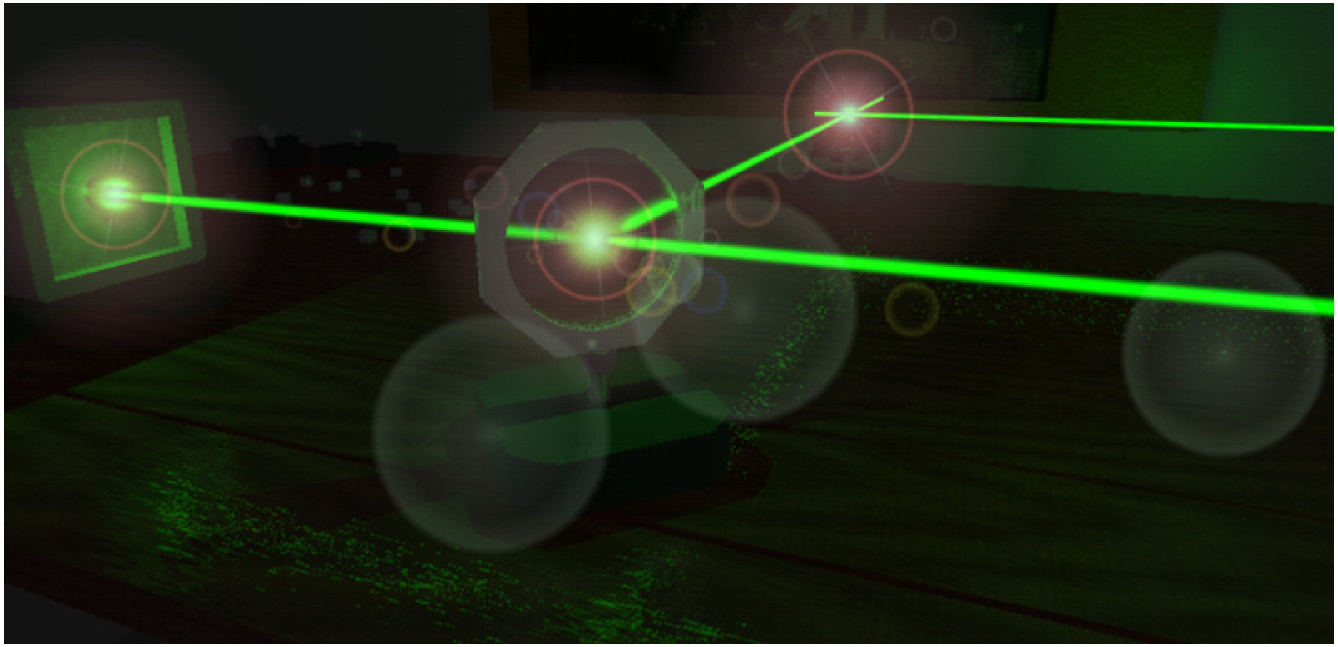
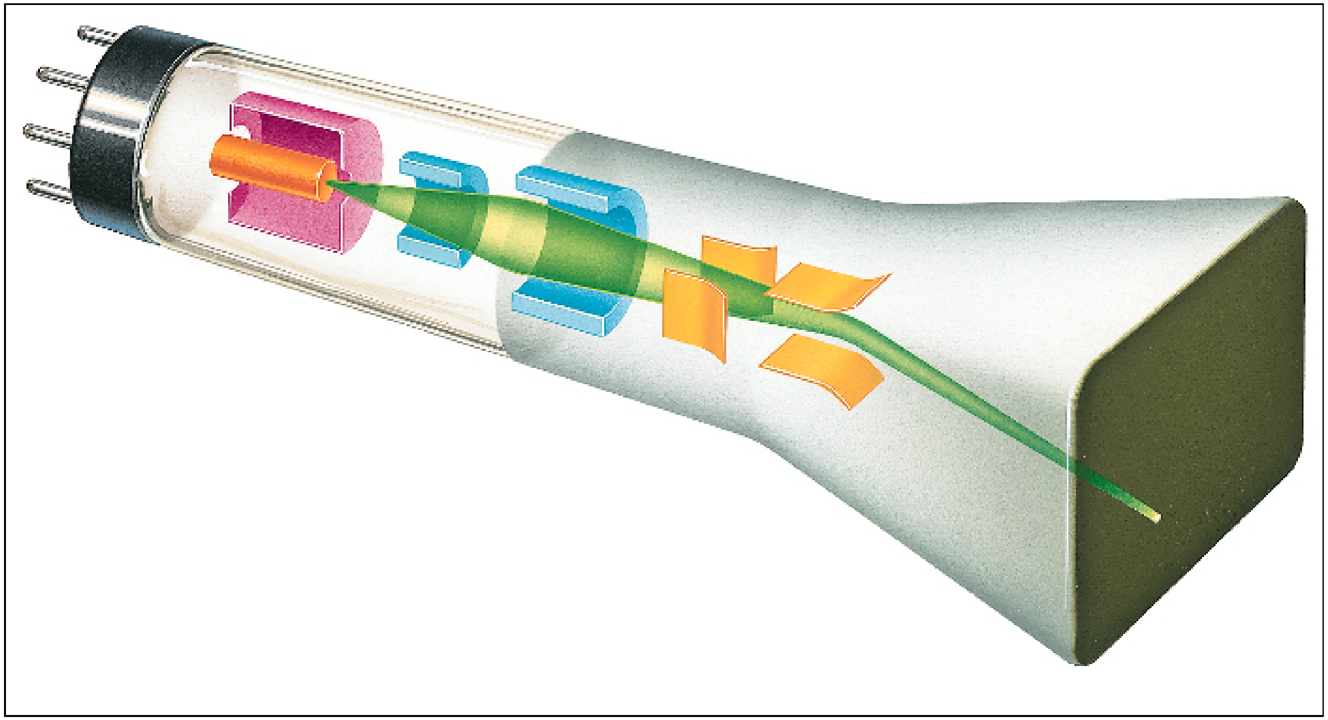
    - Neon light tube
    - Light emitting diods (LED)
    - Light emitting condensators (LEC)
    - Laser (Light Amplification by Stimulated Emission of Radiation)



# 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

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  - **Chemoluminescence**: Stimulation through chemical reaction

# Basics: Light: Photon Model: Light Sources

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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)

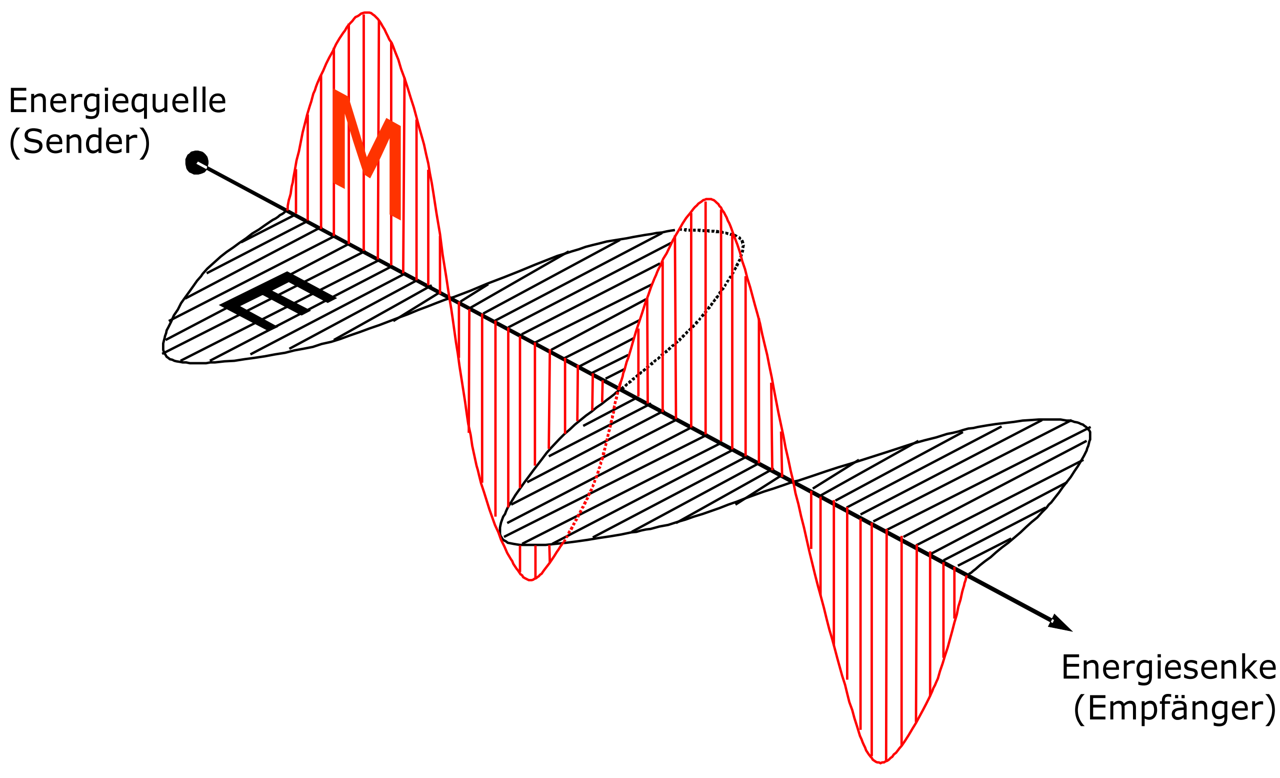
- The **wavelength** is inverse proportional to the energy E:

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

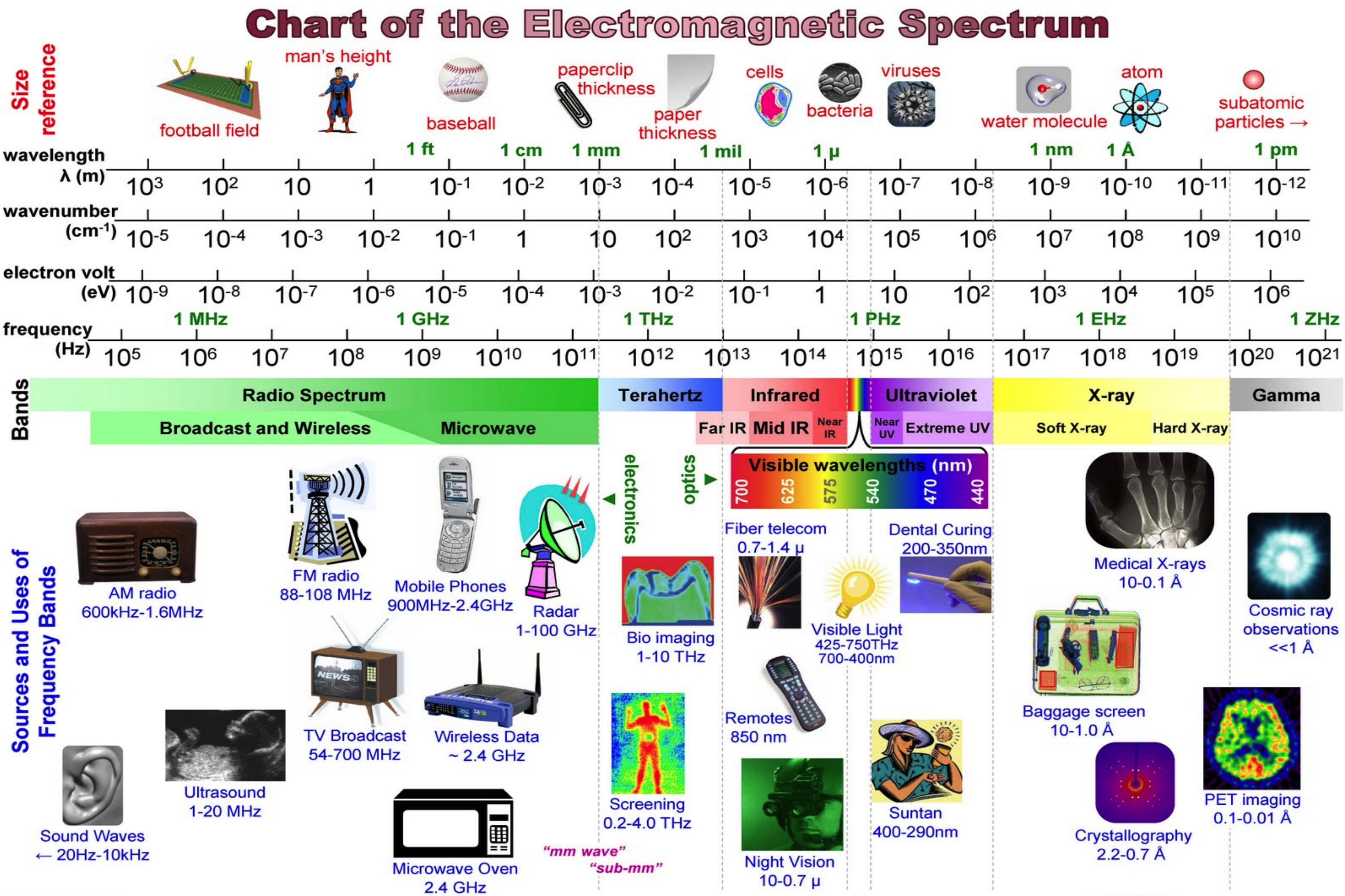
- c is the speed of light in vacuum (299'792'458 m/s)

# 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

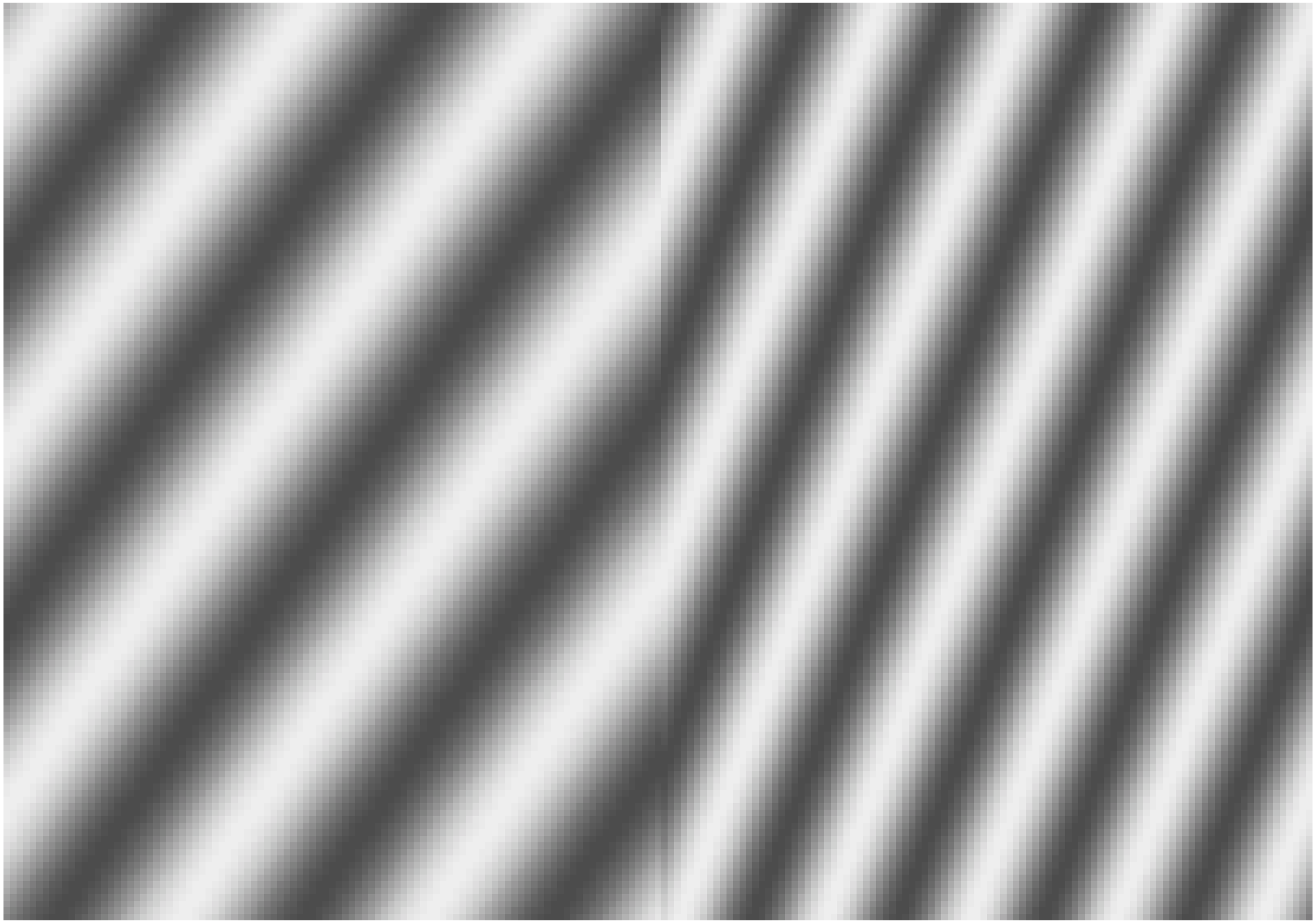


# Light: Wave Model: Electromagnetic Spectrum



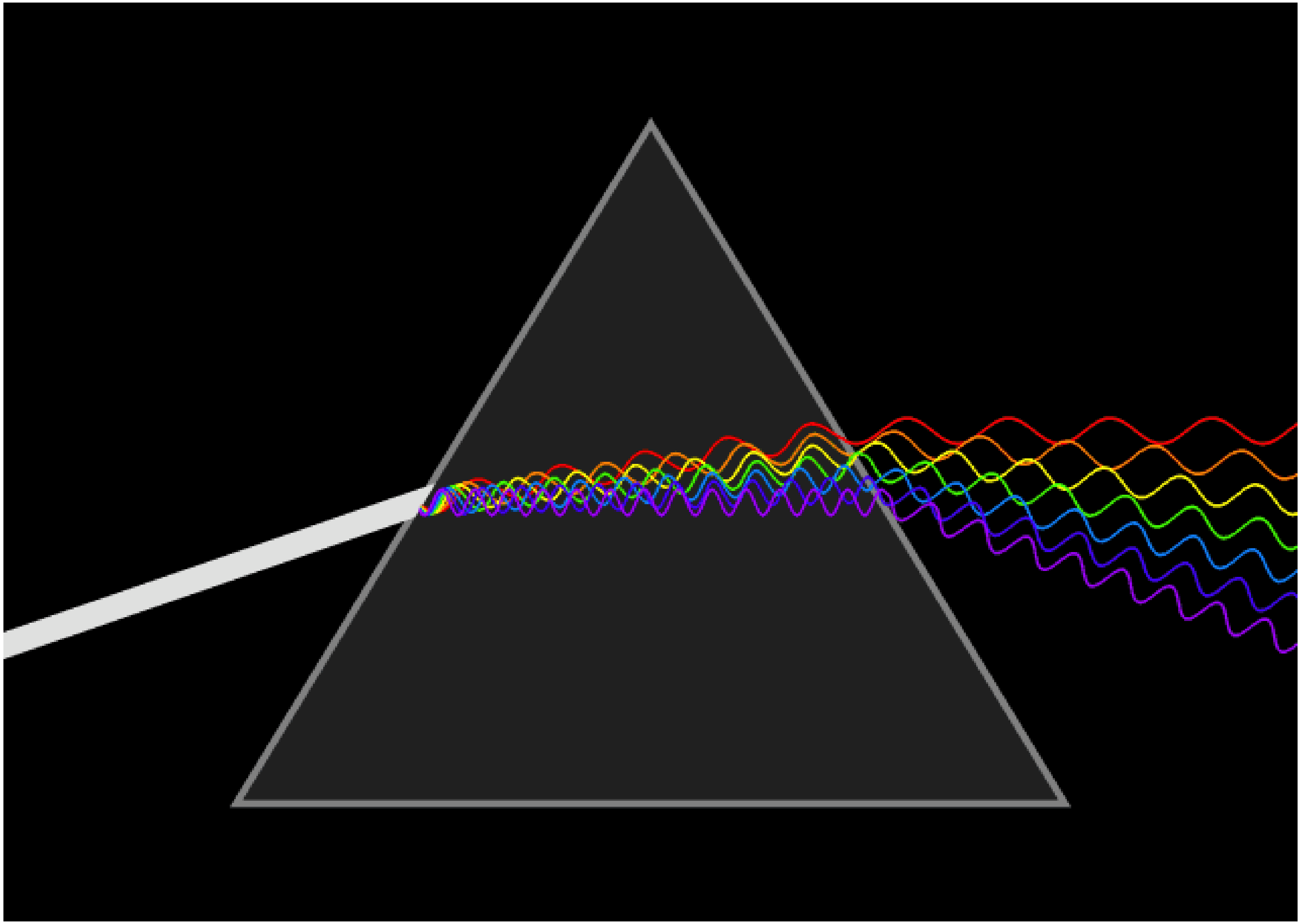
# Basics: Light: Wave Model: Refraction

**Why does a light ray get bended?**



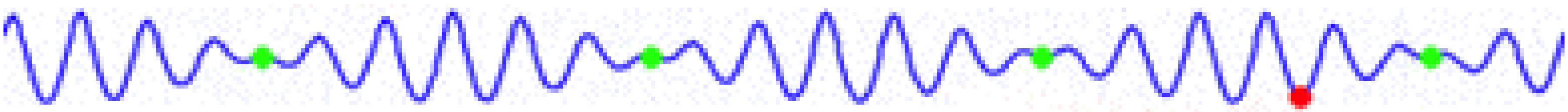
# Basics: Light: Wave Model: Refraction

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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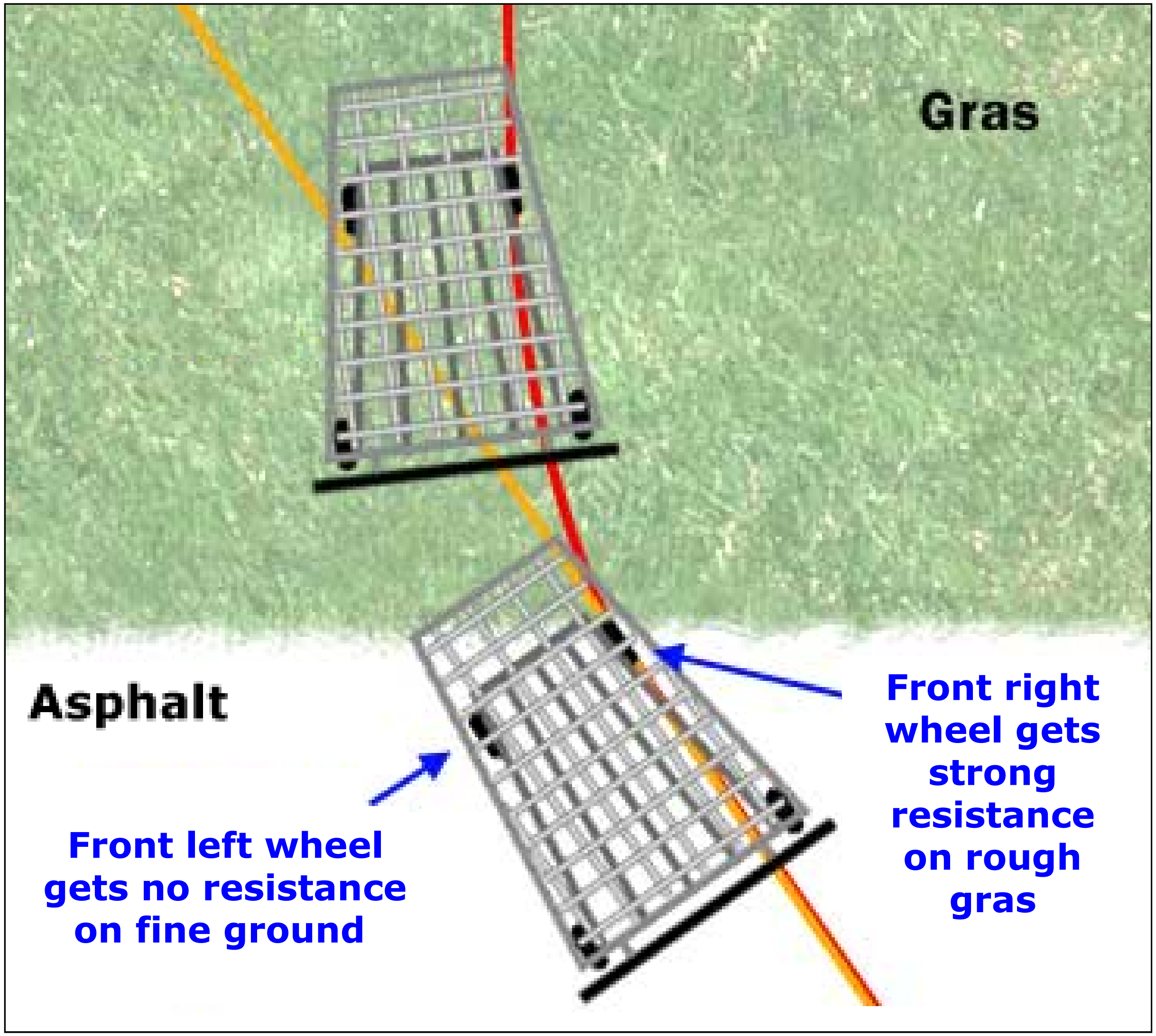

# Light: Wave Model: What causes a rainbow?

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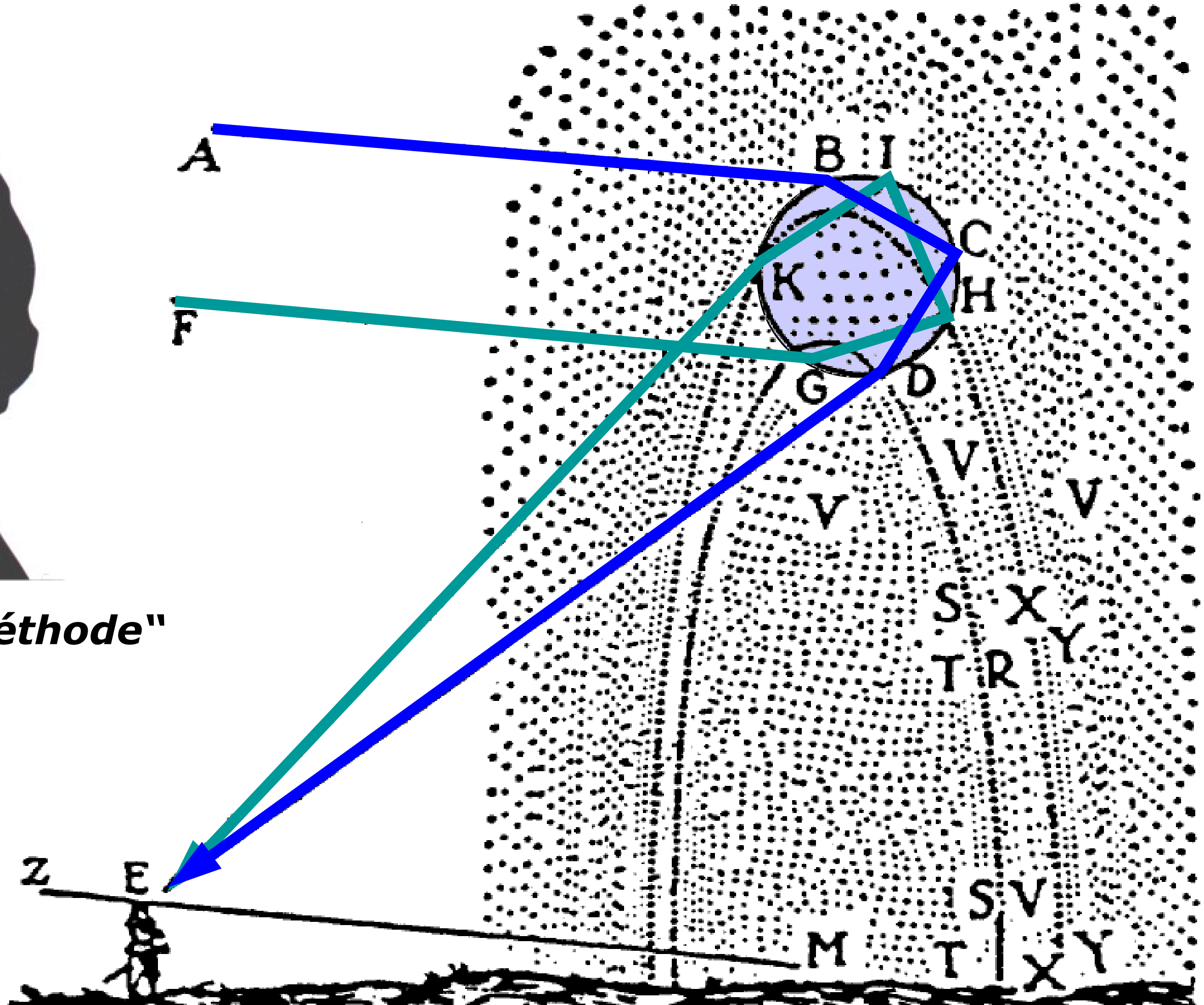
# Light: Wave Model: What causes a rainbow?

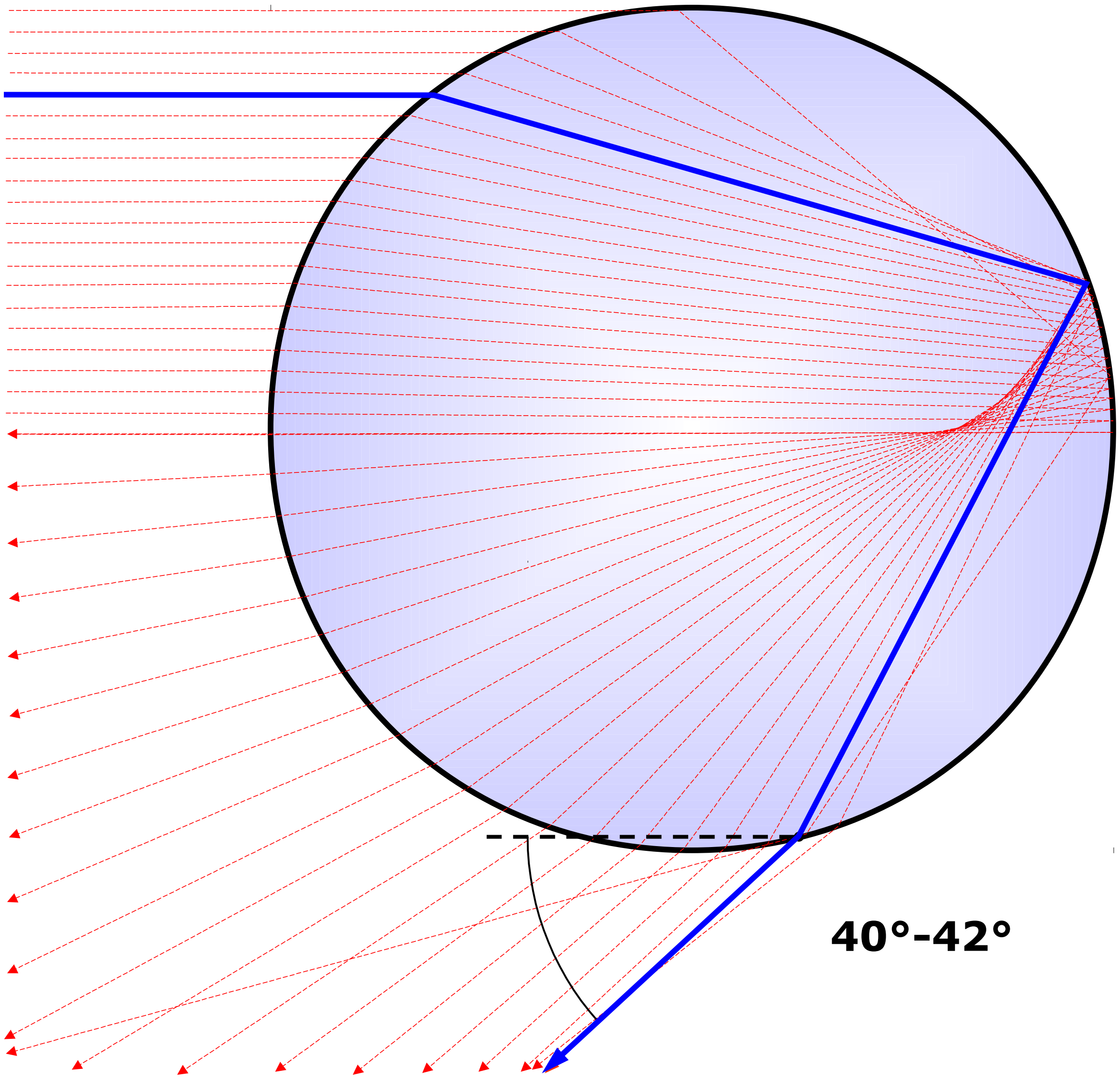
- The first explanation comes from the French mathematician *Henri Descartes.*

***„Discours de la méthode"***



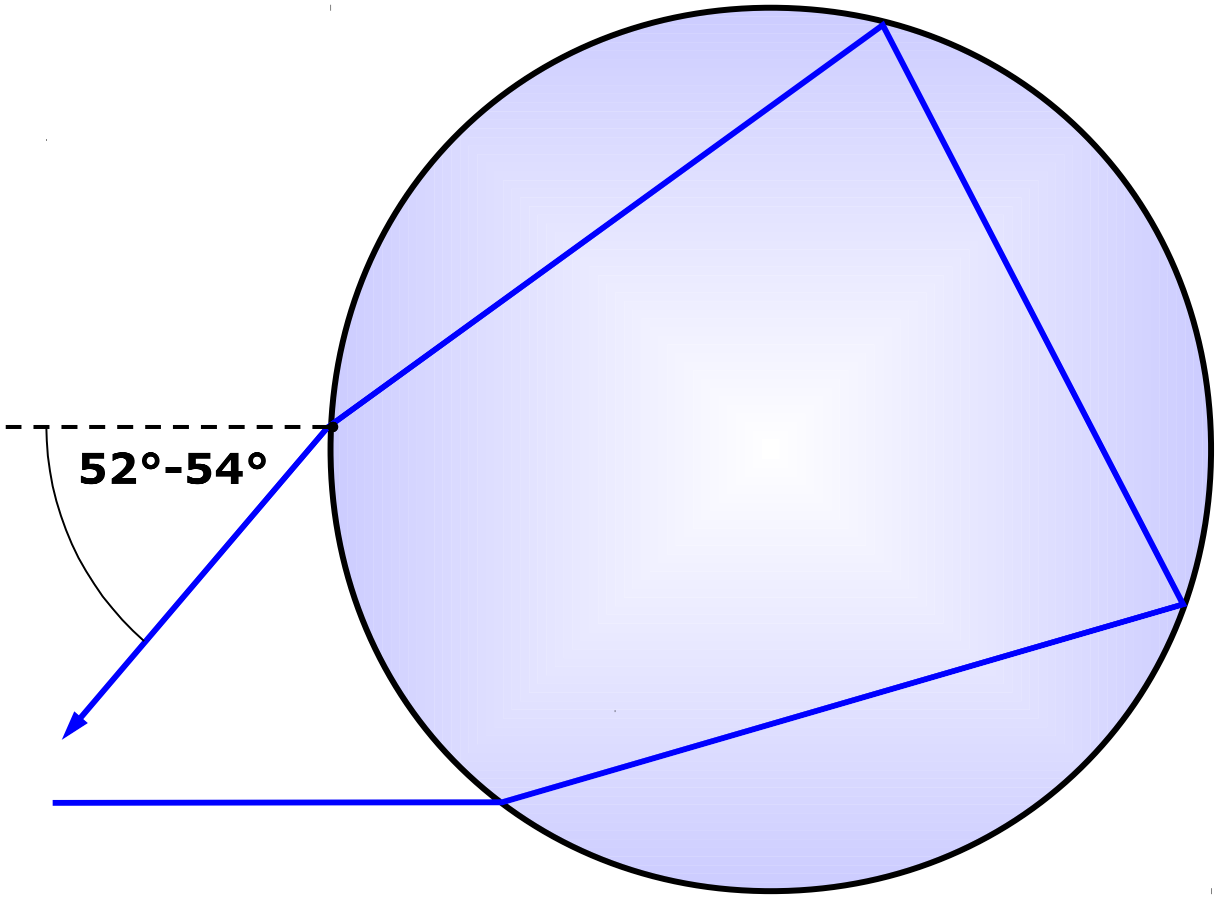
# Light: Wave Model: What causes a rainbow?

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



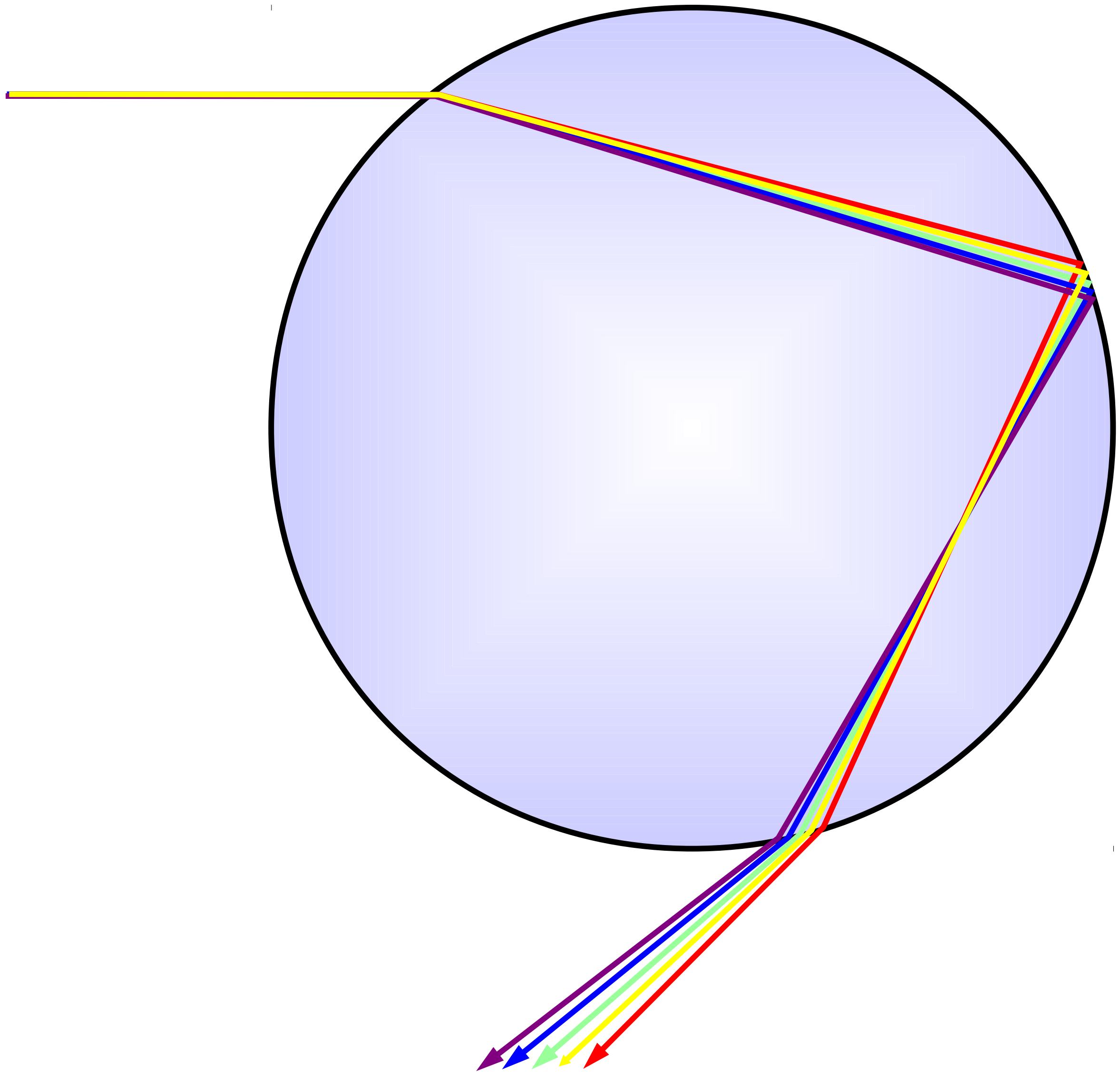
# Light: Wave Model: What causes a rainbow?

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



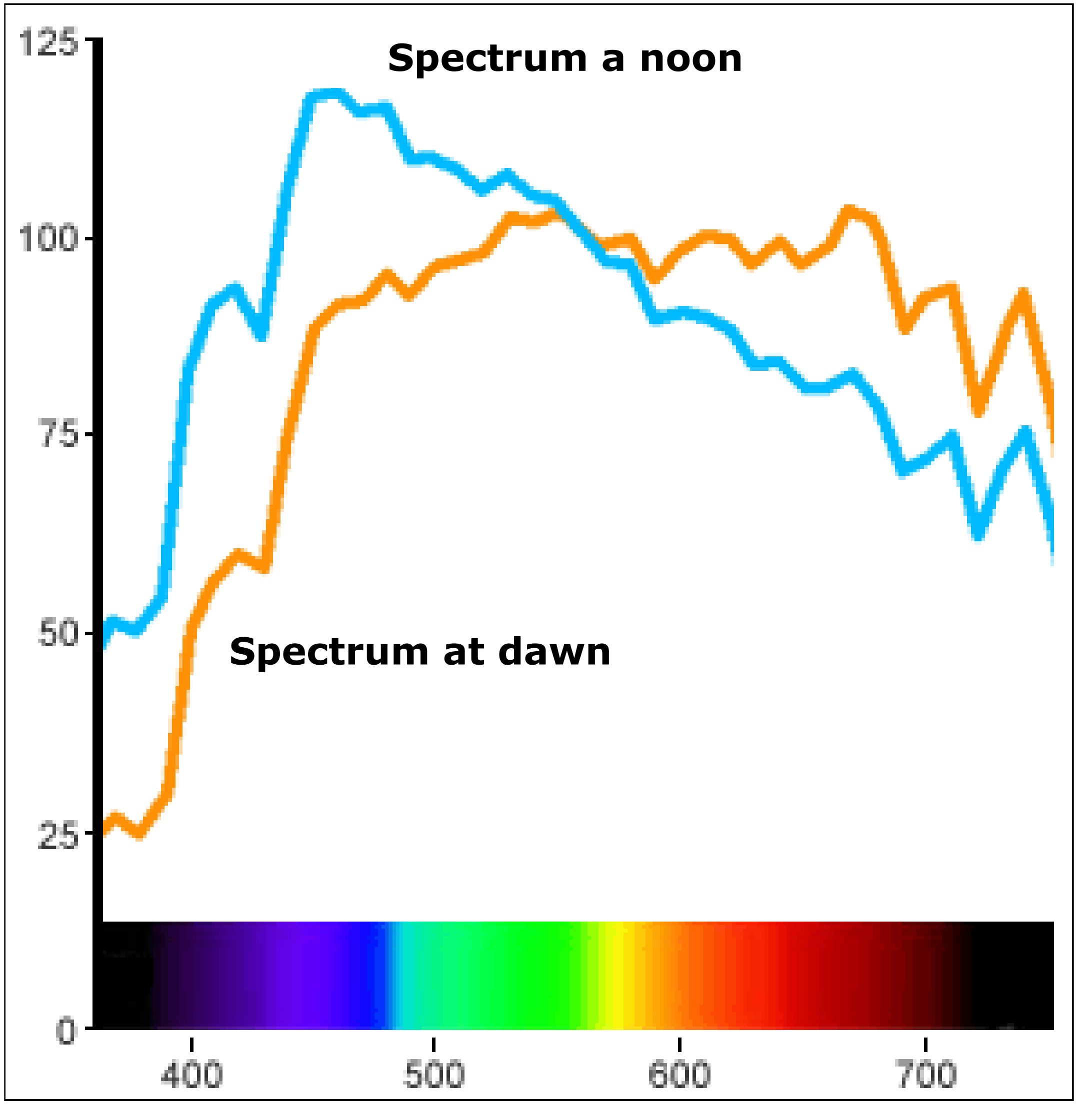
# Light: Wave Model: What causes a rainbow?

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

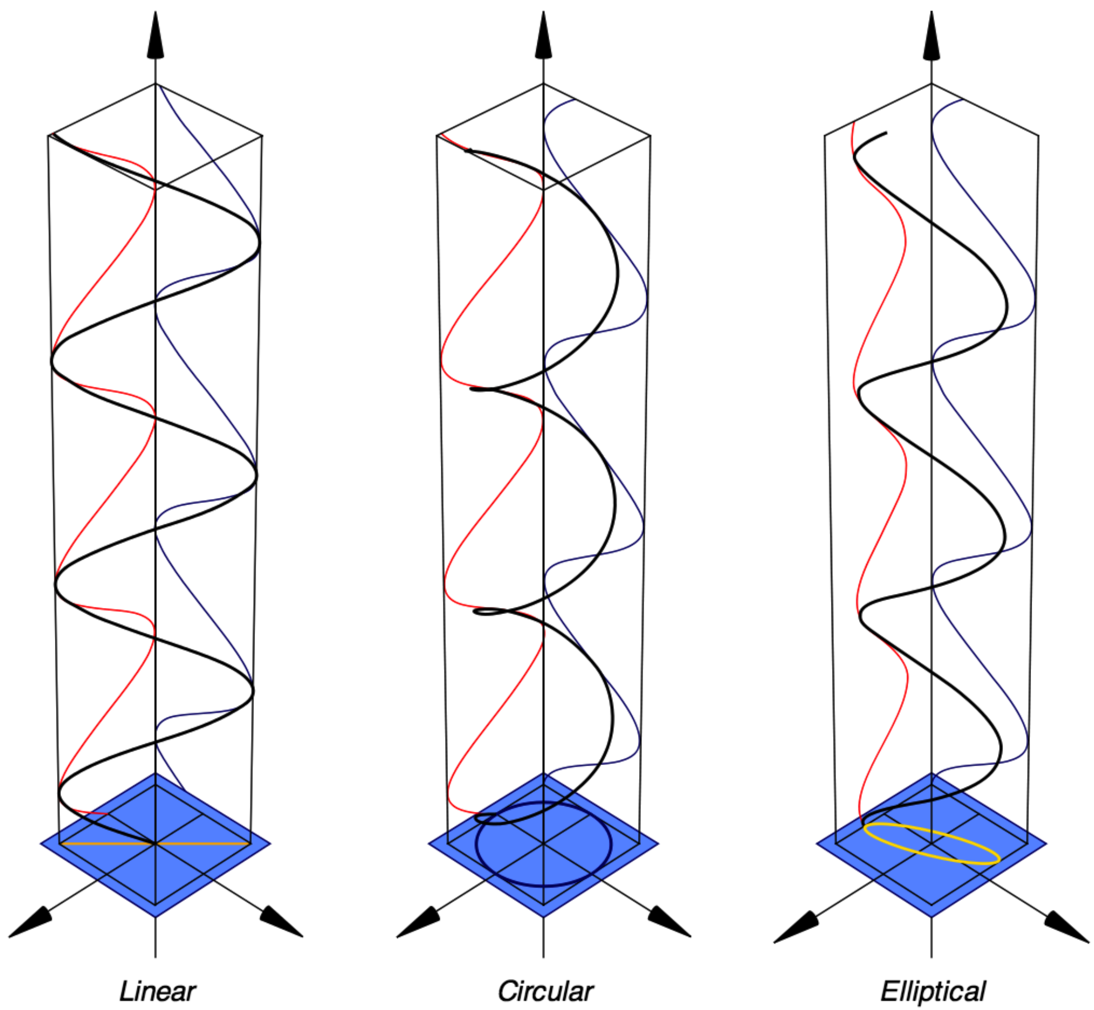
- **The wavelength of visible light is small (400 - 700 nm):**

  > We can see therefore small things sharp

# Basics: Light: Wave Model:

## Light Polarization

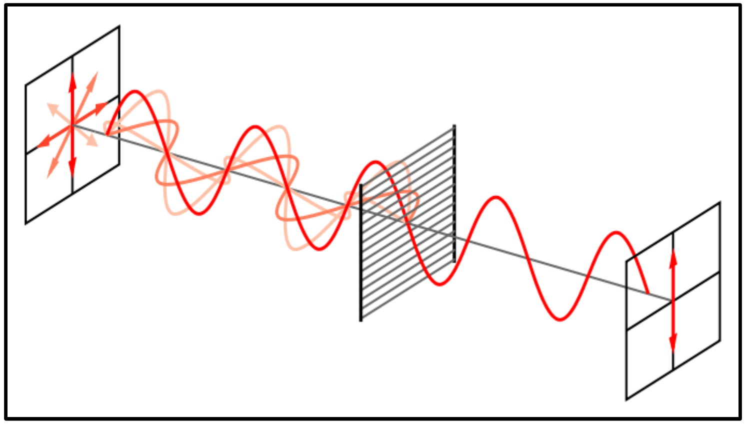
- The light doesn's swing necessarily in a plane. It can rotate around the propgation direction:

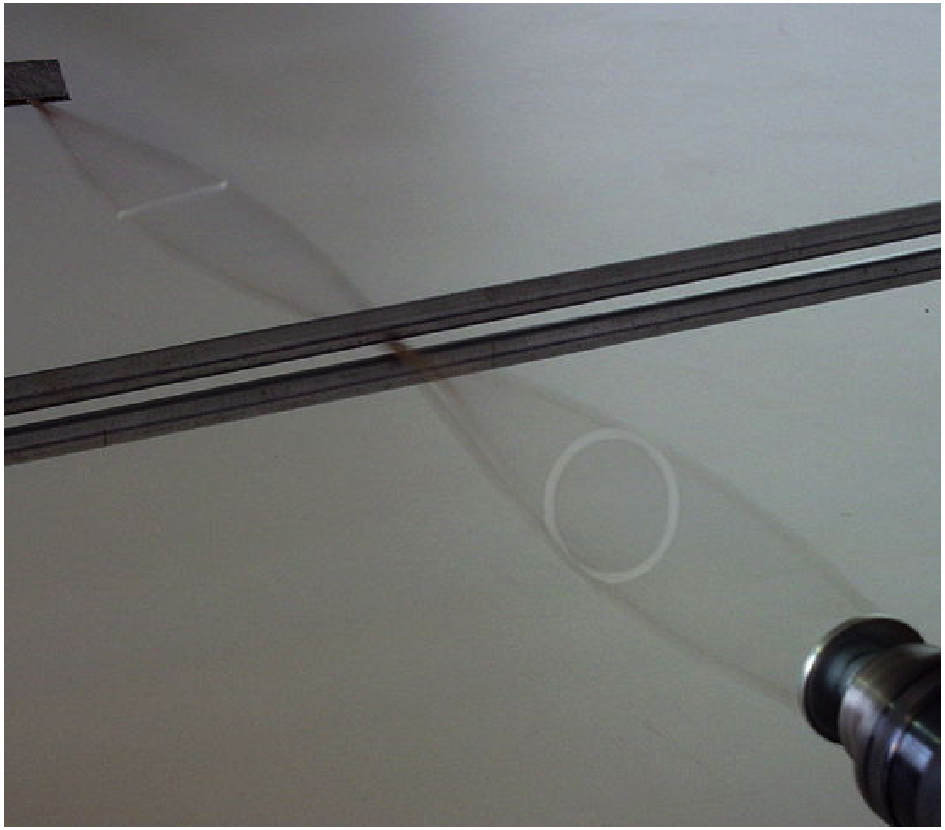


# Basics: Light: Wave Model:

## 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

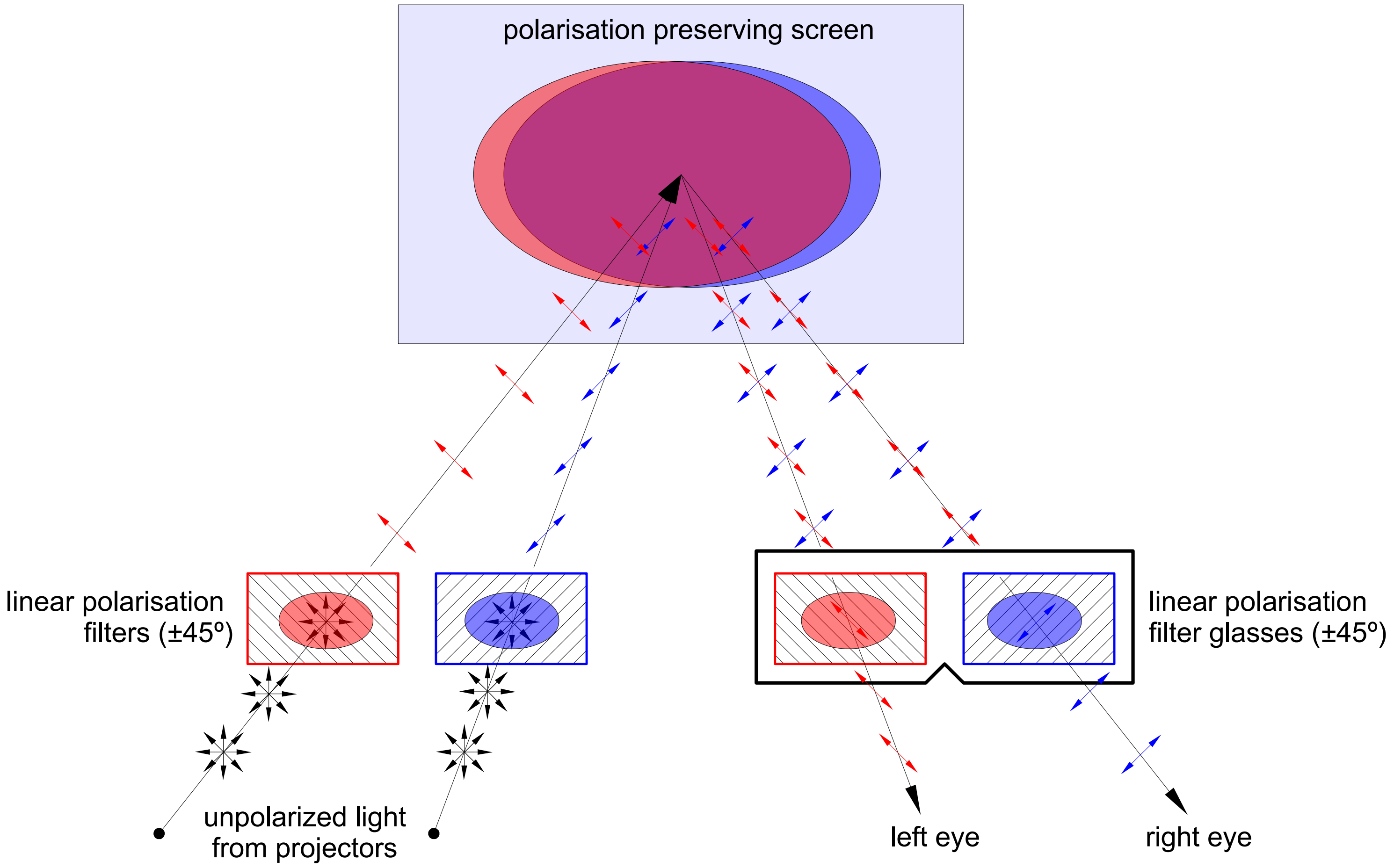
## Light Polarization

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

# Basics: Light: Wave Model

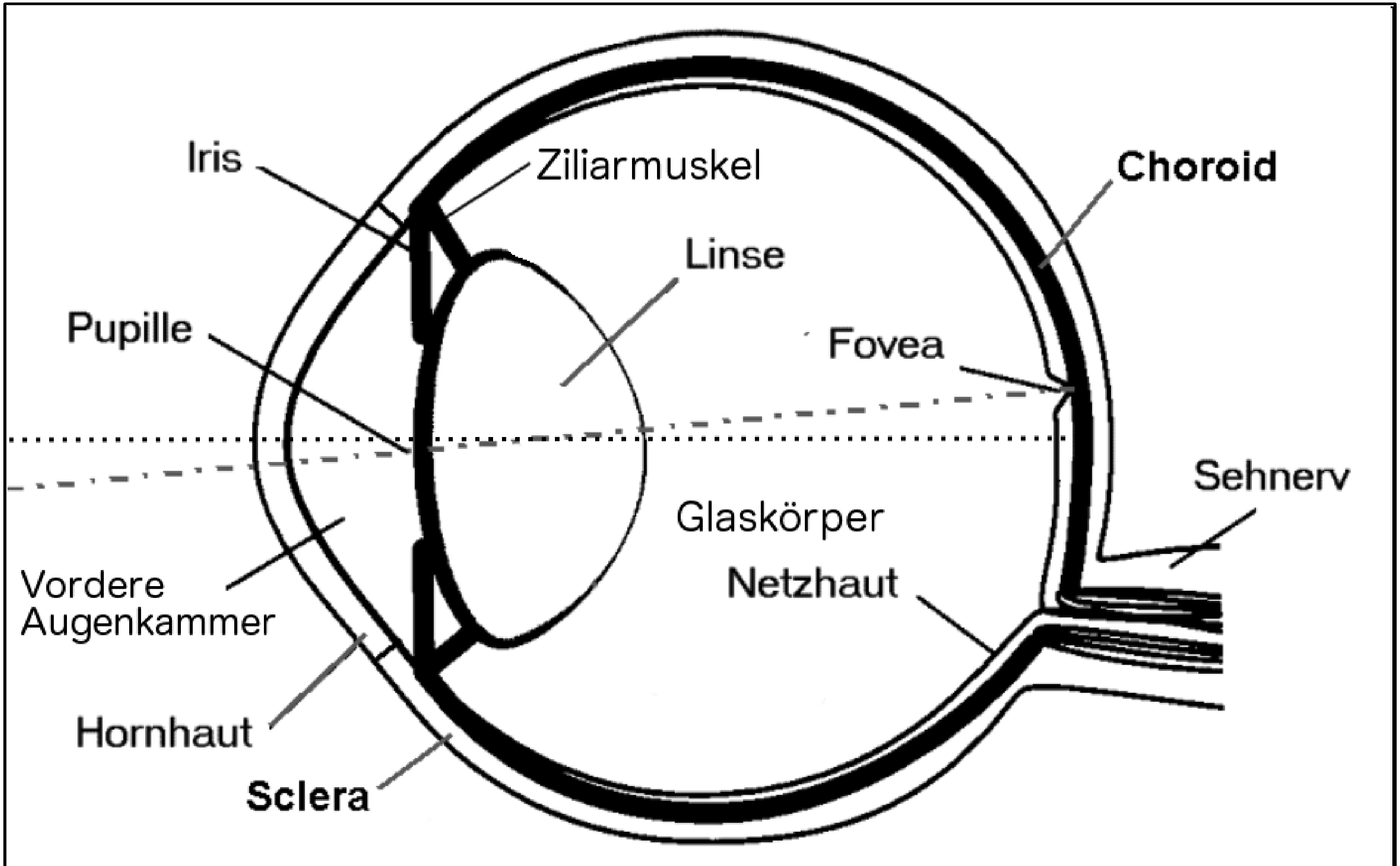
## Light Polarization

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



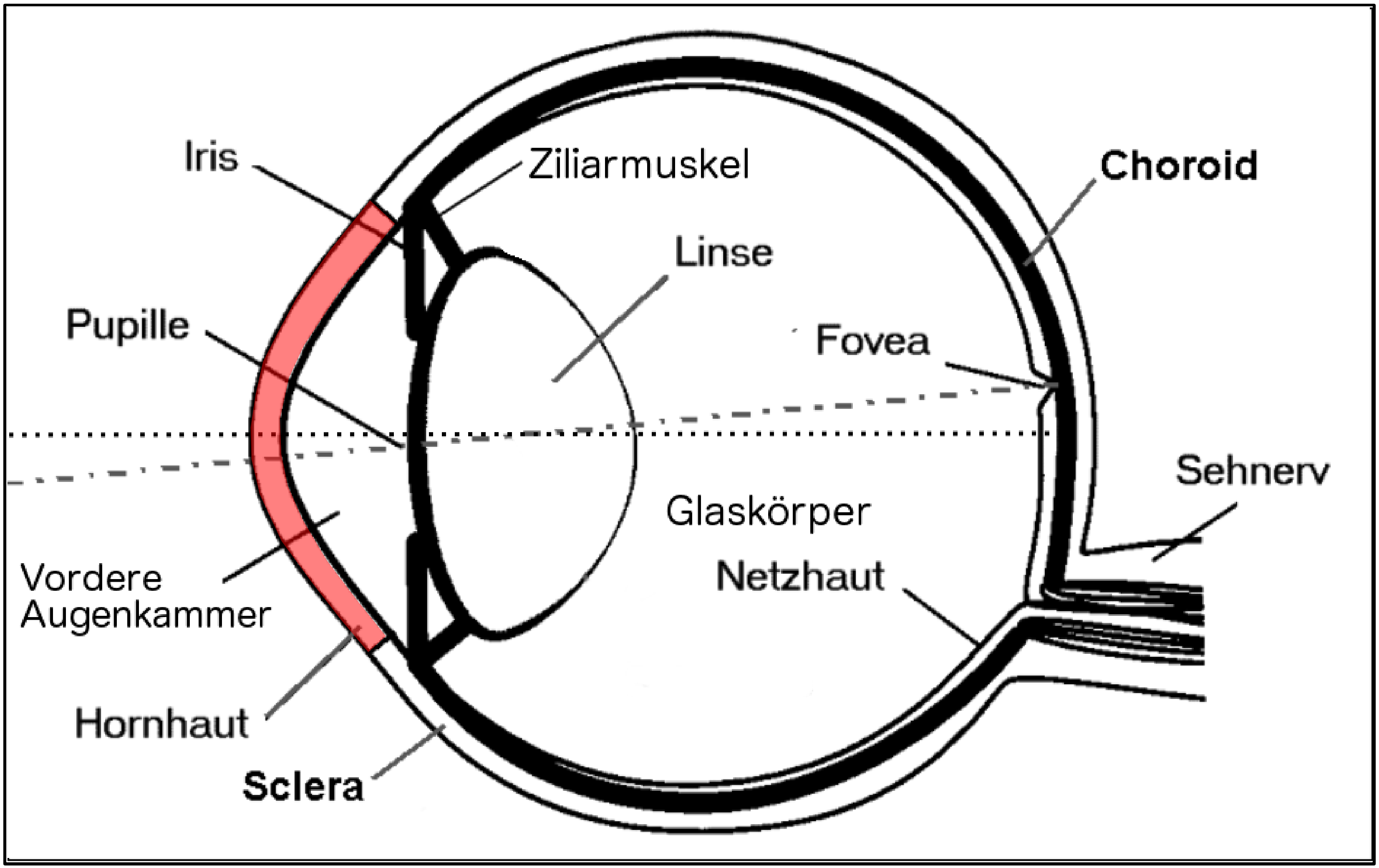
# Basics: Eye

About spherical, ca. 22mm diameter



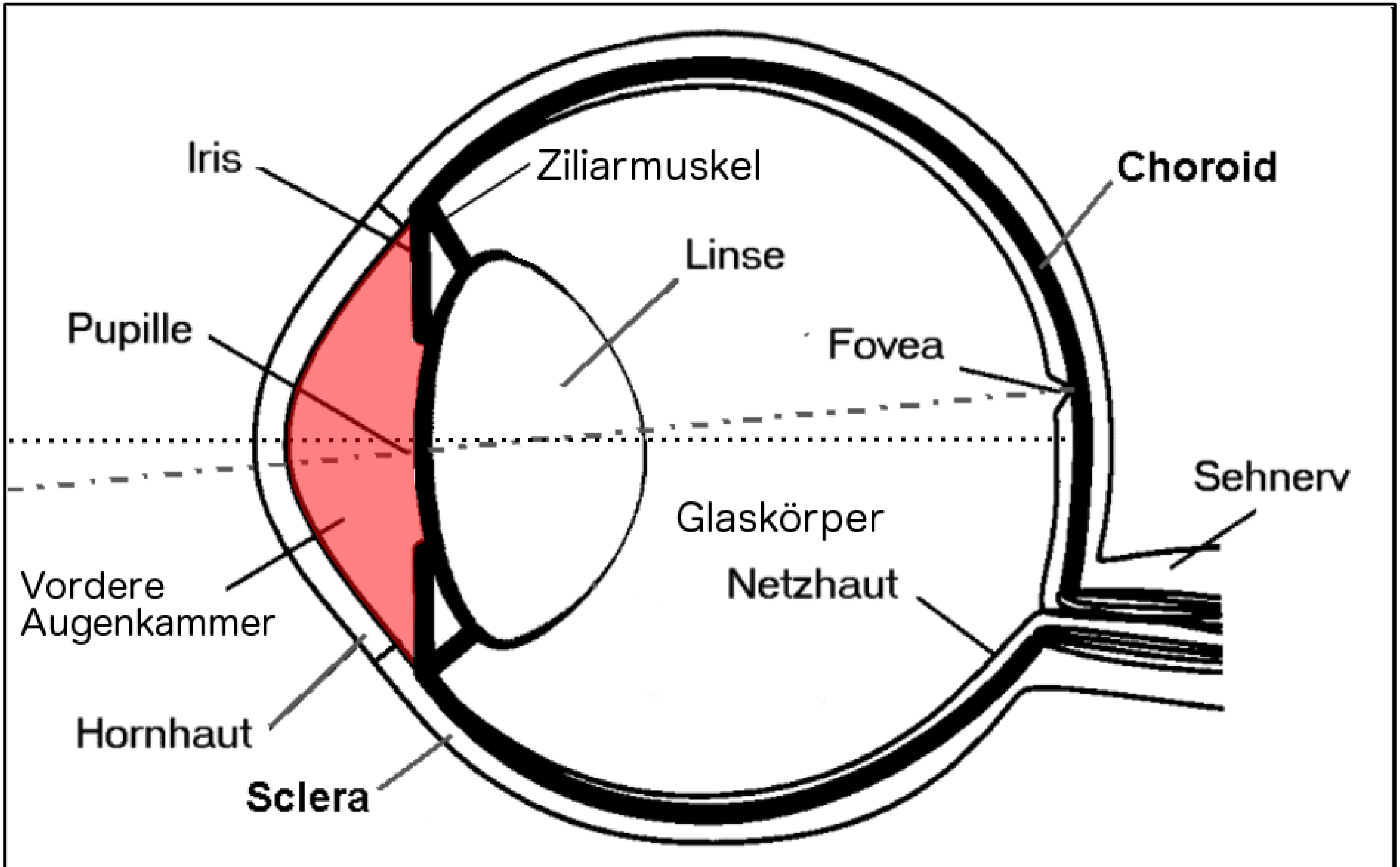
# Basics: Eye: Cornea (Hornhaut)

Though, transparent, thickness only 0.5-0.7mm



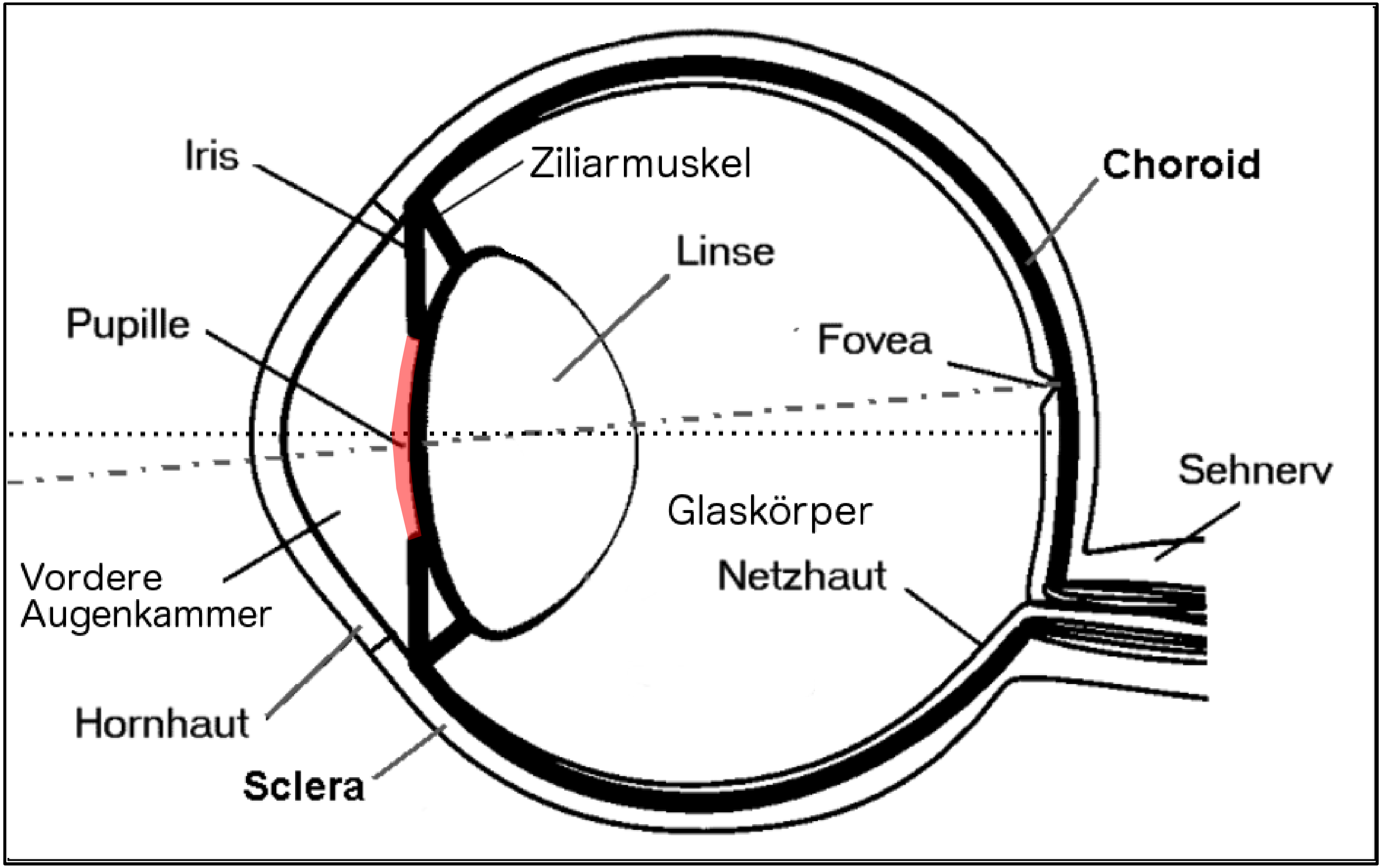
# Eye: Anterior Chamber (Vordere Augenkammer)

Highly transparent liquid, constantly rebuilt.



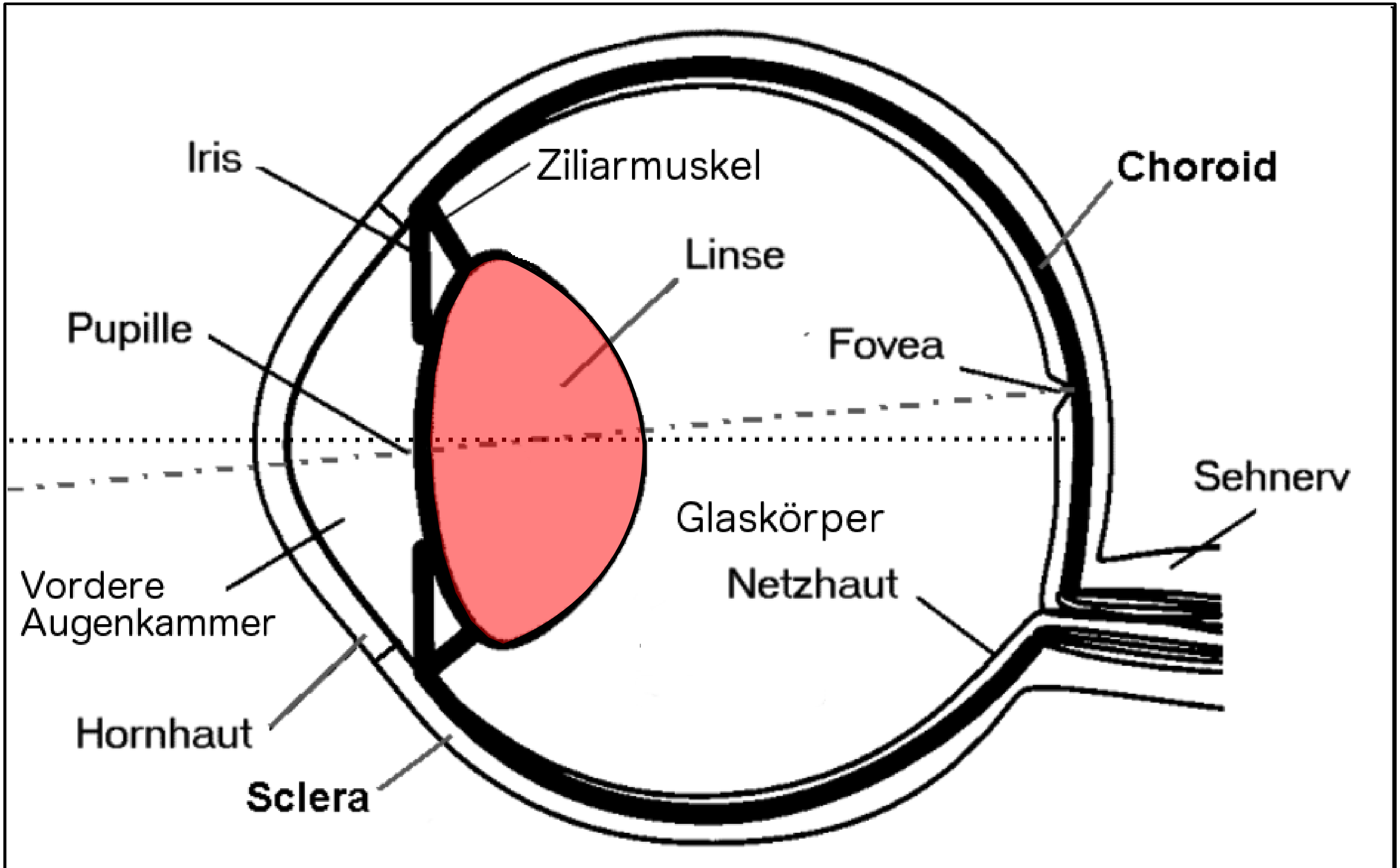
# Basics: Eye: Pupil

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



# Basics: Eye: Lens

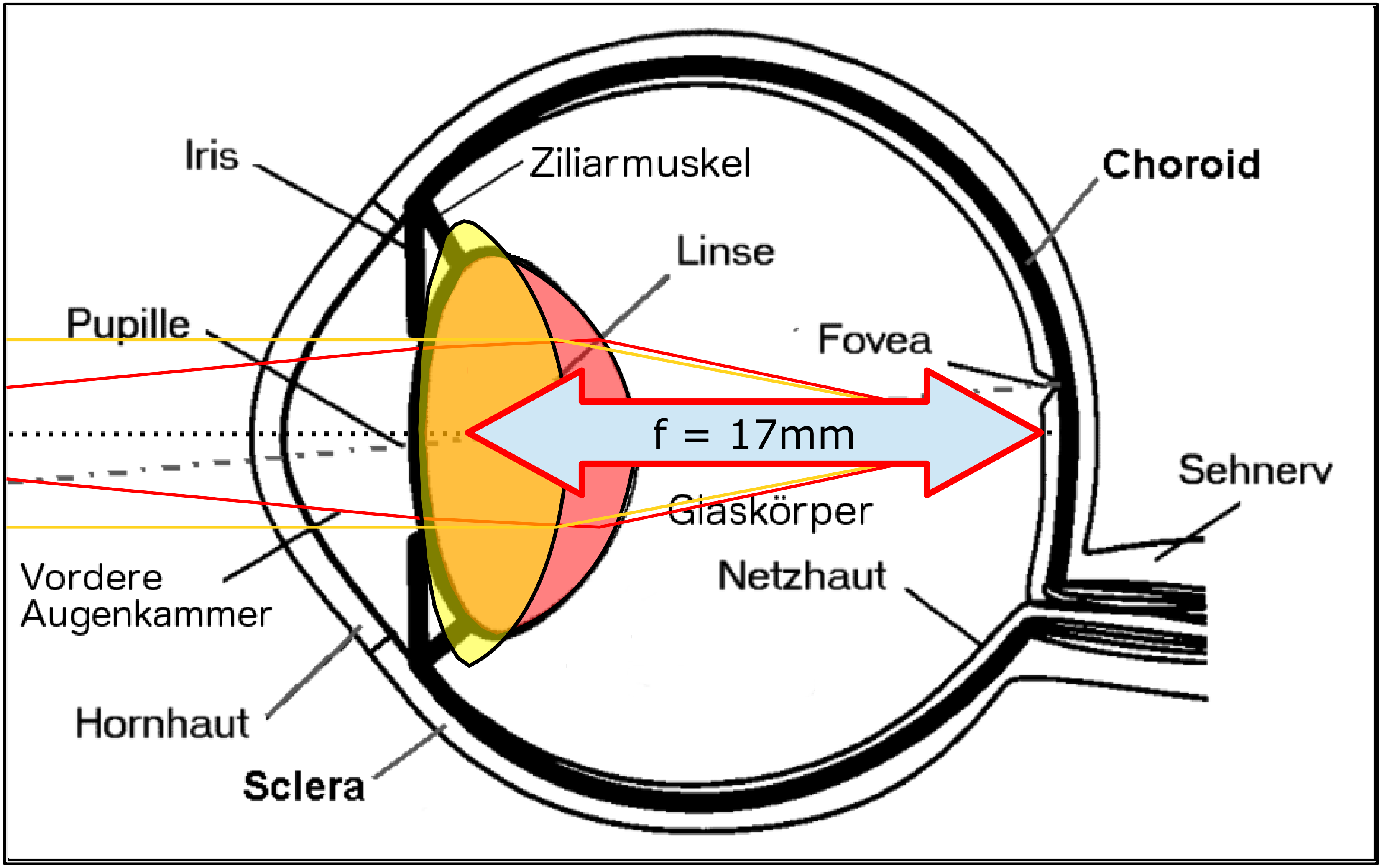
Contains 70% water, the rest (fat & proteines) absorbs infrared & UV light



# Basics: Eye: Lens

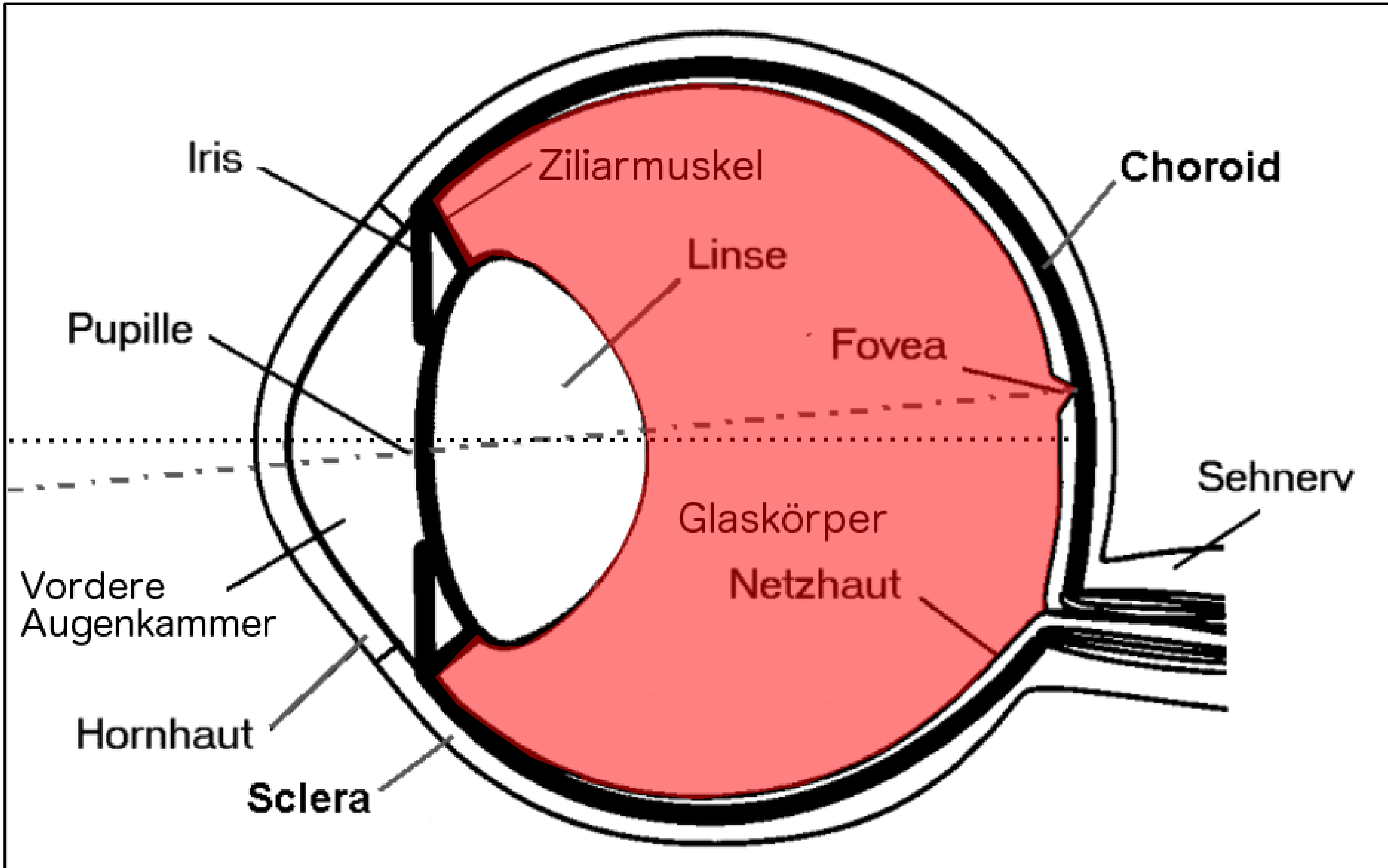
With relaxed ciliar muscles we focus to the near.

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



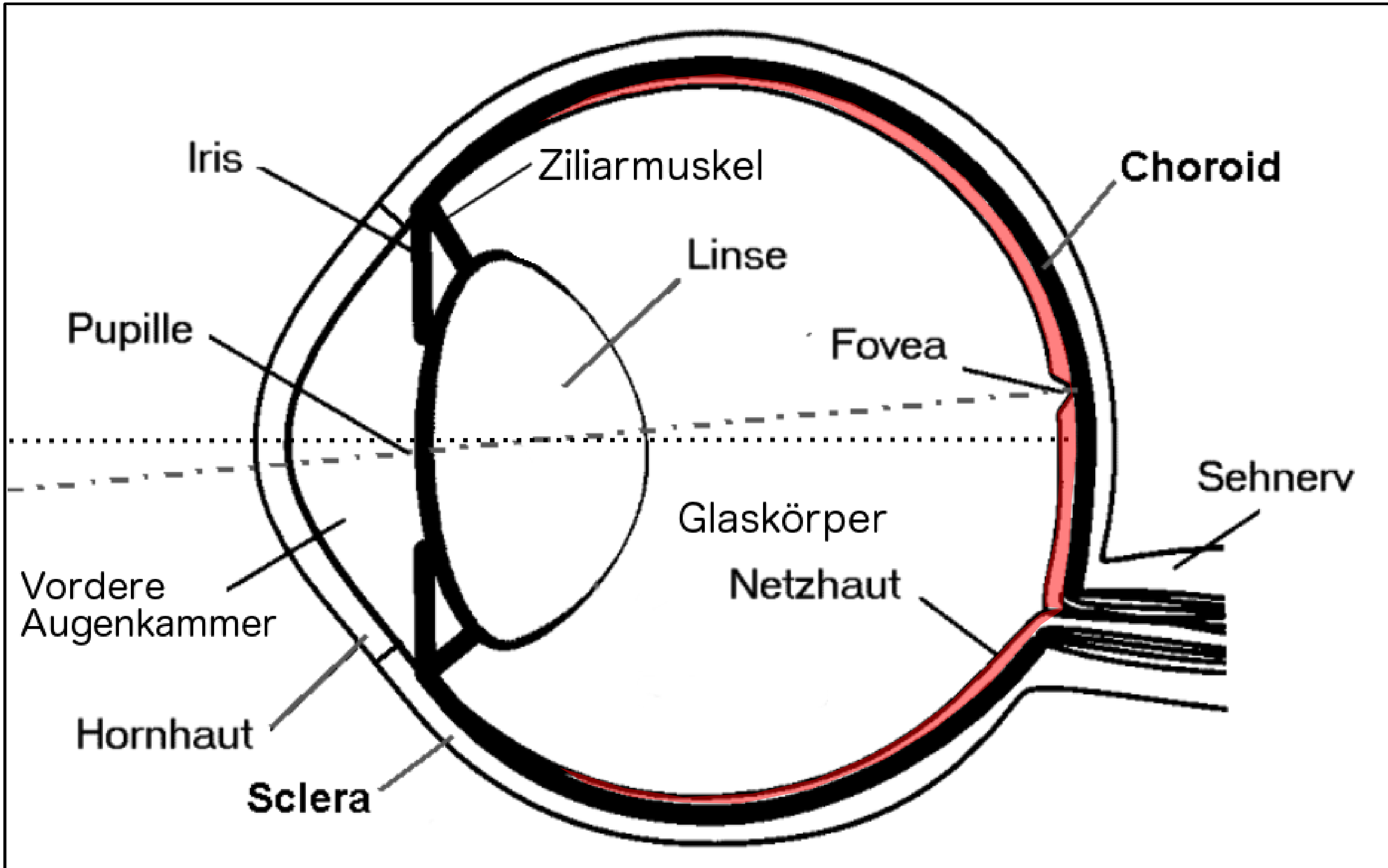
# Basics: Eye: Vitreous Body (Glaskörper)

Highly transparent gelatinous mass fills the eye body



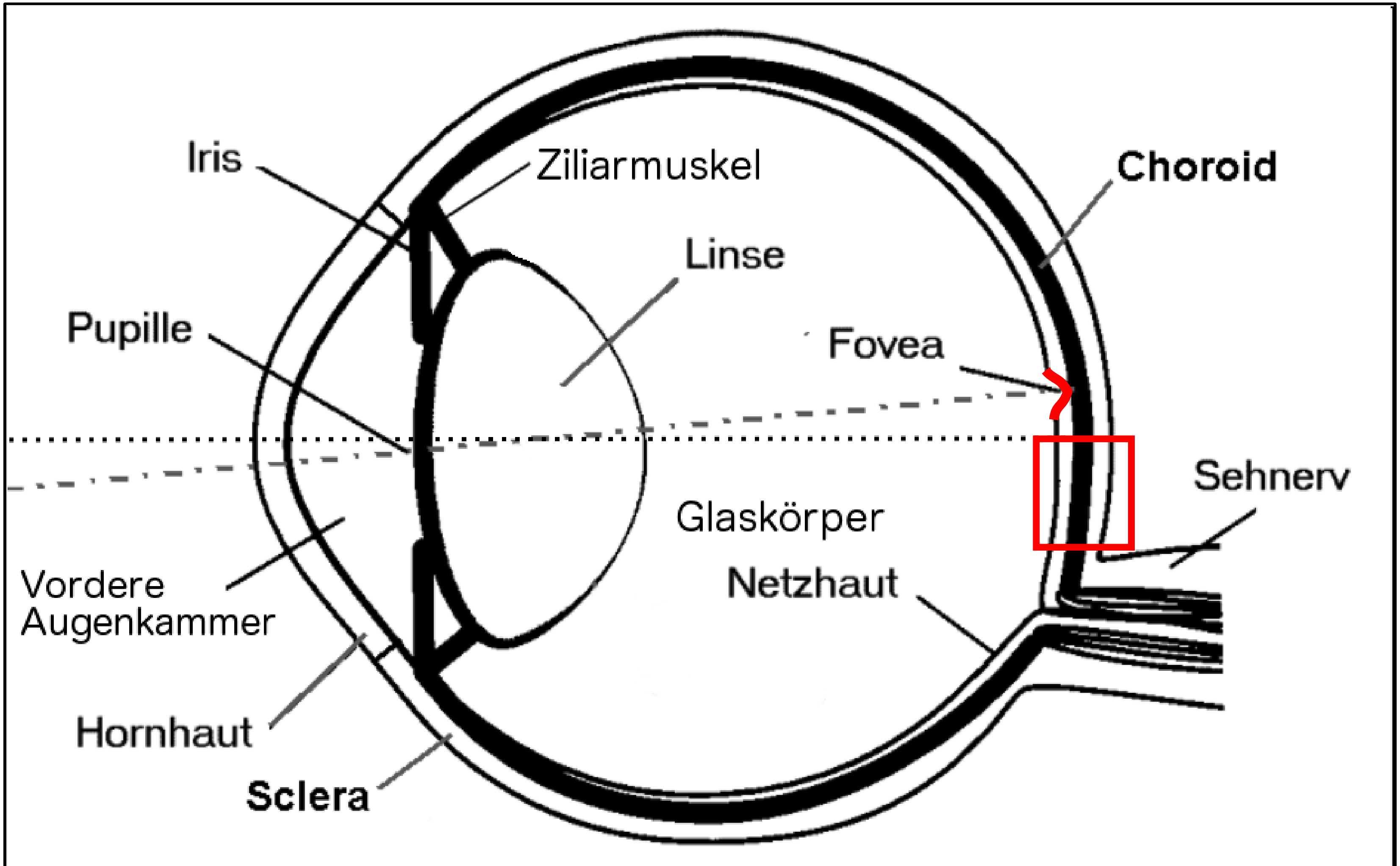
# Basics: Eye: Retina (Netzhaut)

Contains the light sensitive cells, the blood vesels and nerves



# Basics: Eye: Fovea Centralis

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



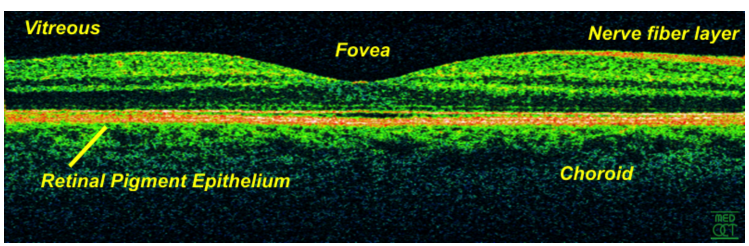
# Basics: Eye: Retina

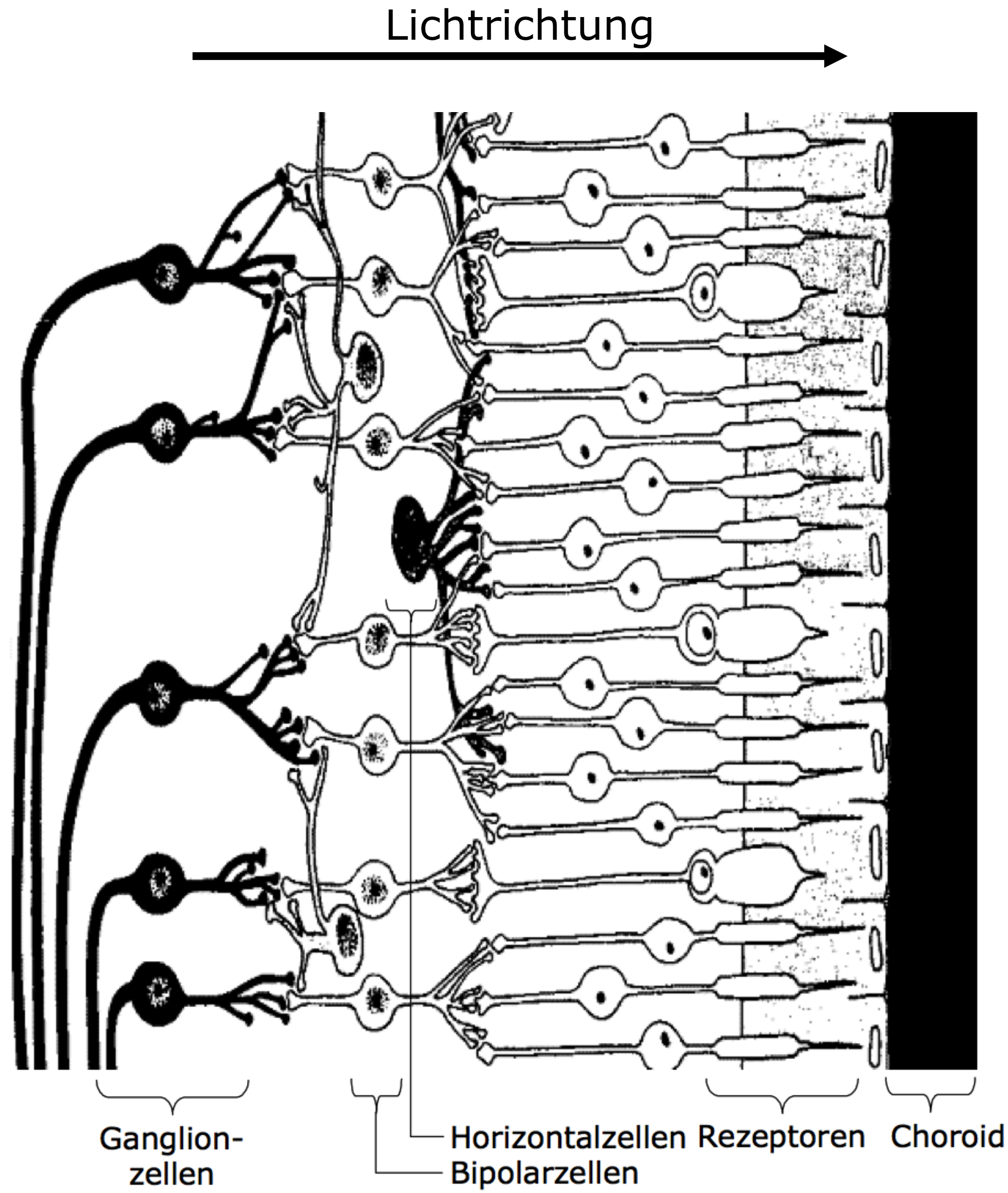
**Ganglion cells** lead about 1 mio. nervs to the blind spot.

**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:



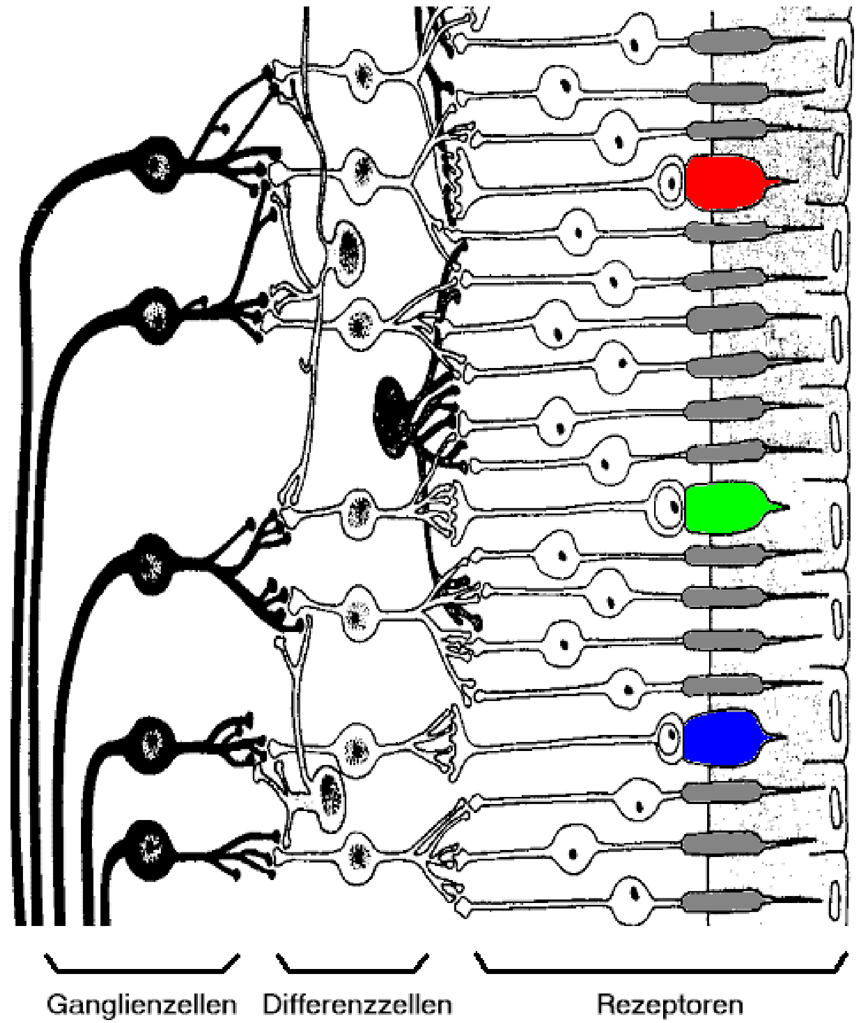
# Basics: Eye: Retina

**Receptors**

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

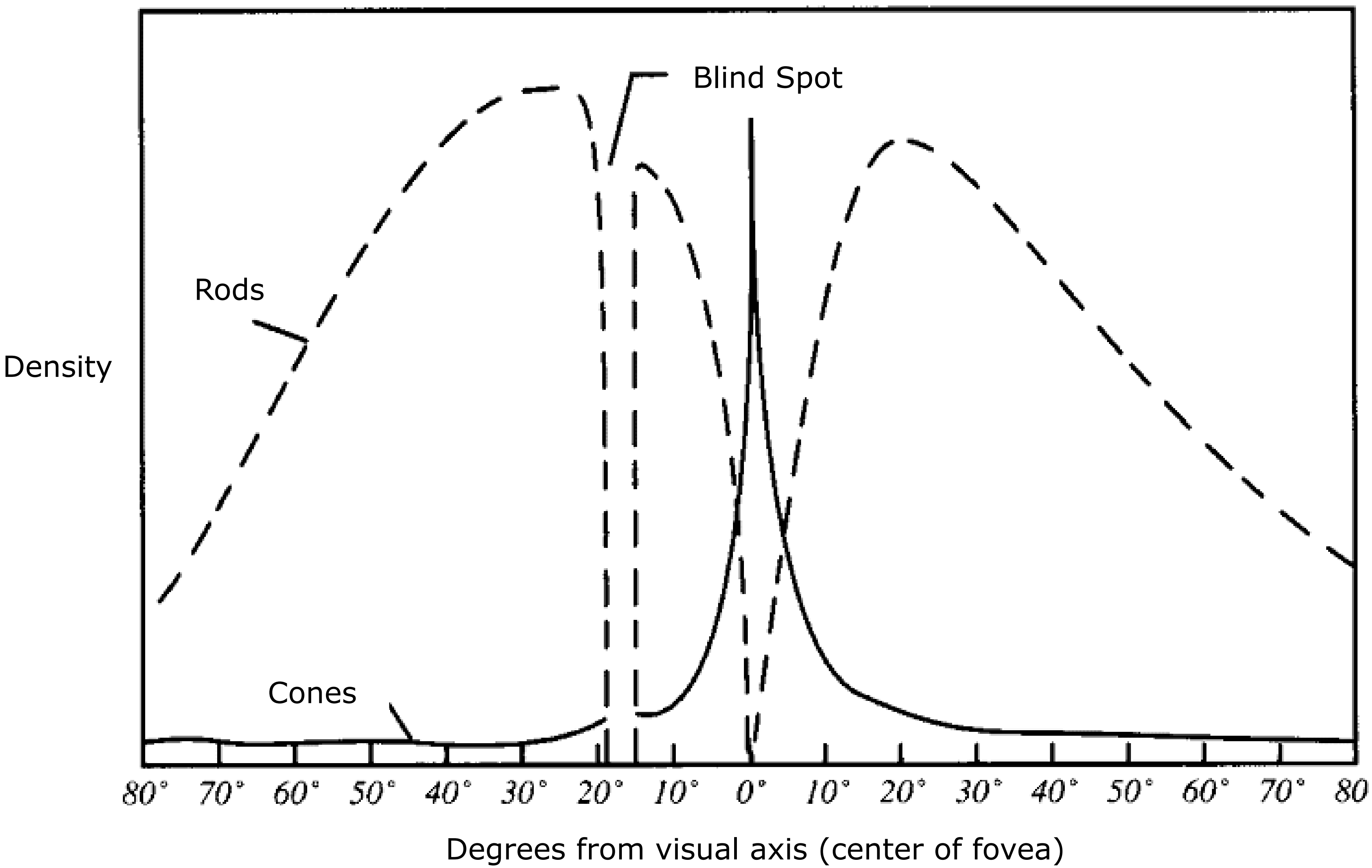
**110-130 mio. rods (Stäbchen, bâtonnets)** are sensitive to the full visible spectrum and therefore important for luminance sensitivity.

**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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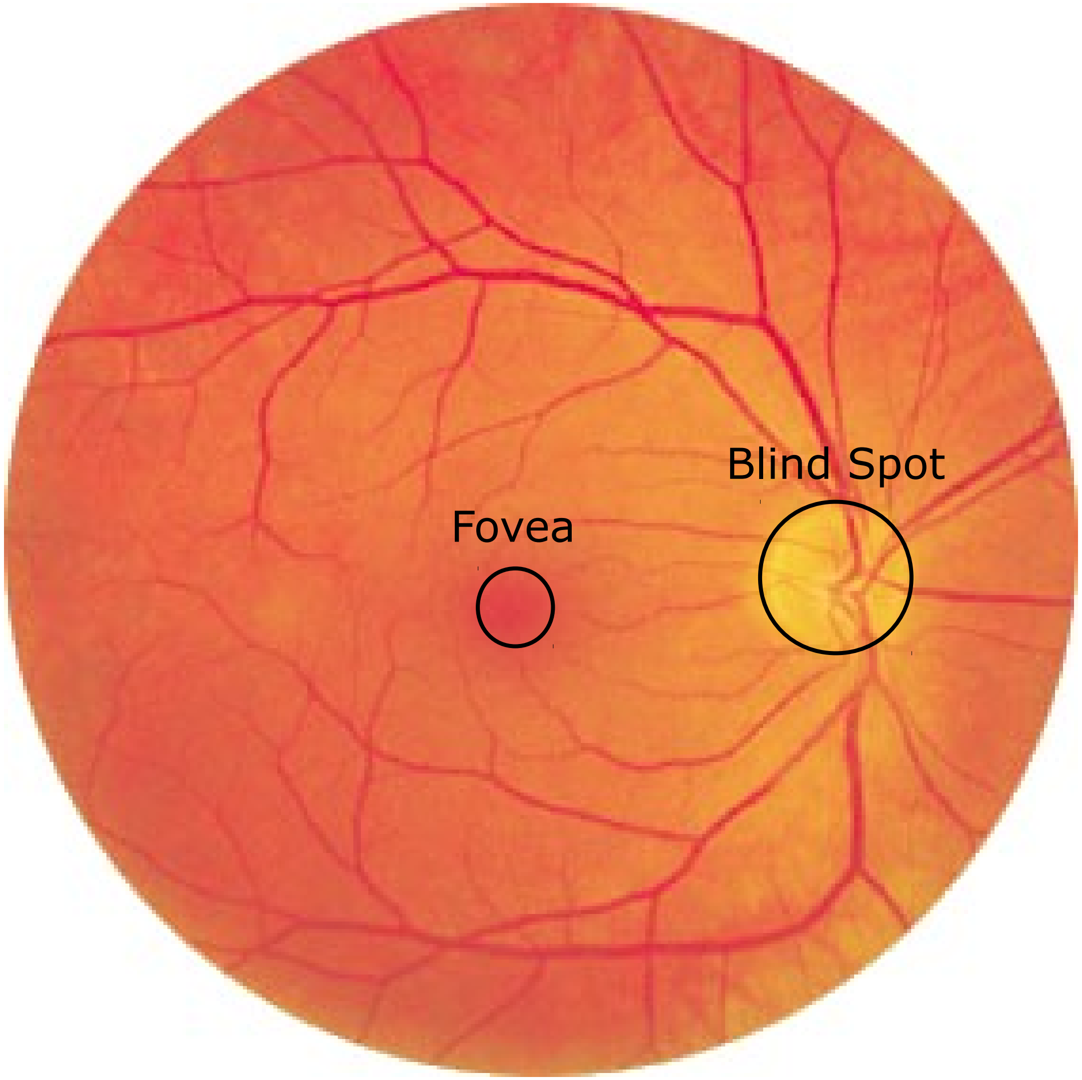


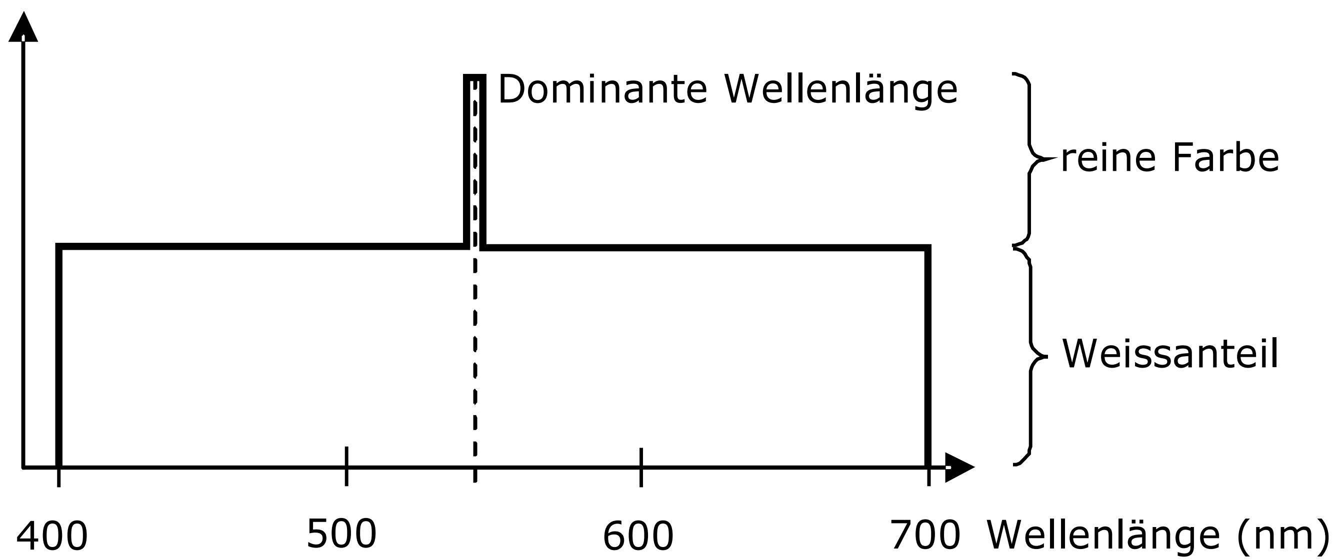
# Basics: Eye: Color Sensitivity

- 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:**

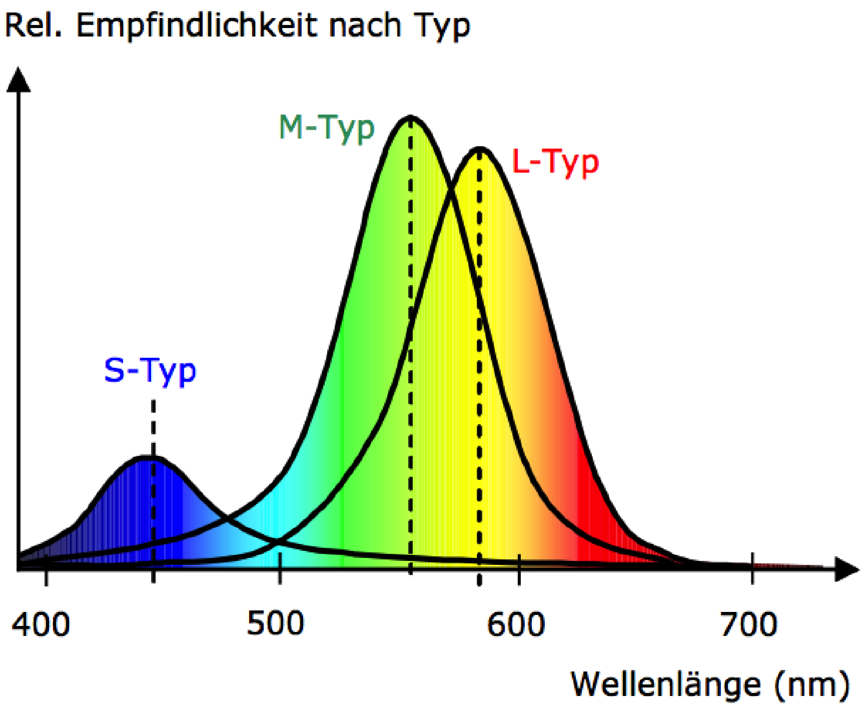
- **Hue (Farbton, teinte)** corresponds to the **dominant wavelength**
- **Luminosity (Helligkeit, luminosité)** corresponds to the **radiance energy**.
- **Saturation (Sättigung, saturation)** corresponds to the **purity of stimulus**.

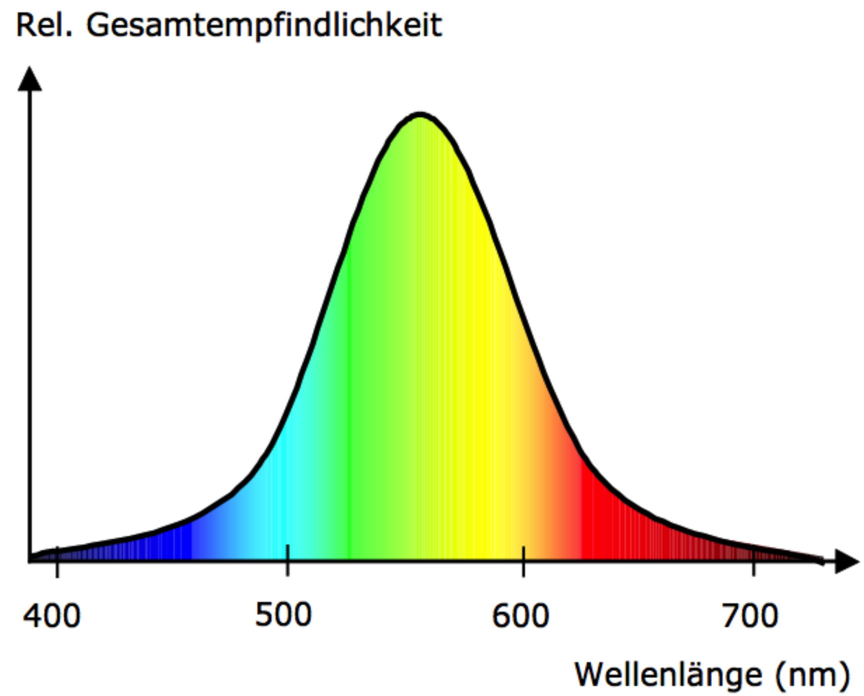


# Basics: Eye: Color Sensitivity

**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*

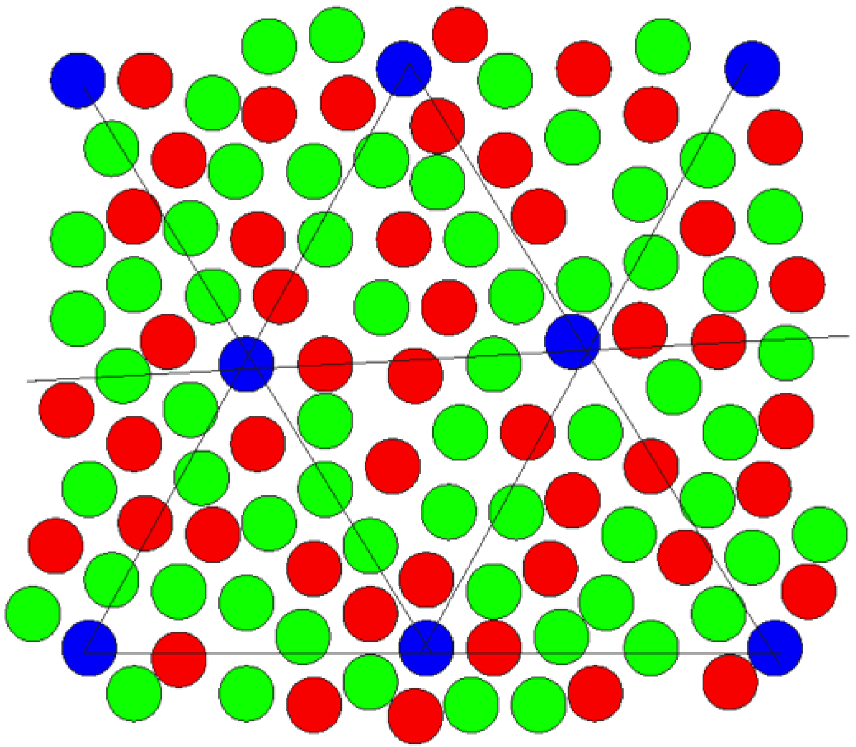


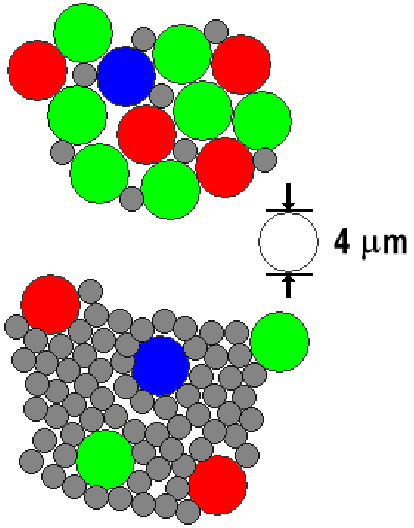
# Basics: Eye: Color Sensitivity

**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:**

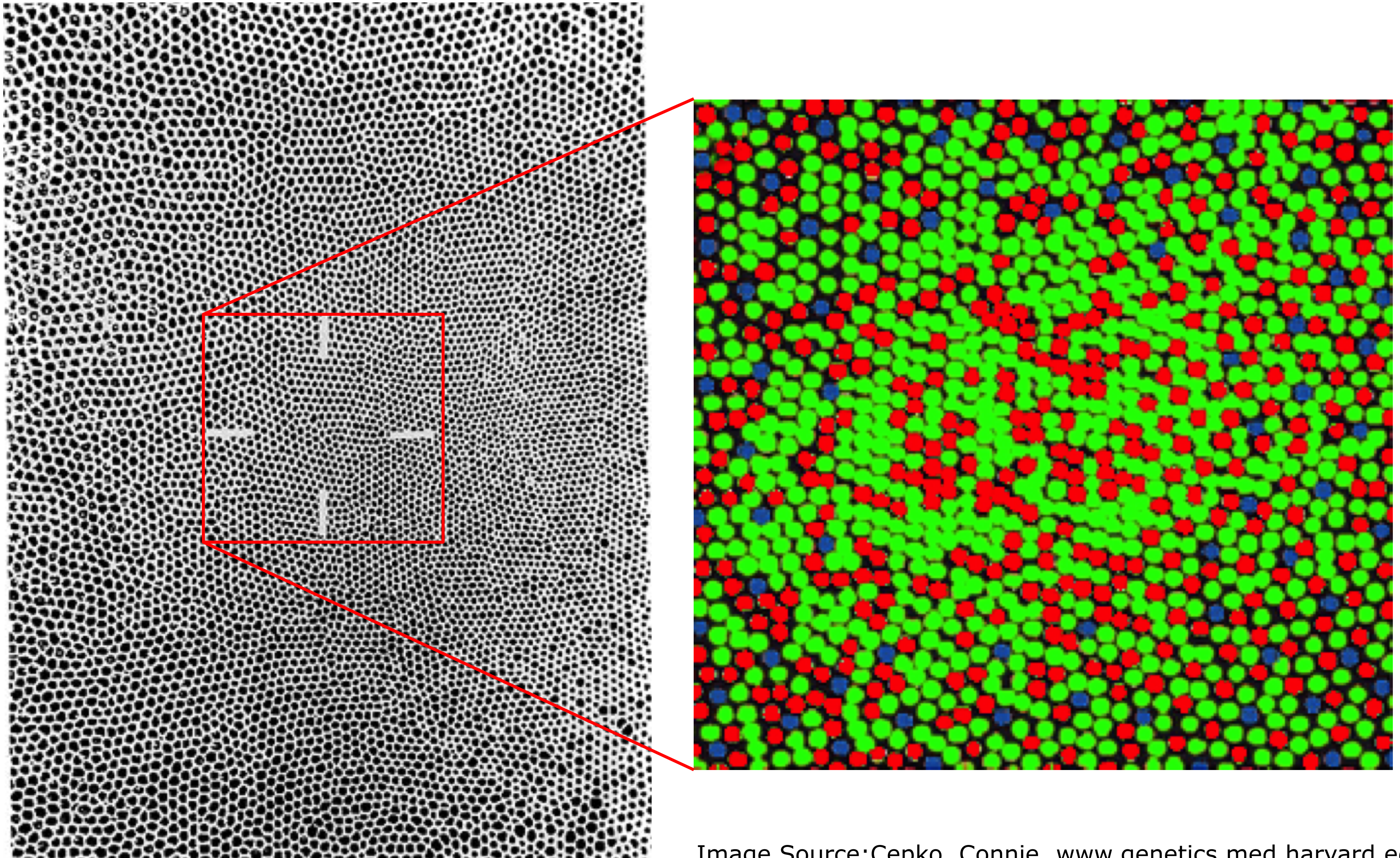
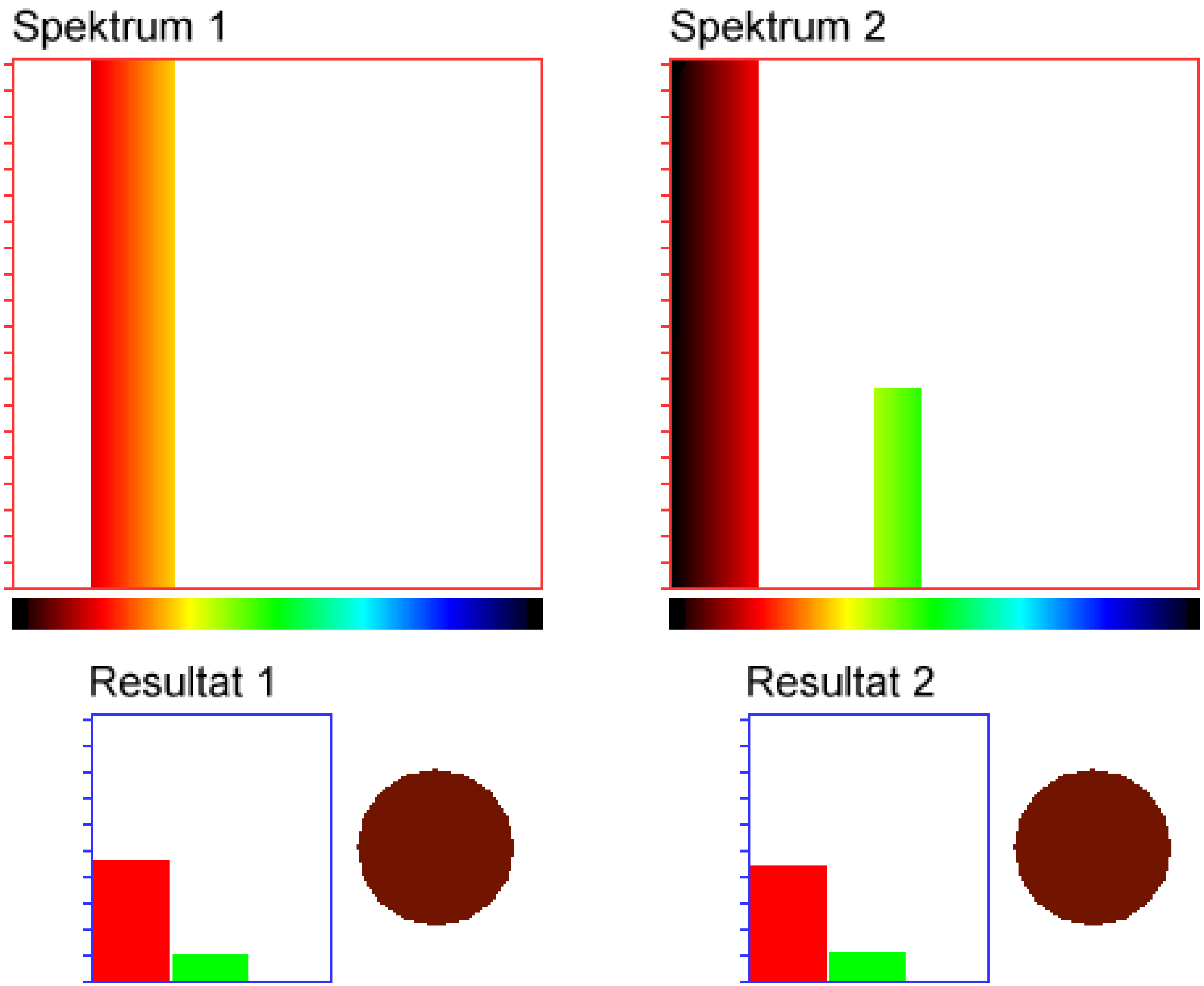


Image Source:Cepko, Connie, www.genetics.med.harvard.edu

# Basics: Eye: Color Sensitivity

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



# Basics: Eye: Color Sensitivity

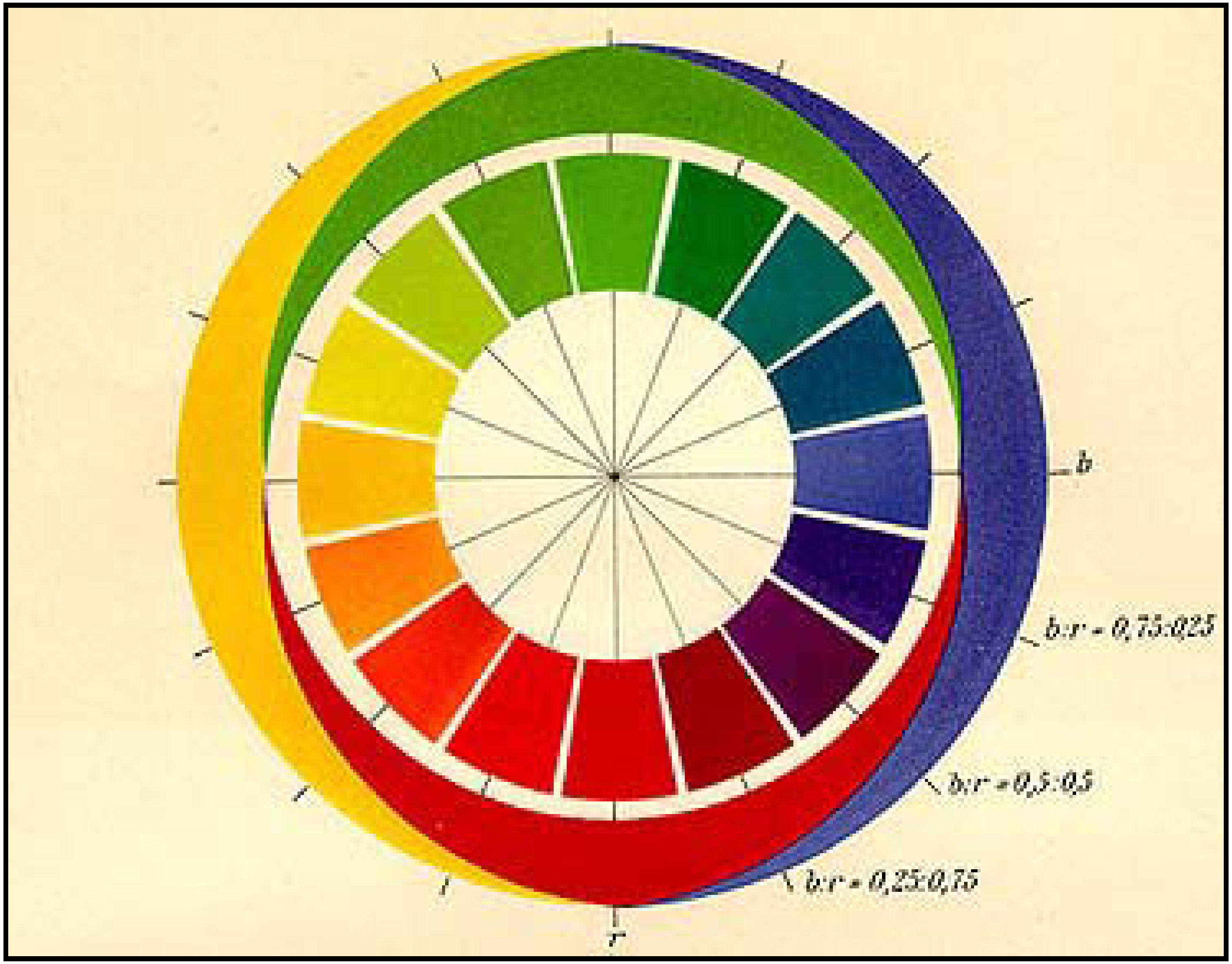
**Opposite Color Theory**

- 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

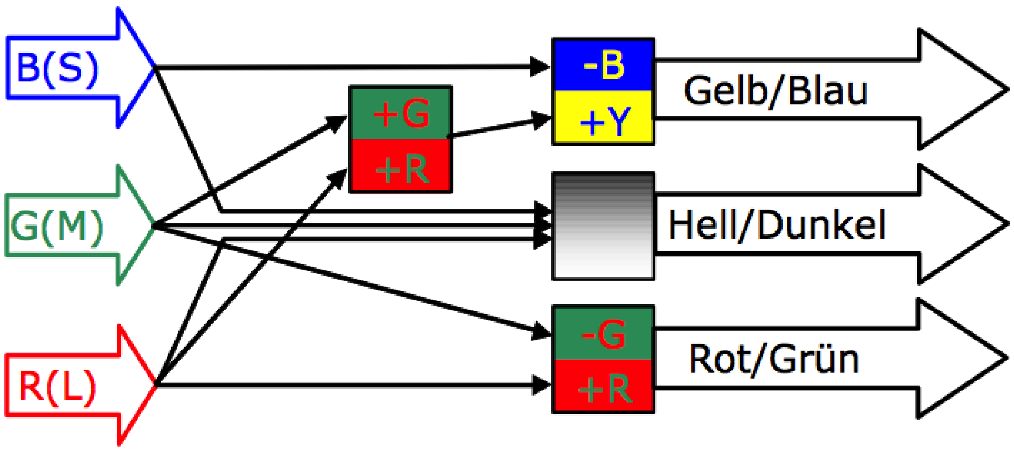
## Opposite Color Theory: Opposite Color Circle

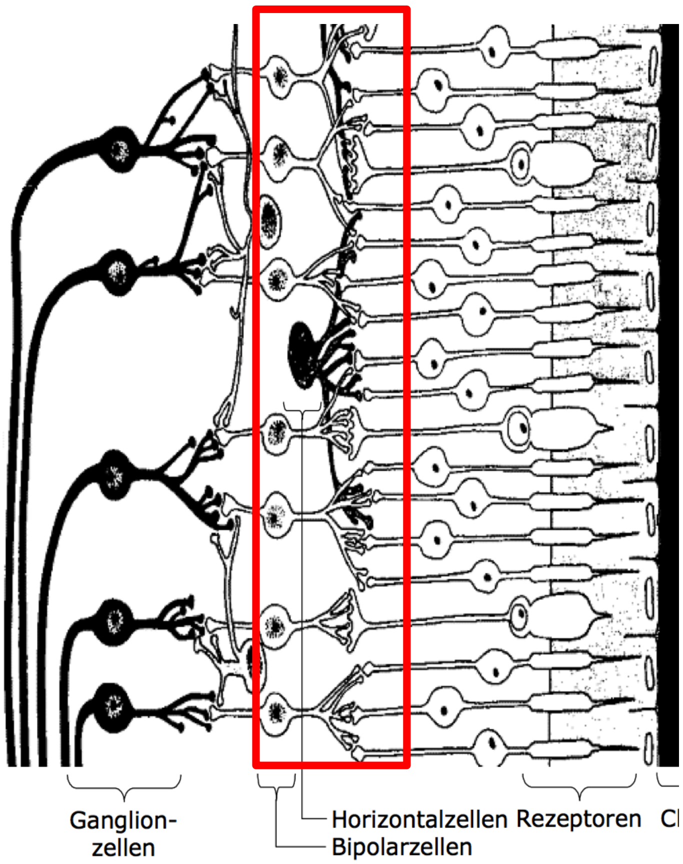


# Basics: Eye: Color Sensitivity

**Opposite Color Theory:**

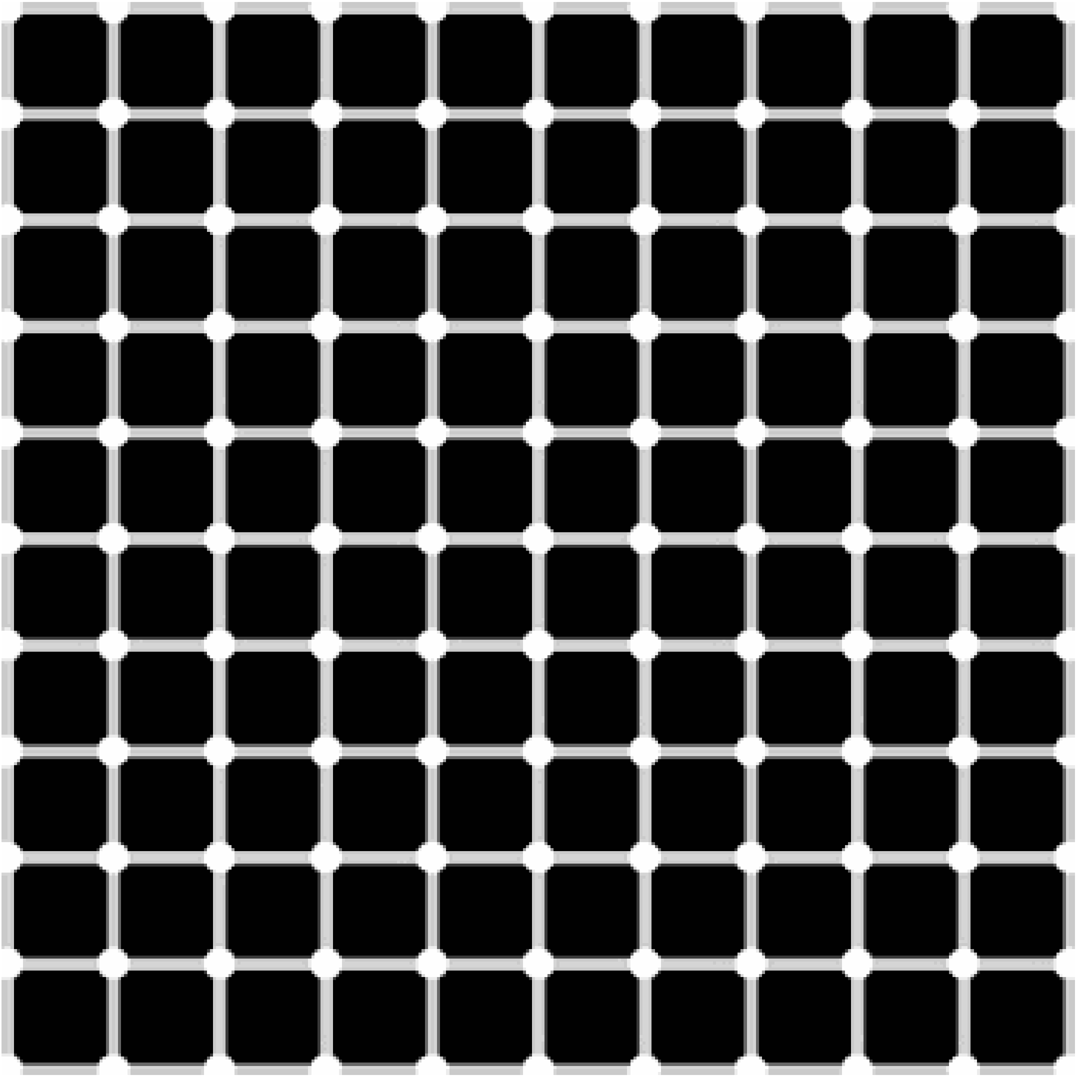
- In the mid 80'ies researchers found that this color encoding happens in the horizontal and bipolar cells of the retina:



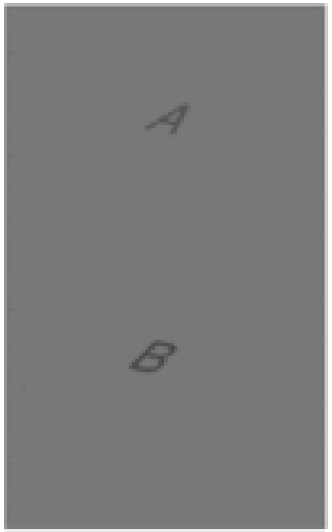
# Basics: Eye: Contrast Sensitivity

The percepted brightness depends on neighbourhood:



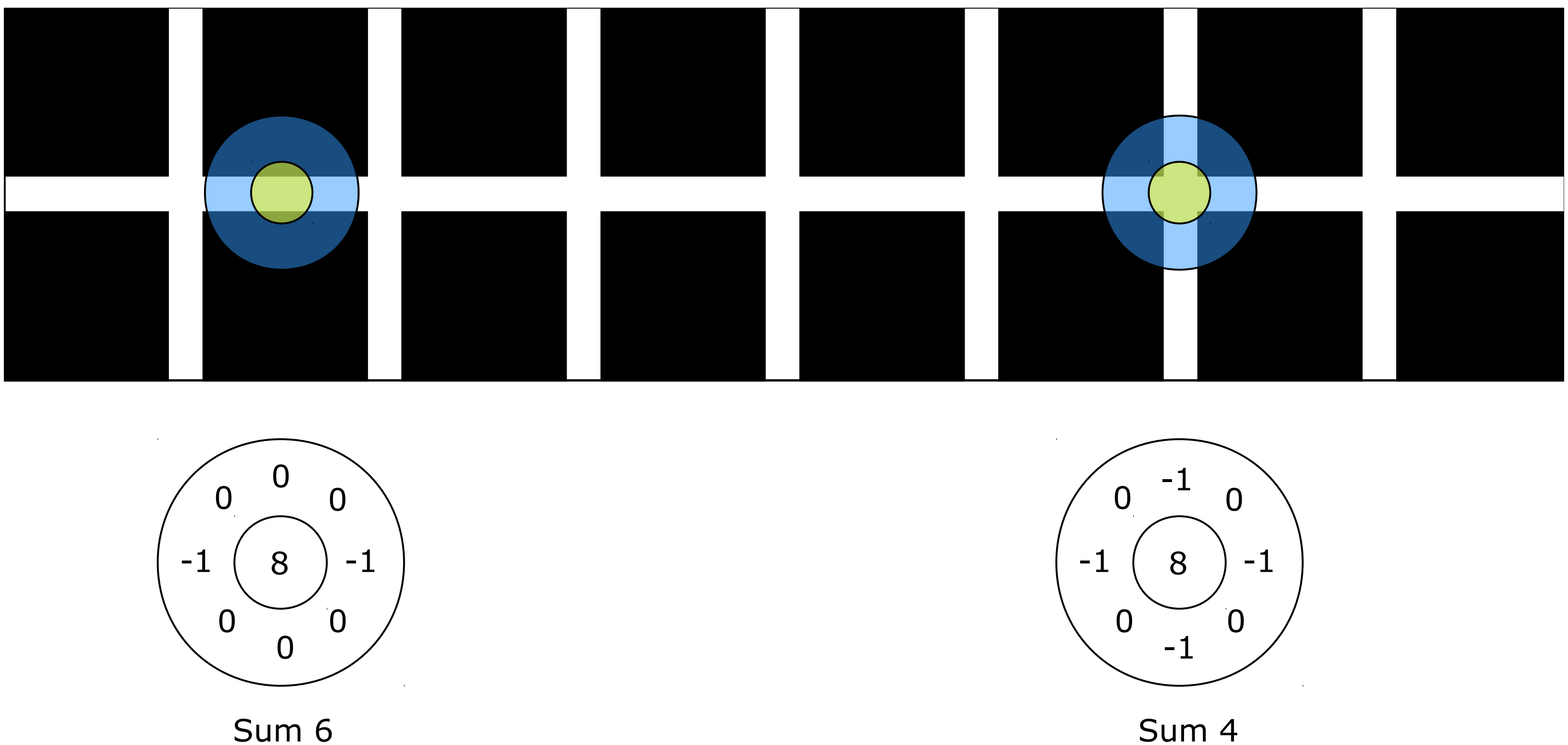
# Basics: Eye: Contrast Sensitivity

The percepted brightness depends on neighbourhood:



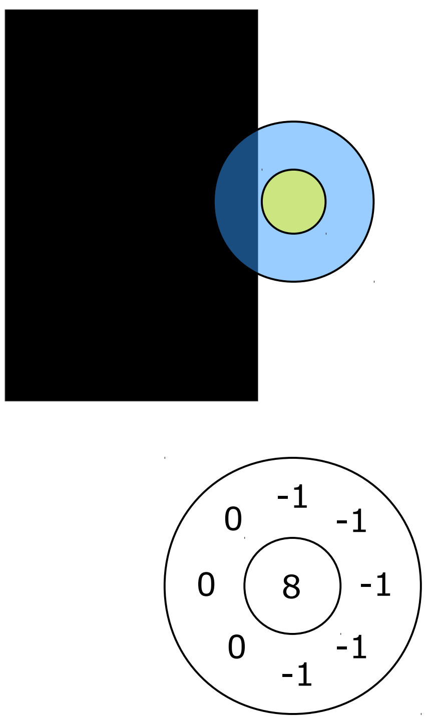
# Basics: Eye: Contrast Sensitivity

- 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

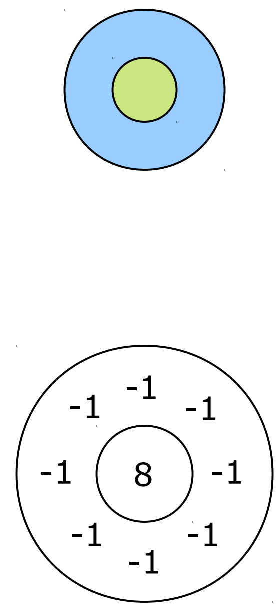


# Basics: Eye: Contrast Sensitivity

- 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

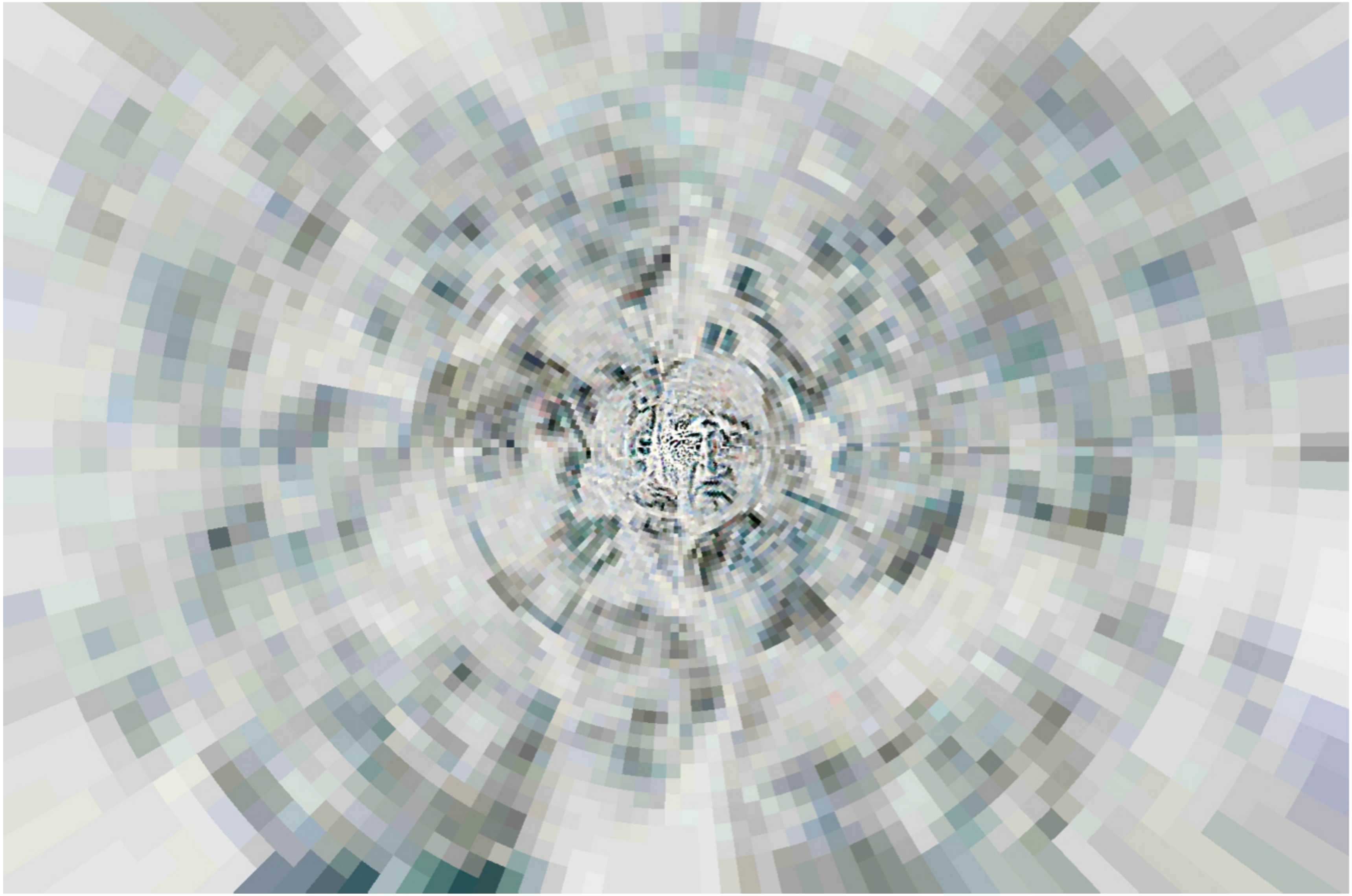
# Basics: Eye: Contrast Sensitivity

- 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

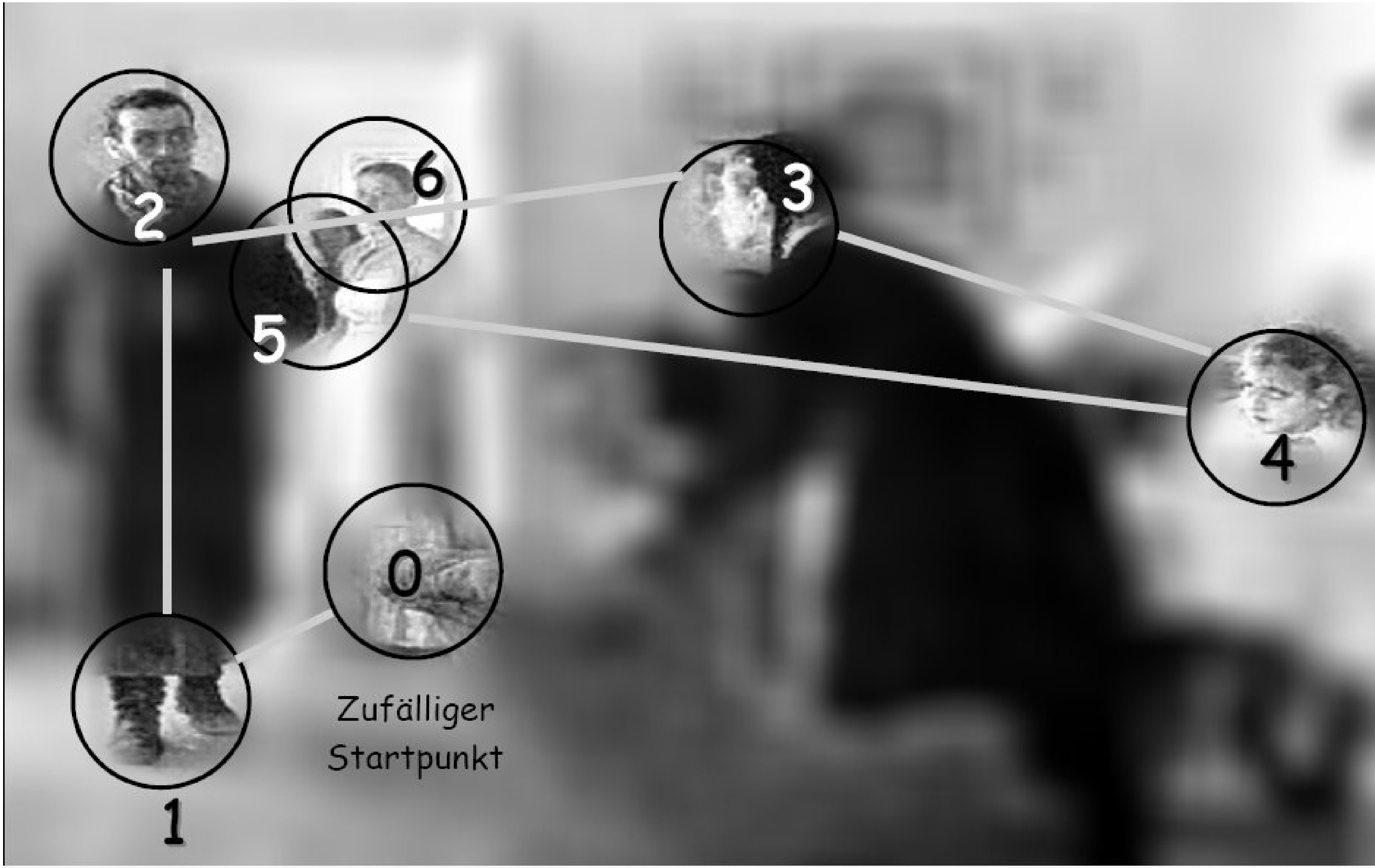
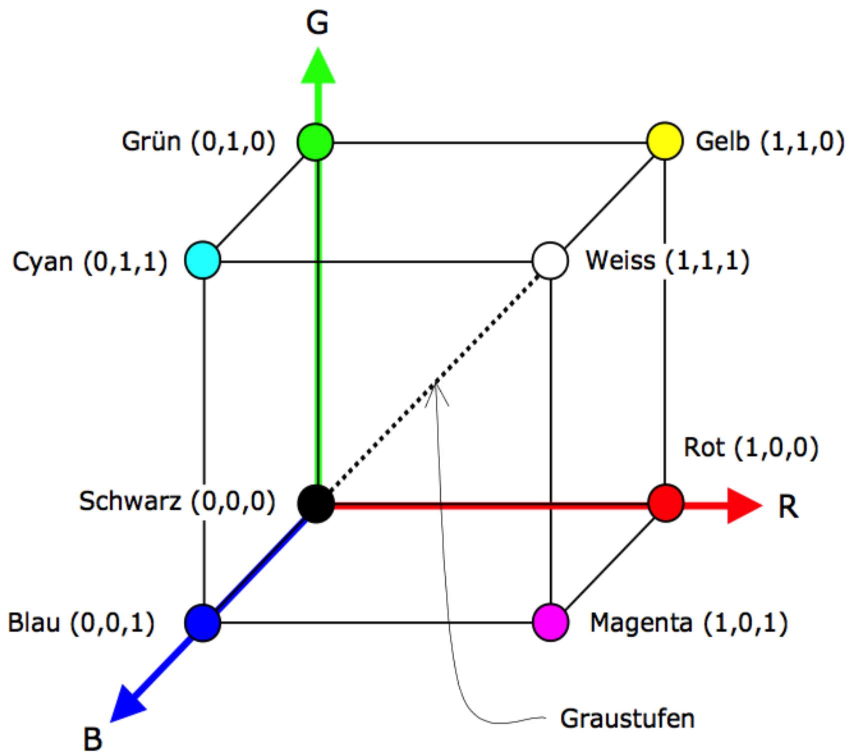


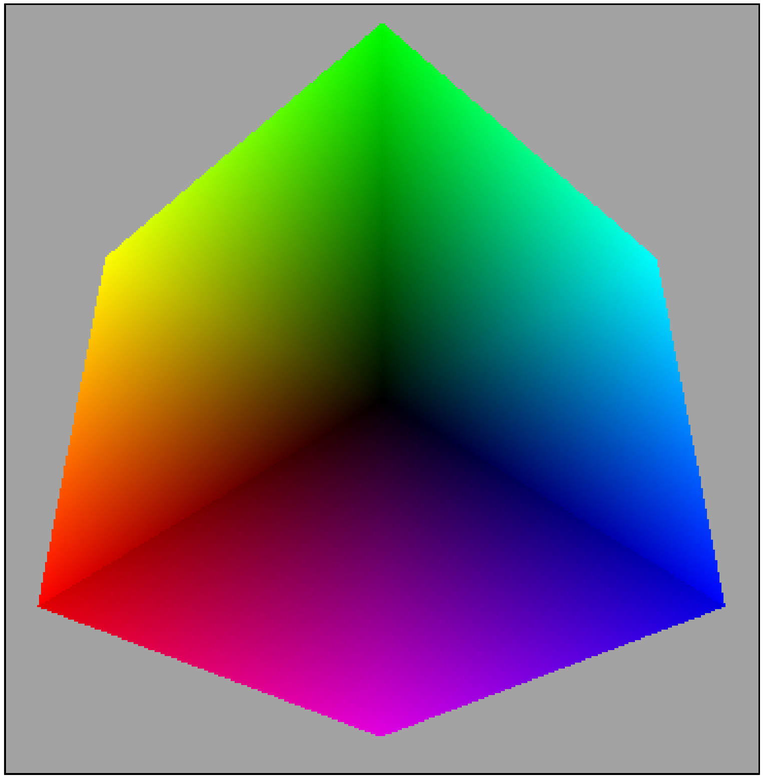

**Bild 11:** Foveale Ergänzung durch die ersten 6 Fixationen (nach Daten von *Yarbus,1967*)

# Color Models

# Basics: Color Models: RGB

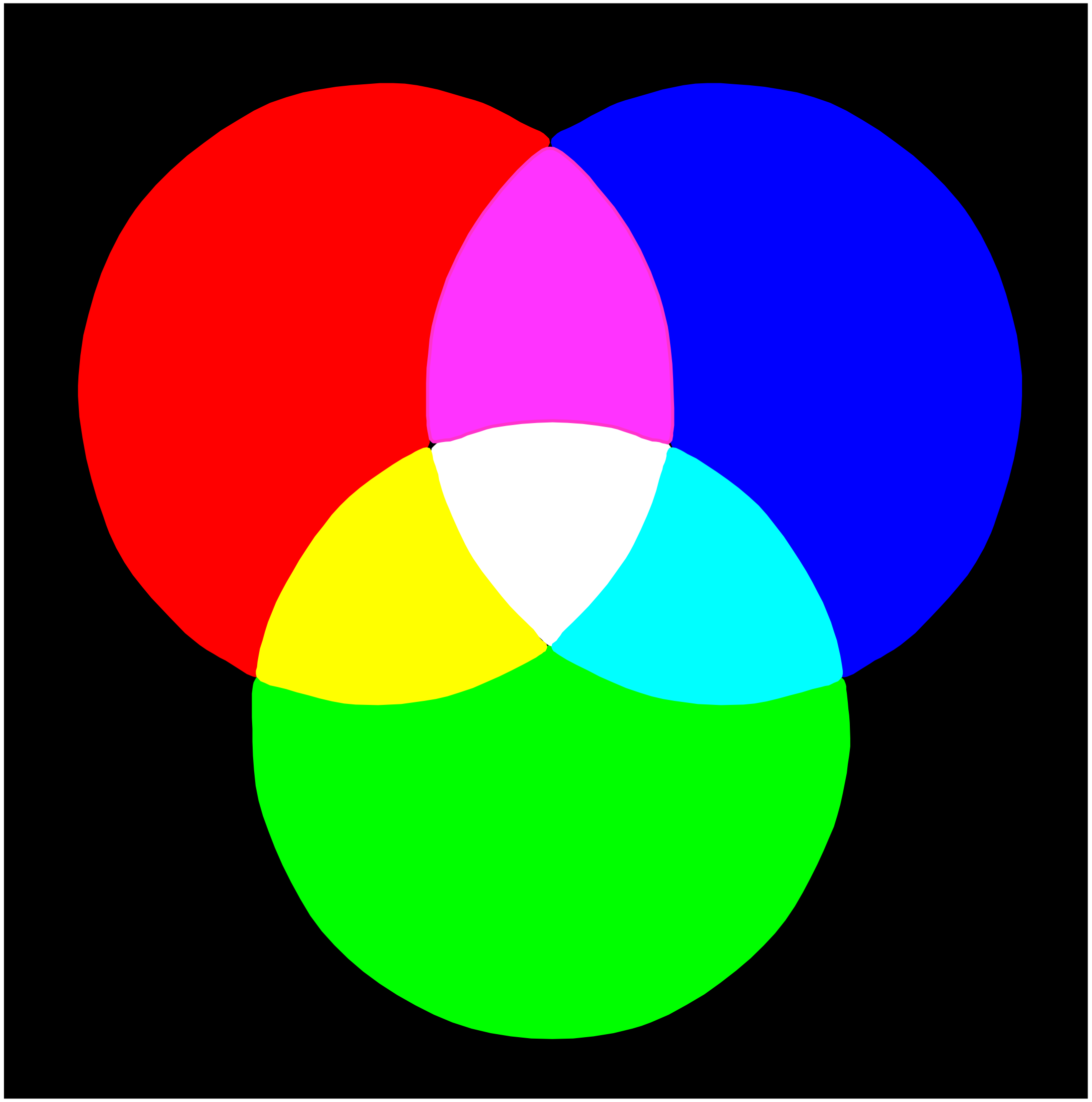
- The RGB color system can be imagined as a 3D coordinate system.
- Every point in the unit cube is a mix of RGB colors
- Colors can be combined with vector algebra.



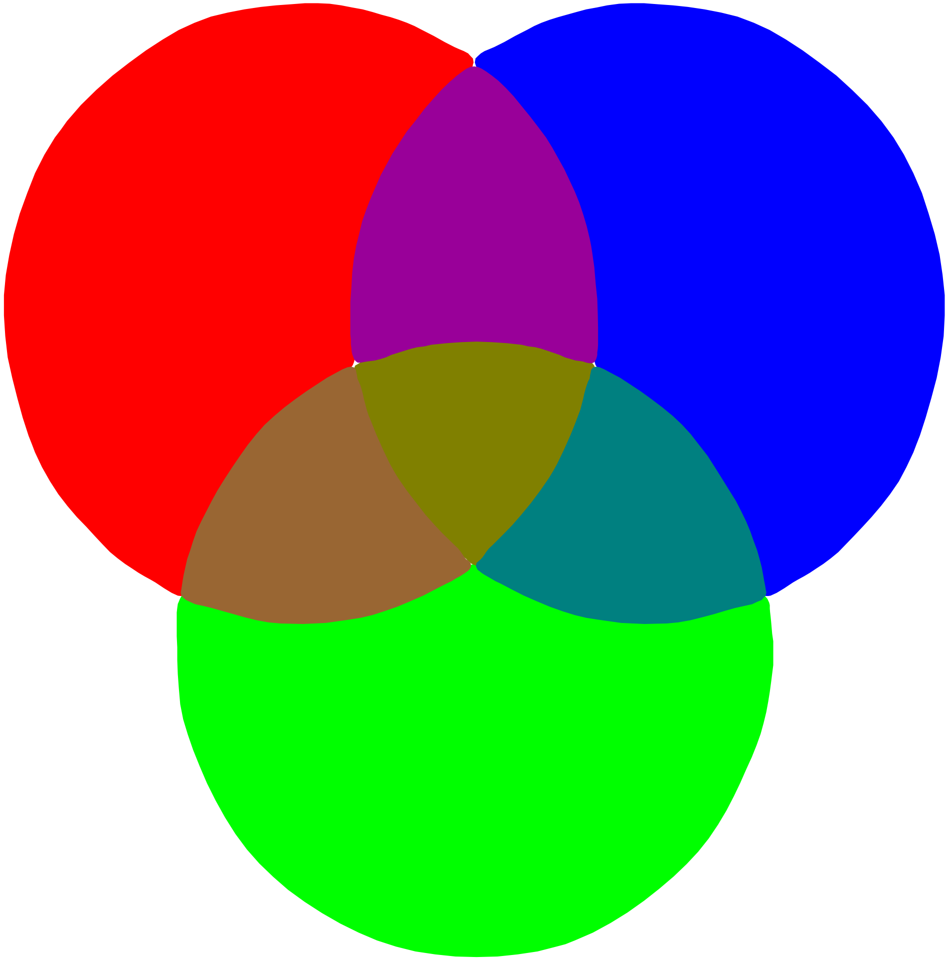
# Basics: Color Models: RGB

- 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:

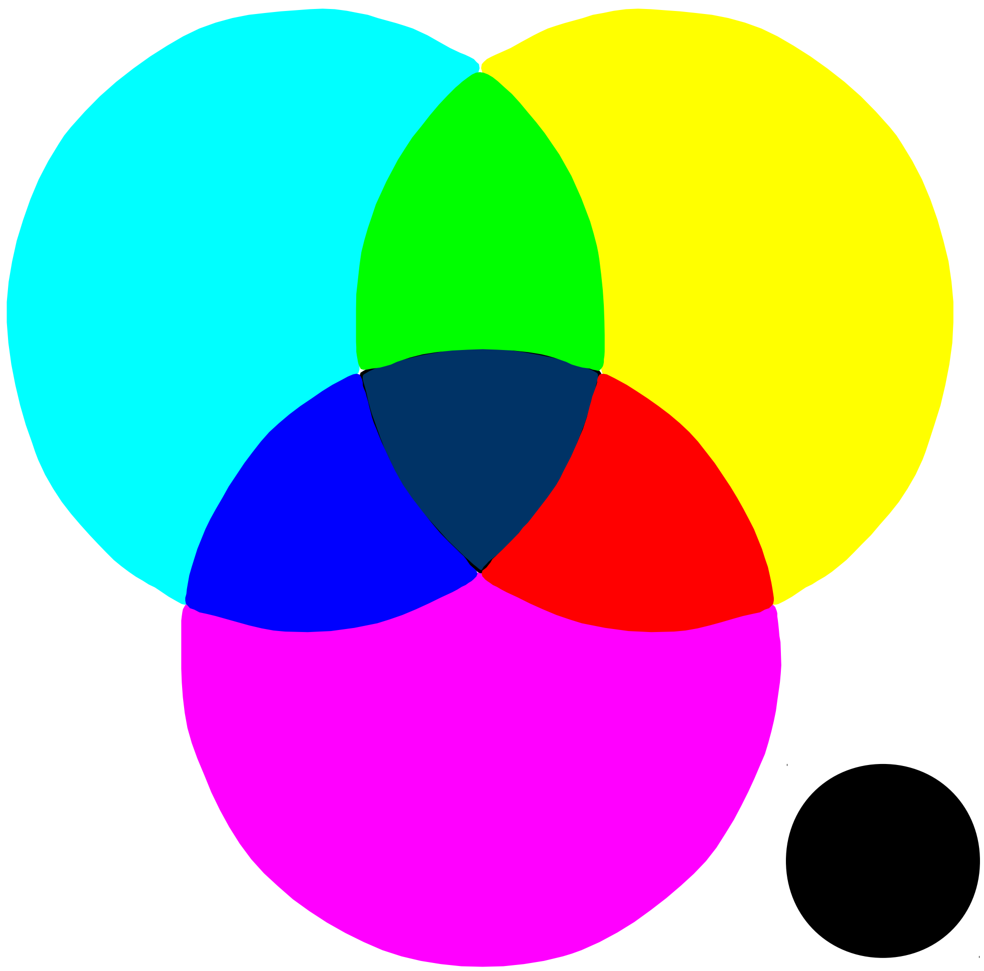
| Print Color | absorbed | reflected |
|---|---|---|
| Cyan | Red | Blue, Green |
| Magenta | Green | Blue, Red |
| Yellow | Blue | Red, Green |
| All | All | nothing |

- 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

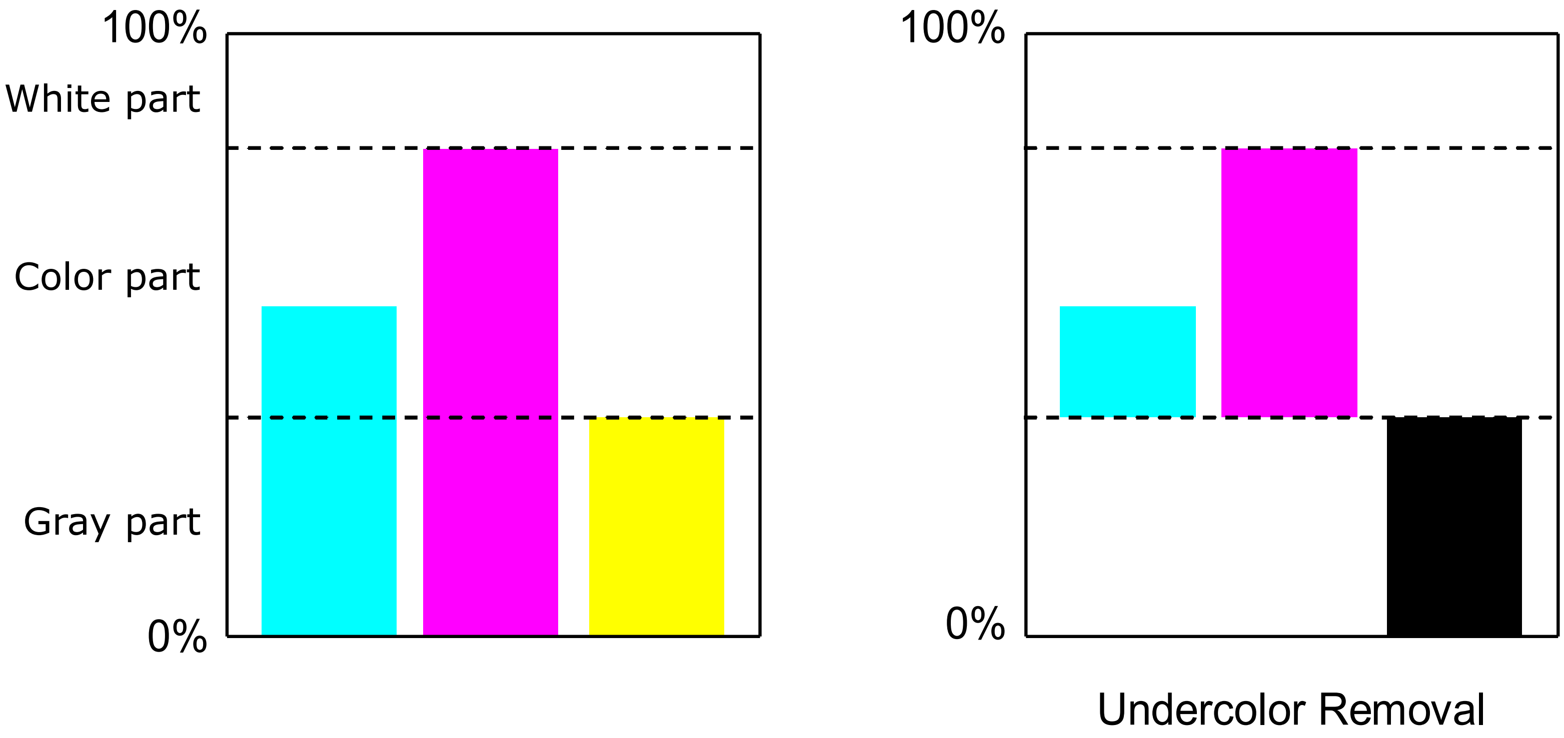


$$\begin{bmatrix} C_K \\ M_K \\ Y_K \\ K \end{bmatrix} = \begin{bmatrix} C \\ M \\ Y \\ 0 \end{bmatrix} + \begin{bmatrix} -\min(C, M, Y) \\ -\min(C, M, Y) \\ -\min(C, M, Y) \\ \min(C, M, Y) \end{bmatrix}$$

# Basics: Color Models: CMYK

**Undercolour Removal**

The fourth color saves color ink:



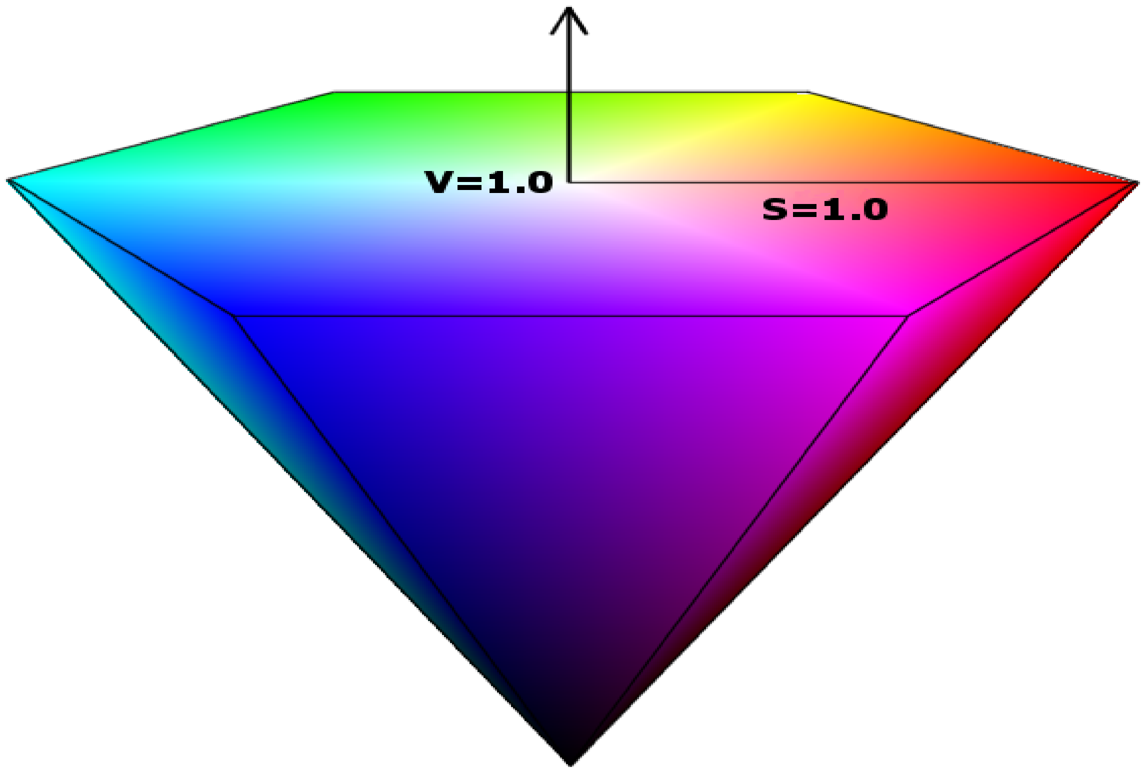
# Basics: Color Models: CMYK

# 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:

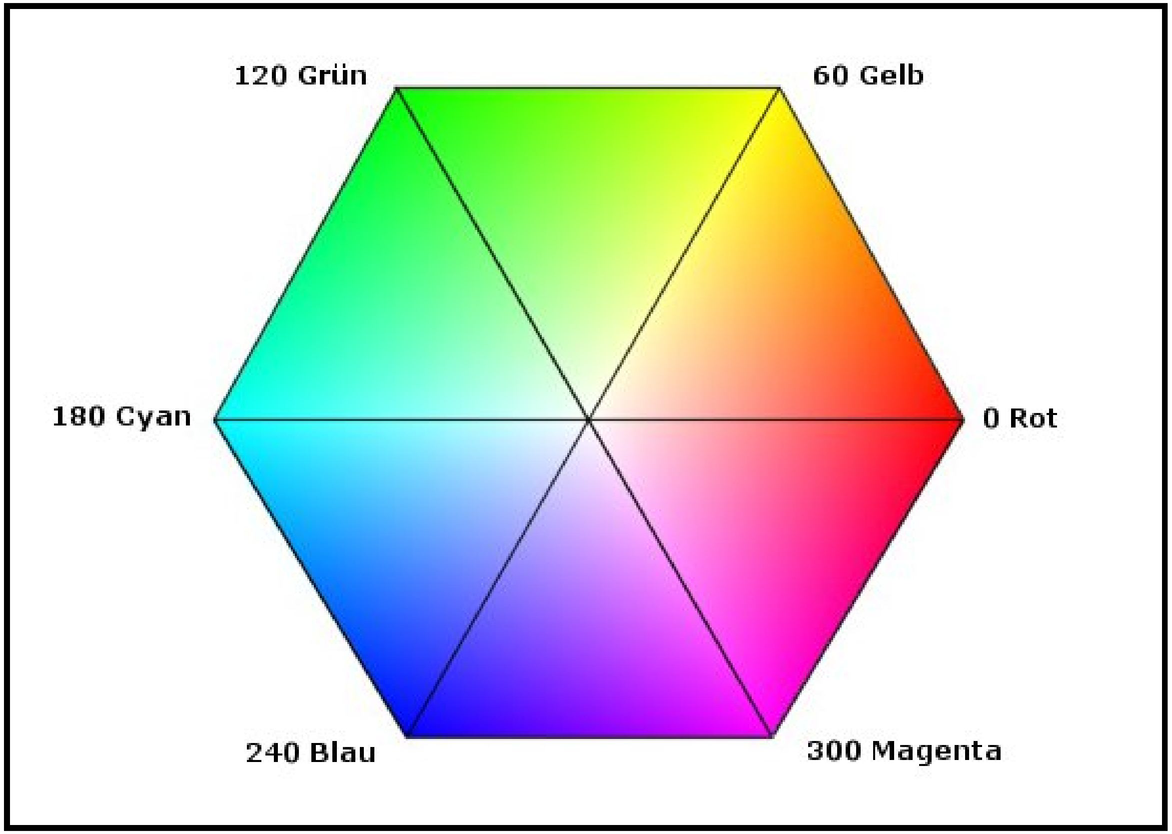
- **Hue**
- **Saturation**
- **Value (Luminosity)**



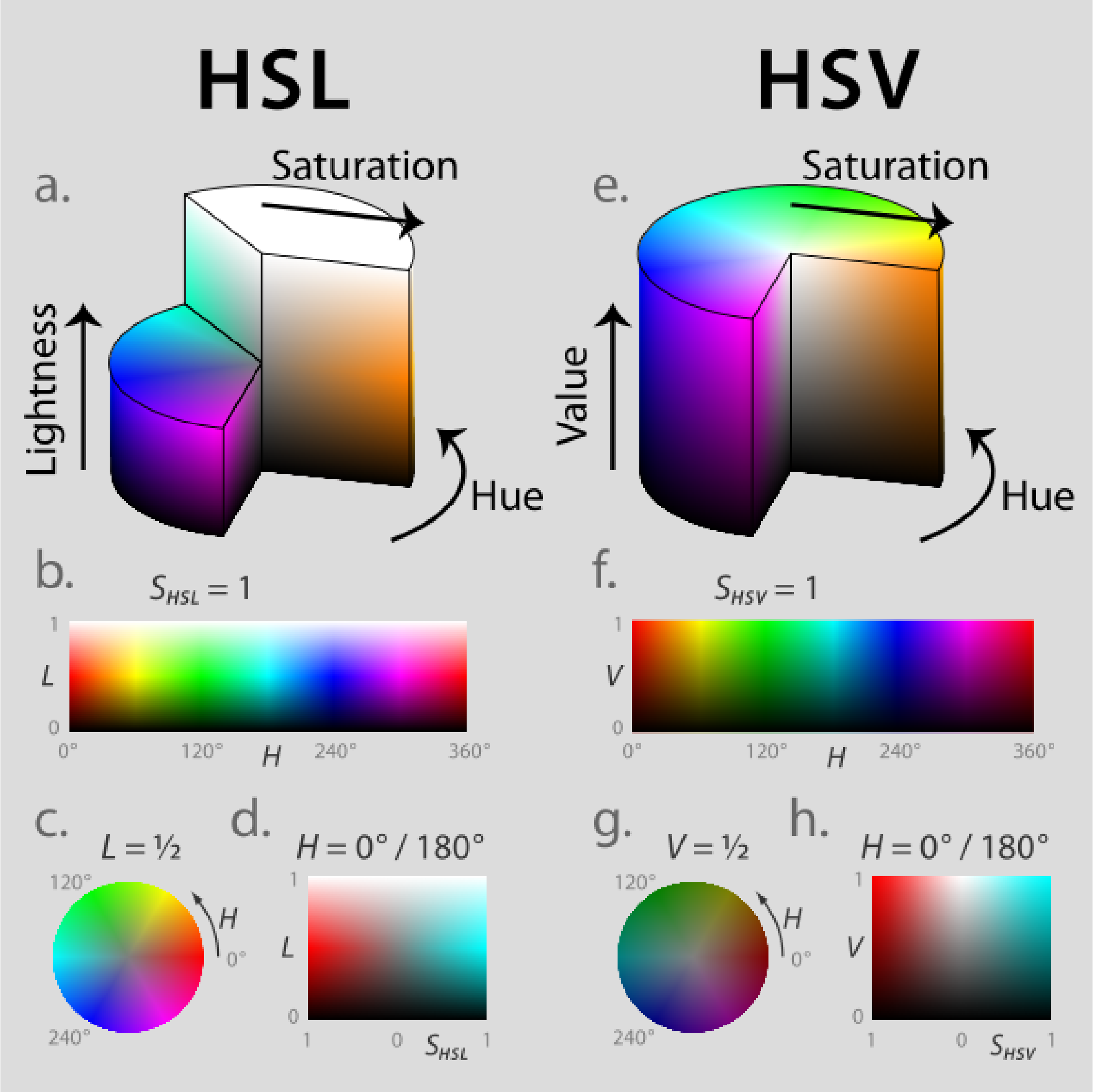
# Basics: Color Models: HSV

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



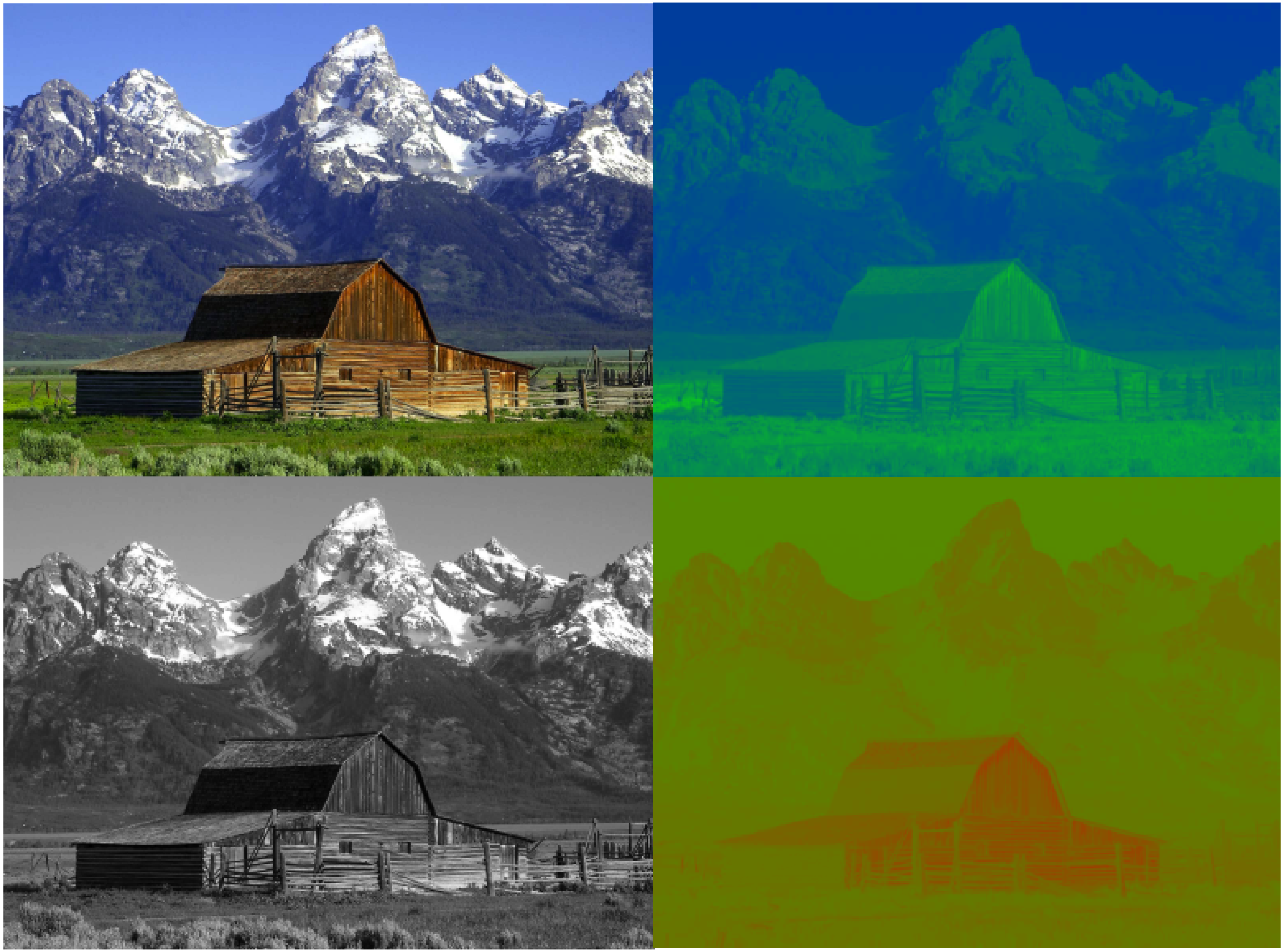
# Basics: Color Models: YUV

- 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.

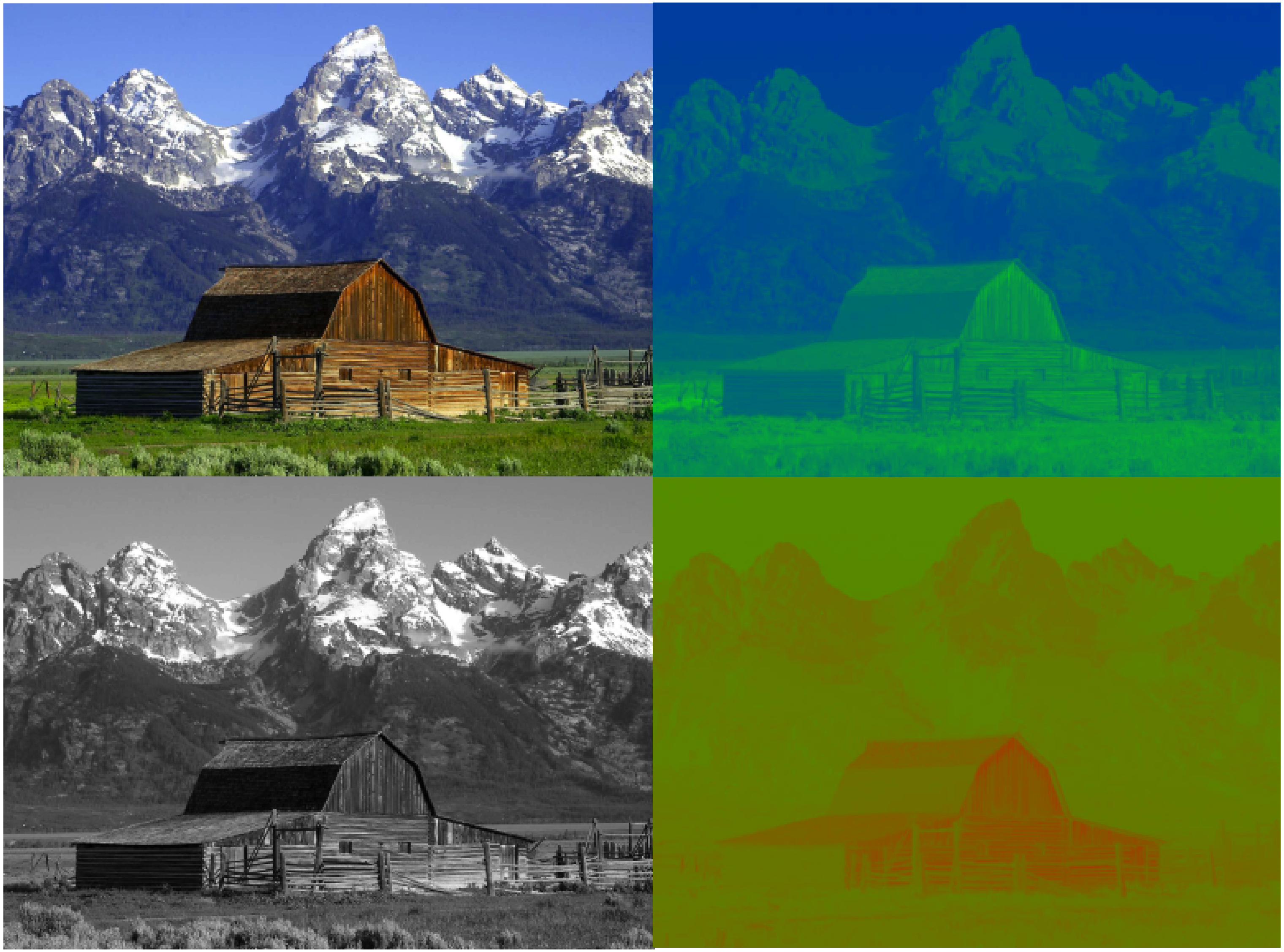
```
Y = round( 0.257*R + 0.504*G + 0.098*B) + 16
U = round(-0.148*R - 0.291*G + 0.439*B) + 128
V = round( 0.439*R - 0.368*G - 0.071*B) + 128
```

```
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

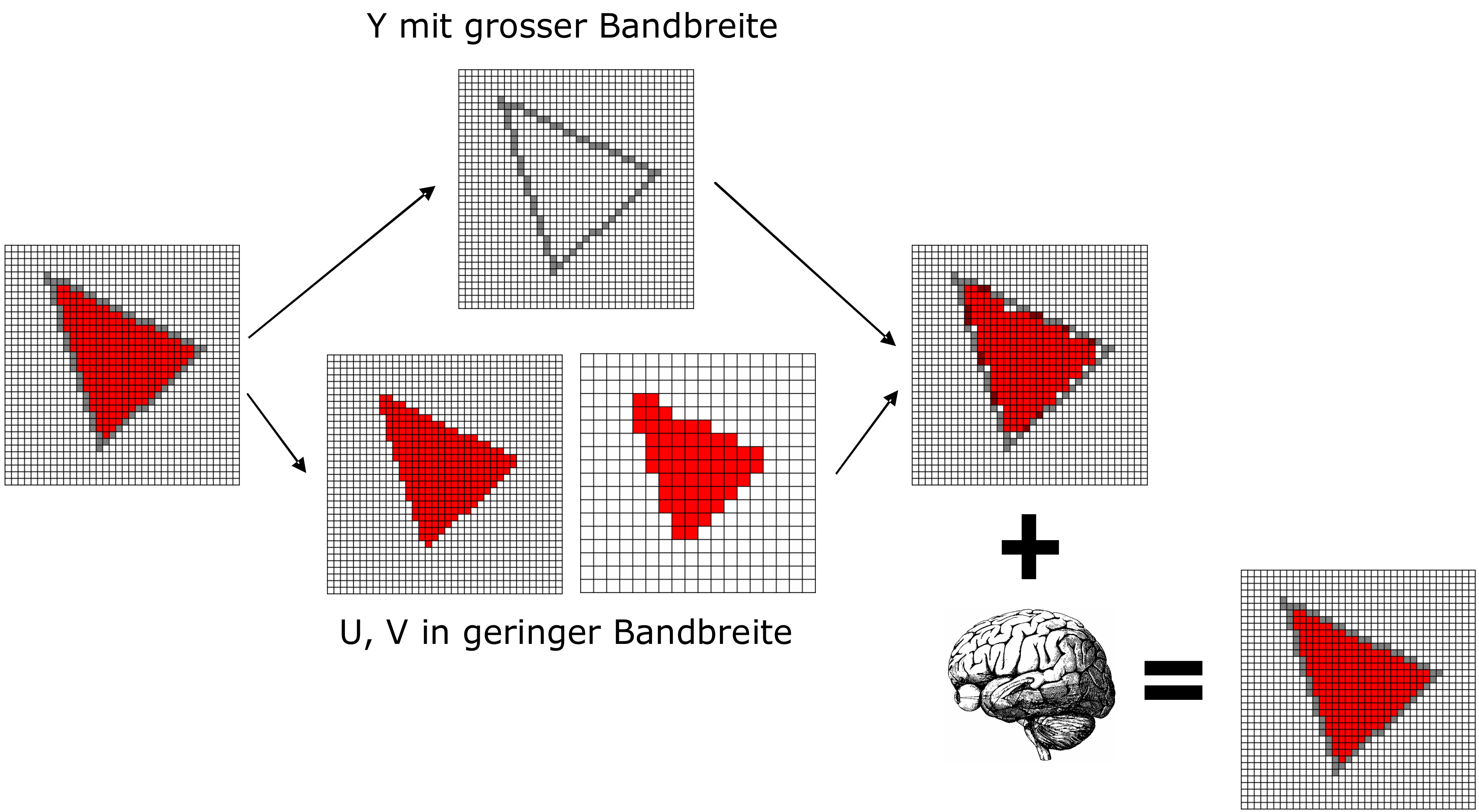


# Basics: Color Models: YUV



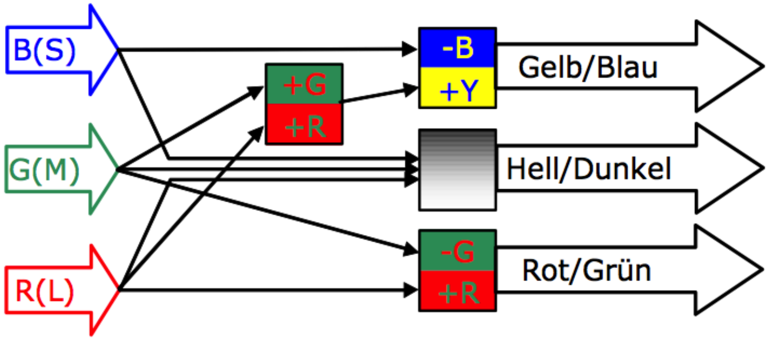
# Basics: Color Models: YUV

- 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:

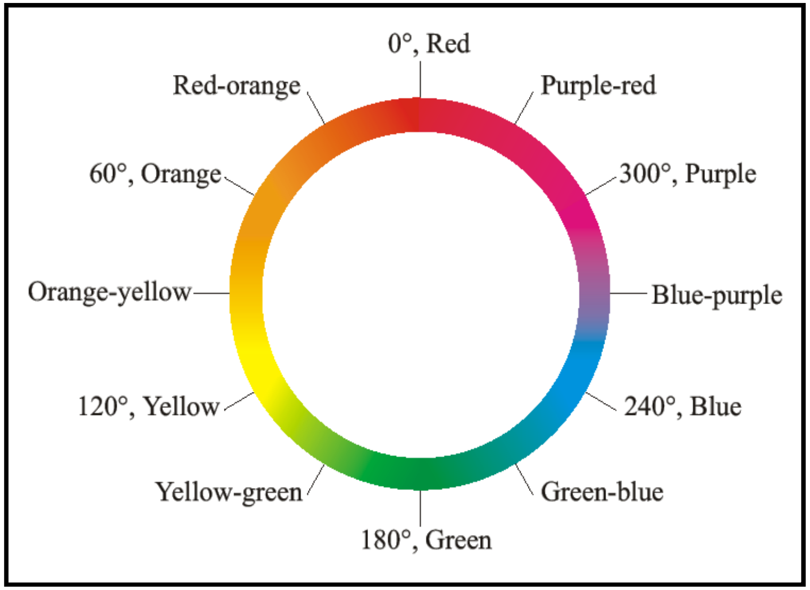
```
Y  = round( 0.299*R + 0.587*G + 0.114*B)
Cb = round(-0.169*R - 0.331*G + 0.500*B) + 128
Cr = round( 0.500*R - 0.419*G - 0.081*B) + 128
```

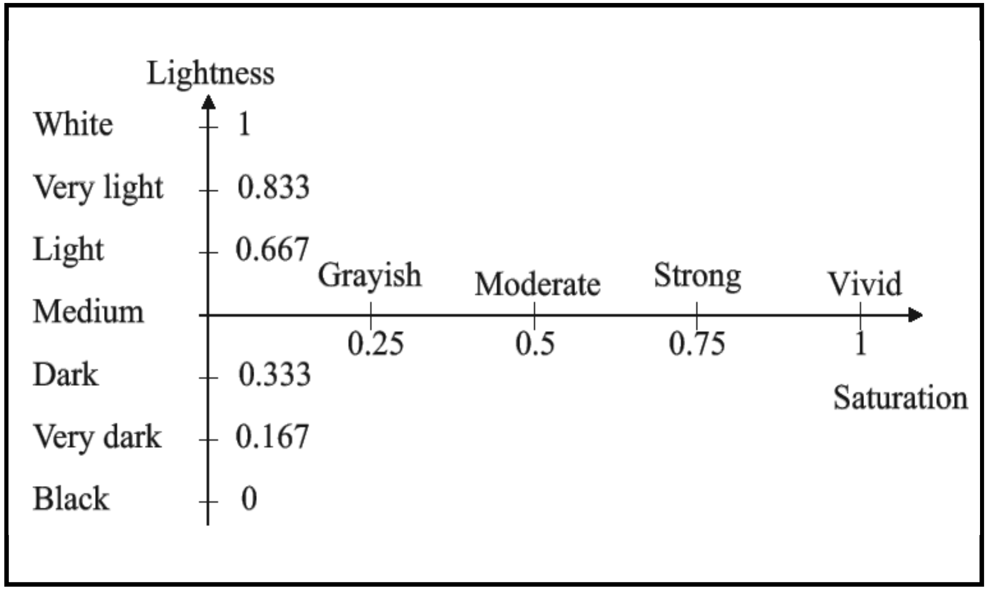
# Basics: Color Models: YCbCr

# 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**

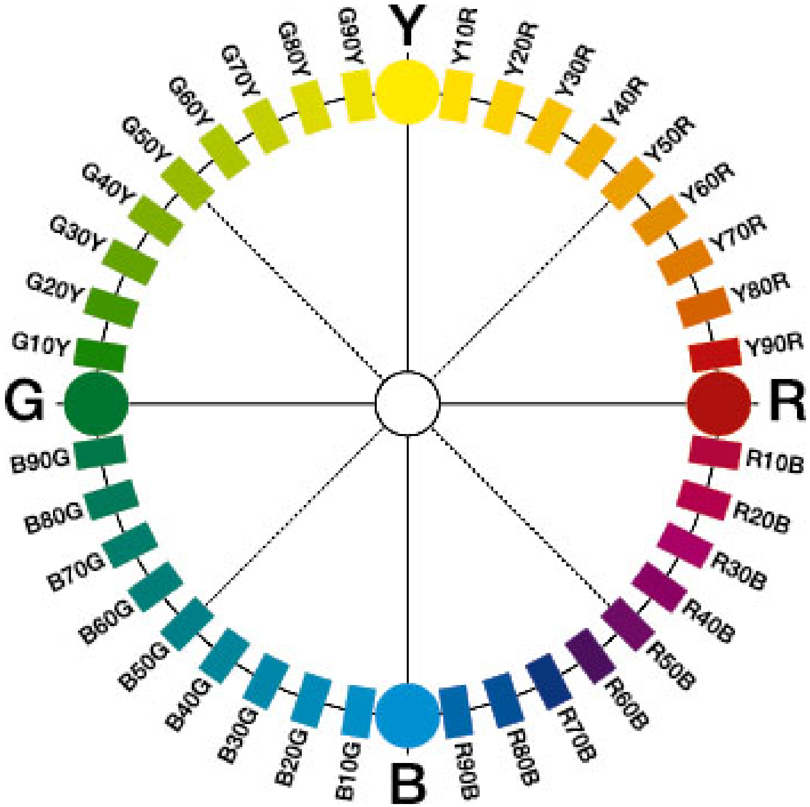


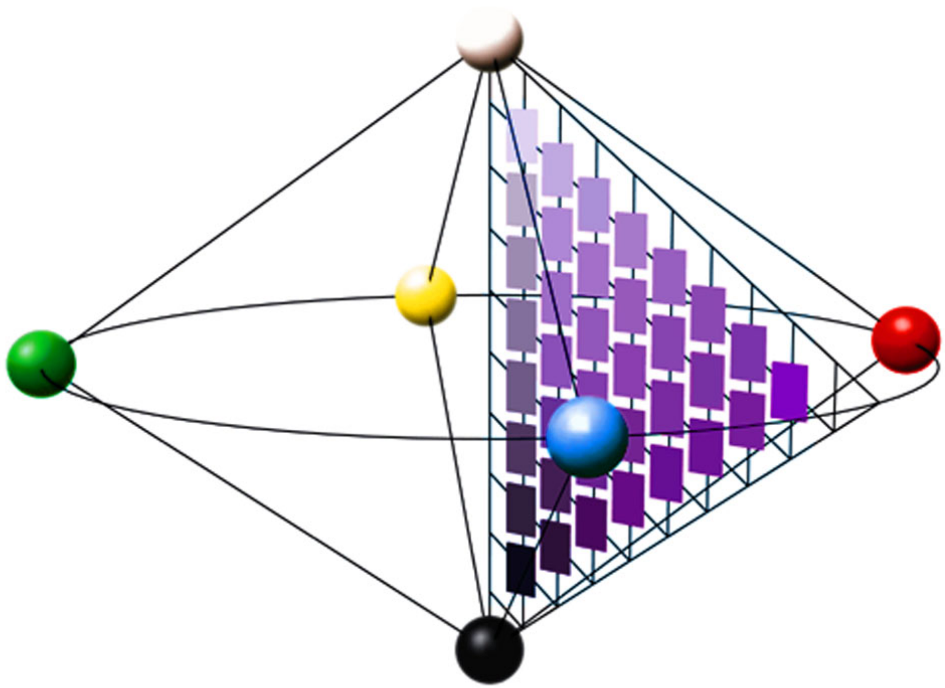



# Basics: Commercial Color Systems: NCS

**NCS: Natural Color System** (Scandinavian Color Institute)

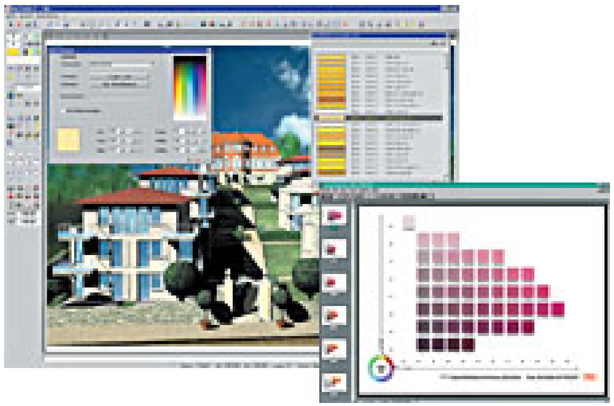
http://www.ncscolour.com/ncs_int.asp



# Basics: Commercial Color Systems: RAL

**RAL: Reichsausschuss für Lieferbedingungen**

# Basics: Tools for Image Processing

We use the tools that are the most appropriate for the task. This can be:

- **Learning Speed**:
  - Easy to use, little to learn: **Image Play**
- **Implementation Speed**:
  - Rapid prototyping for simple to complex tasks: **Matlab**
  - Rapid prototyping with JAVA & **ImageJ** or **Fiji**
- **Runtime Speed**:
  - Highest Performance: **C++ with OpenCV & CUDA**