

MSc in Digital Humanities



Image Processing/Analysis

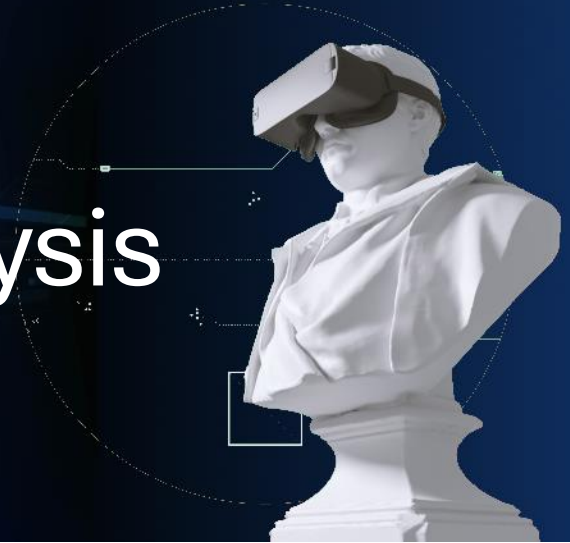


Image digitization process

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Image Processing/Analysis



- Course ID
 - Semester 1
 - 3 hours/week
 - 6 ECTS
 - Modules
 - ▶ **Data Analytics for Humanities (compulsory)**
 - ▶ **3D Technologies (compulsory)**
 - ▶ Augmented Textual Studies
 - ▶ **Geographic Information Systems (elective)**

Image Processing/Analysis



- Course description
 - Image digitization
 - Digital image capture devices
 - Image transformations
 - Image registration
 - Image segmentation
 - Image enhancement
 - Image coding, compression and transmission techniques
 - Image analysis, feature extraction, image categorization
 - Image restoration
 - Applications of image processing and analysis in the humanities
 - Optical Character Recognition in printed and handwritten texts, object recognition through image analysis, image reconstruction of objects

Image Processing/Analysis



- Course instructors



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Laboratory Teaching Staff, NKUA



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Dr. Computer Engineering and Informatics
Assistant Professor, NKUA



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Dr. Electrical Engineer
Research Director, Athena RC

Introduction

What's an image?



What's an “image”



- There is no objective image in the Universe
- Image formation is a cognitive function in biological systems
- Image perception
 - Requires
 - A source
 - A detection system
 - A processing system
 - A content analysis and understanding system

A basic model

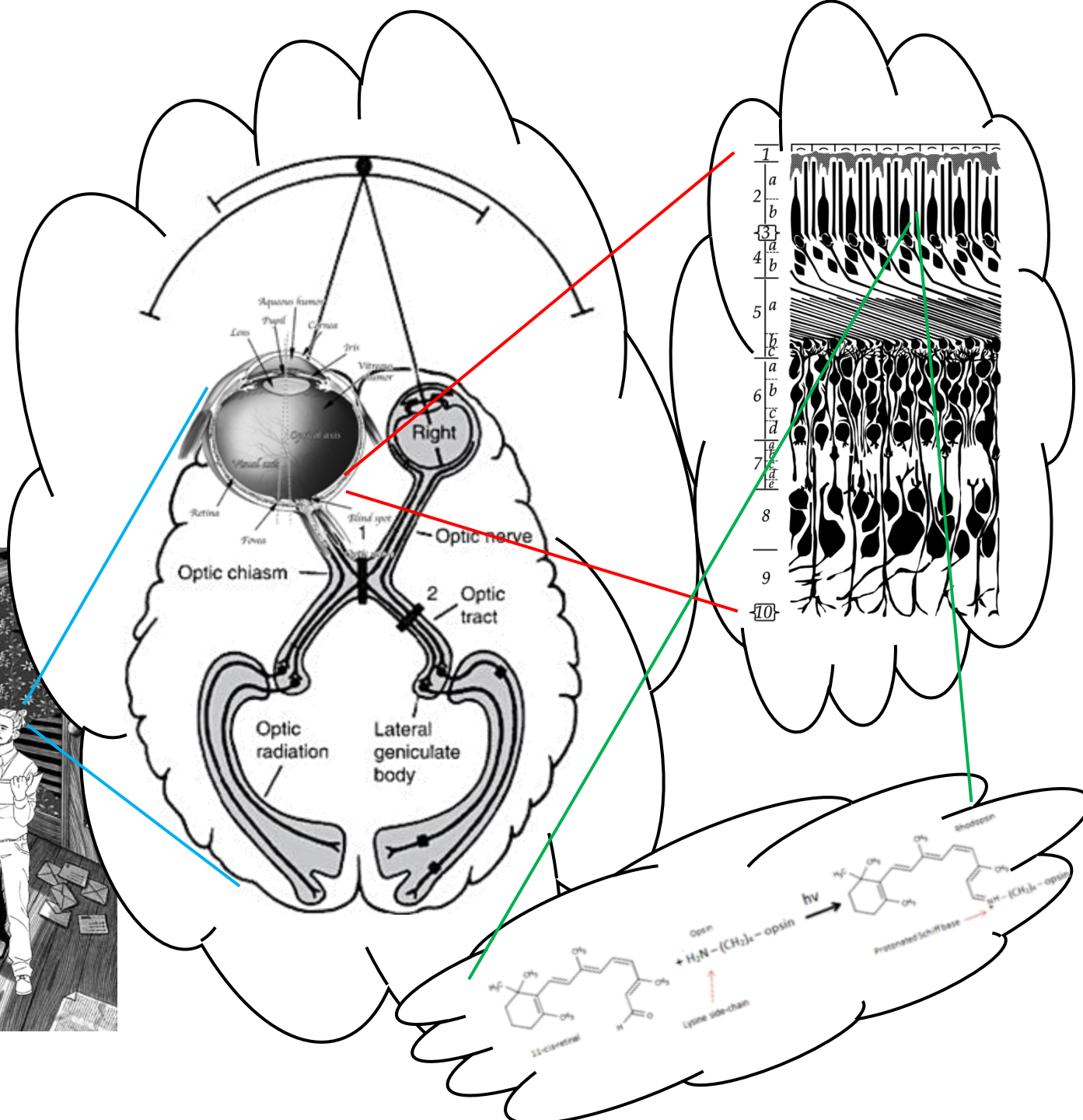
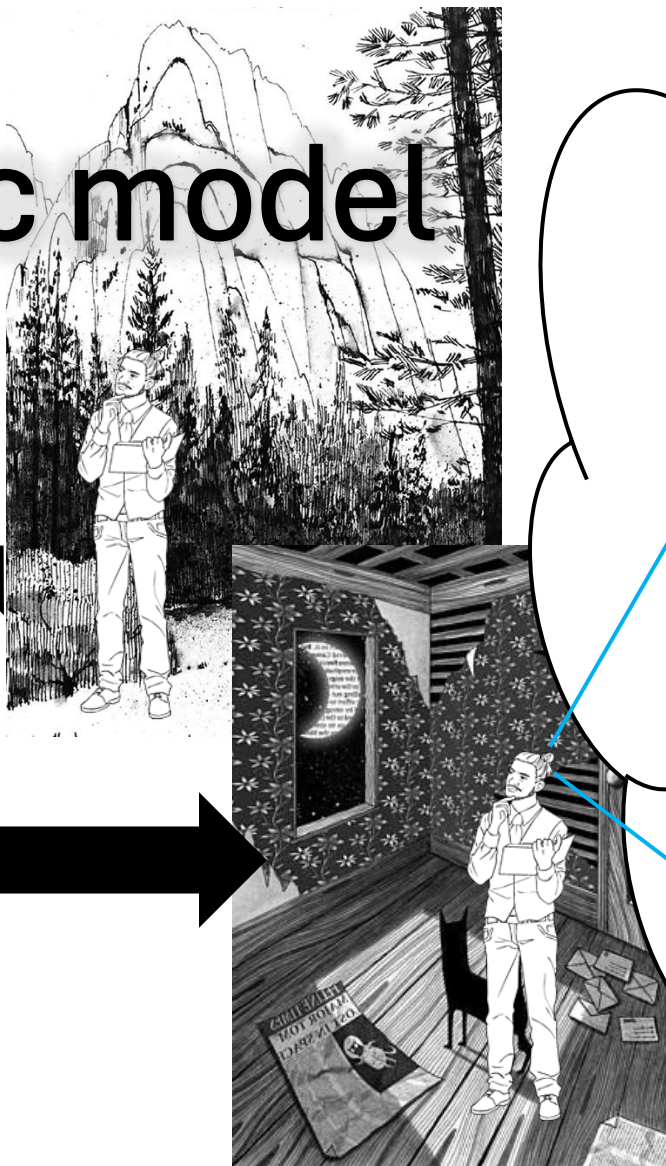
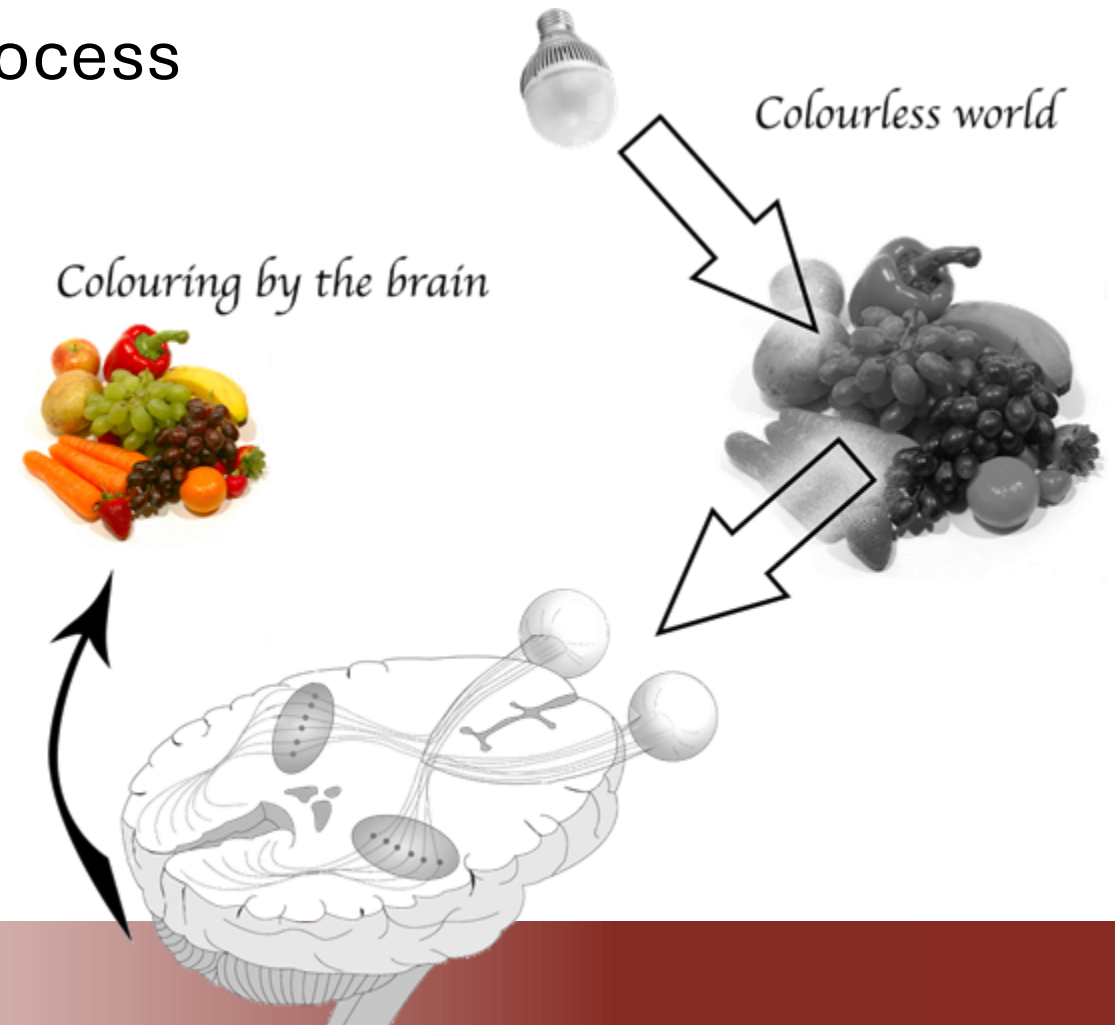


Image formation

- Image formation is a constructive process
- Image as defined by humans
 - Requires light
 - But what is light?

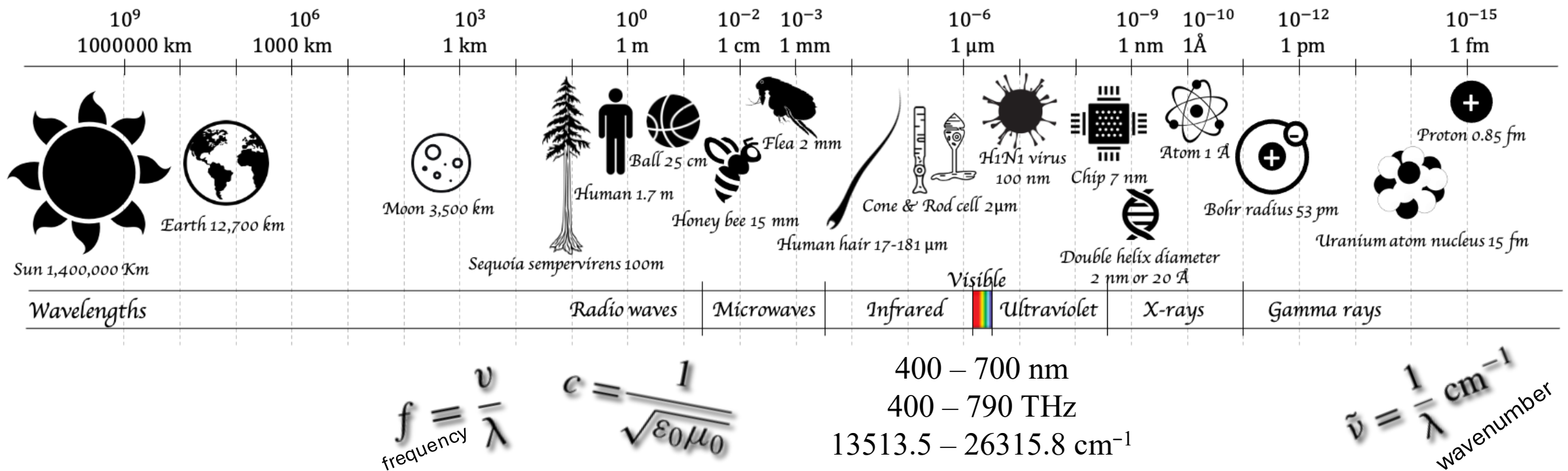


-
- A diagram of a sinusoidal wave on a horizontal dashed line. The wavelength is indicated by a double-headed arrow labeled λ between two consecutive peaks. The amplitude is indicated by a double-headed arrow labeled A from the horizontal line to a peak.

three generations of matter (fermions)			interactions / force carriers (bosons)	
I	II	III		
mass charge spin $\approx 2.2 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$  up	$\approx 1.28 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$  charm	$\approx 173.1 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$  top	 gluon	$\approx 124.97 \text{ GeV}/c^2$ 0 0 0  higgs
$\approx 4.7 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$  down	$\approx 96 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$  strange	$\approx 4.18 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$  bottom	 photon	
$\approx 0.511 \text{ MeV}/c^2$ -1 $\frac{1}{2}$  electron	$\approx 105.66 \text{ MeV}/c^2$ -1 $\frac{1}{2}$  muon	$\approx 1.7768 \text{ GeV}/c^2$ -1 $\frac{1}{2}$  tau	 Z boson	
$< 1.0 \text{ eV}/c^2$ $\frac{1}{2}$  electron neutrino	$< 0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$  muon neutrino	$< 18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$  tau neutrino	 W boson	

Electromagnetic radiation

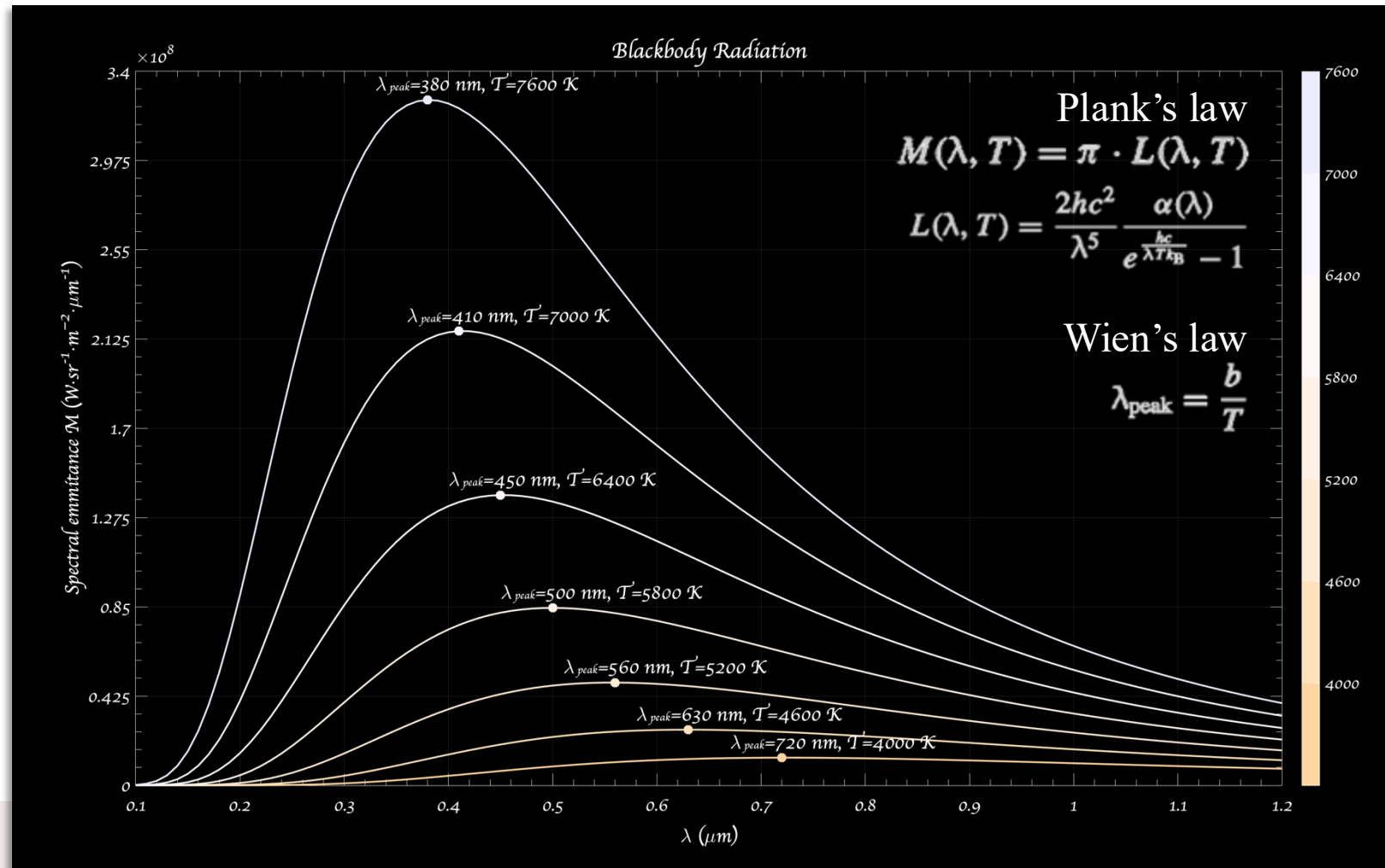
- The whole known radiation spectrum



Where does light come from?



- The blackbody radiation model
 - All known matter with a temperature above absolute zero transmits radiation that represents the energy conversion within it
 - This is why it's called thermal radiation
 - It's a spontaneous process of entropy distribution



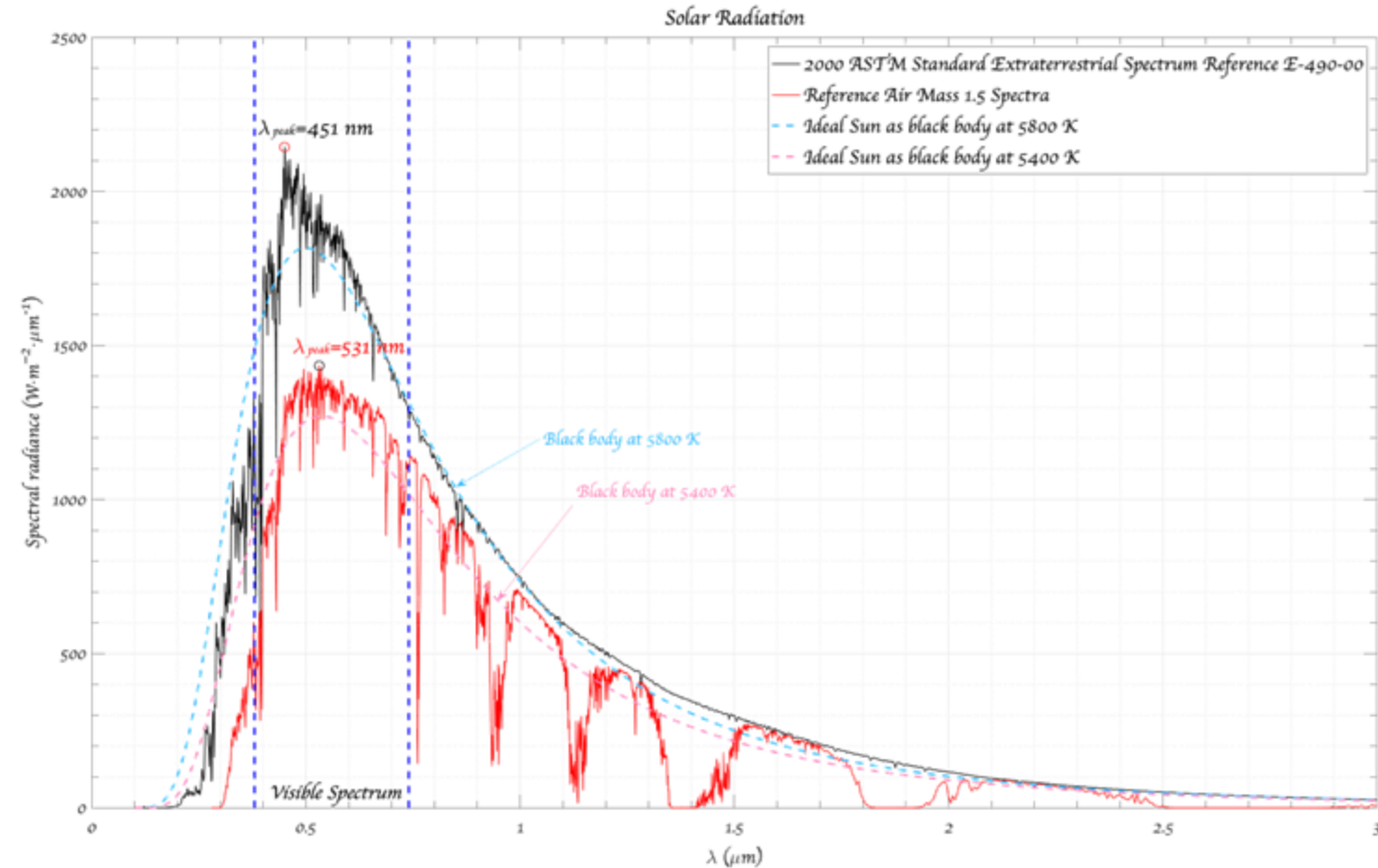
Why light looks like this to us?



- The “visible” light on planet Earth
 - Source: all bodies that produce or reflect light on the sky of the Earth
 - Sun, Moon, all other bodies
 - Sun is 400,000 times brighter than the Moon
 - Sun is 125,000,000 times brighter than sky but Moon

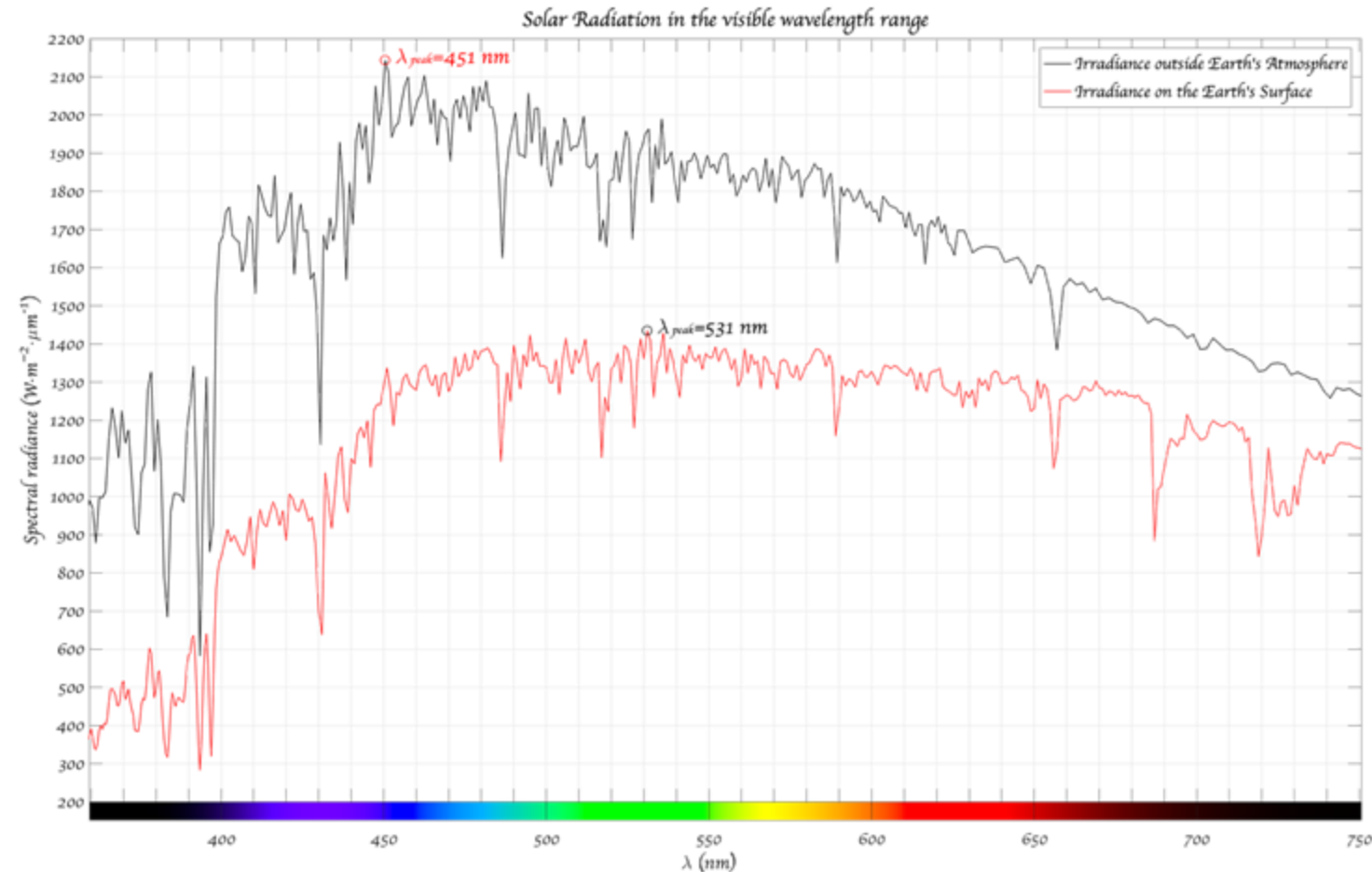
Light on Earth

- Solar radiation profile



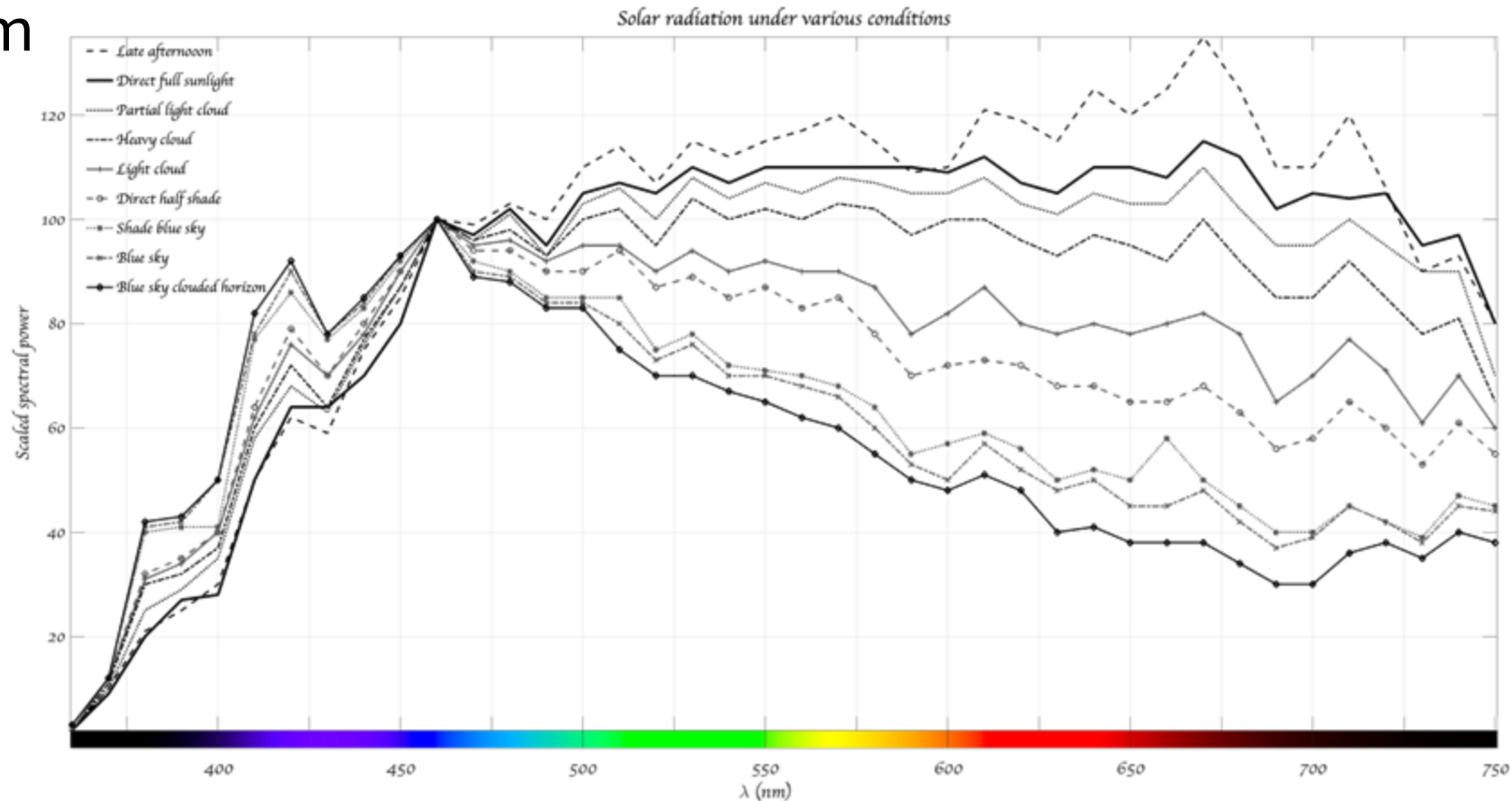
Light on Earth

- The visible part of Sun's spectrum



Light on Earth

- The visible spectrum under varying conditions

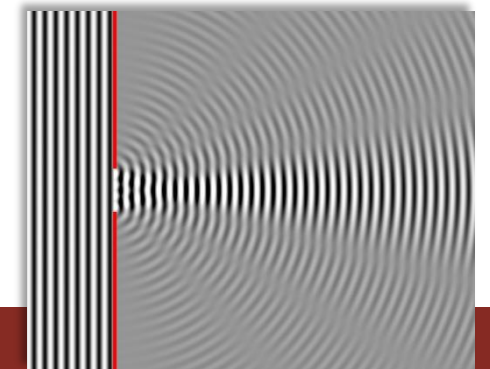
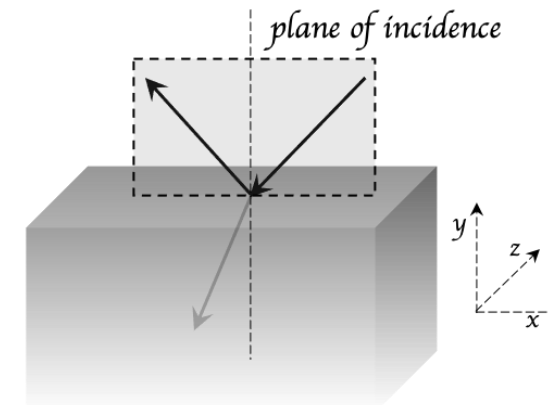
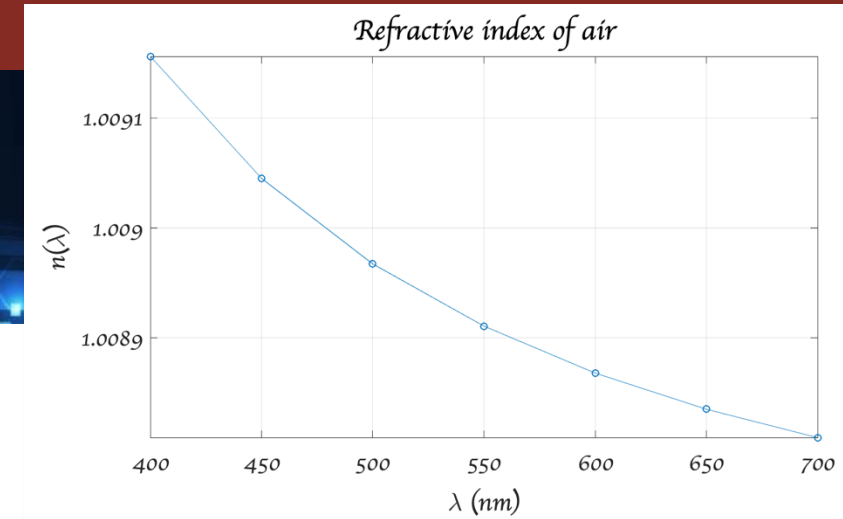
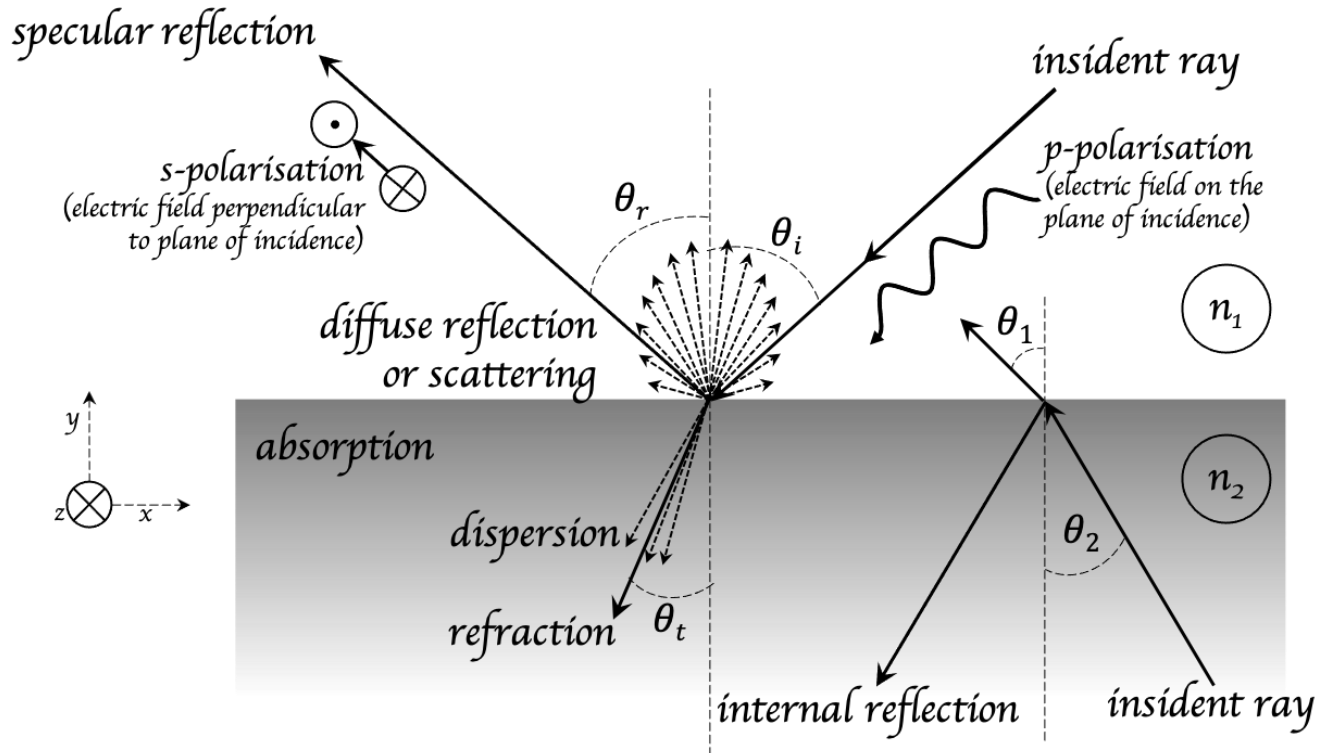


Light on Earth

- The color of the Sun
 - “White” in space, changing on Earth



Light interactions with media

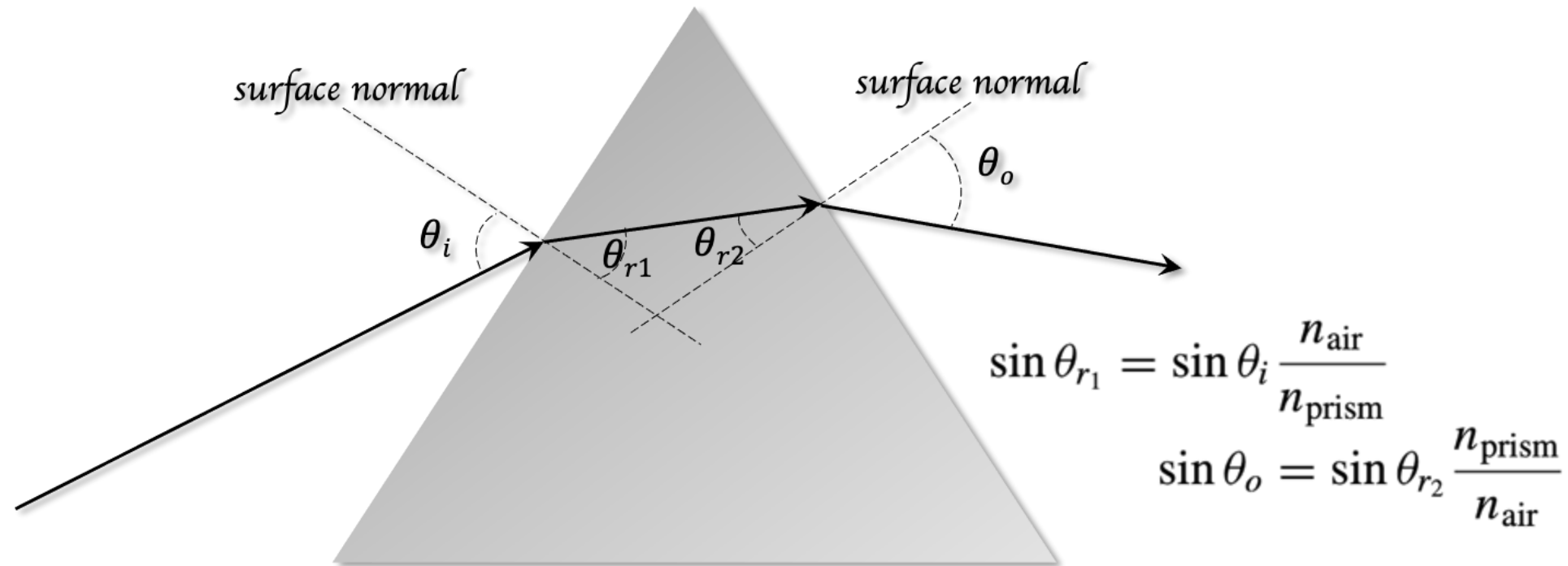


- Emission/reemission, Transmission, Polarization, Absorption, Scattering, Reflection, Diffraction, Refraction, Dispersion

Light interactions with media



- Refraction (change of direction when changing media)



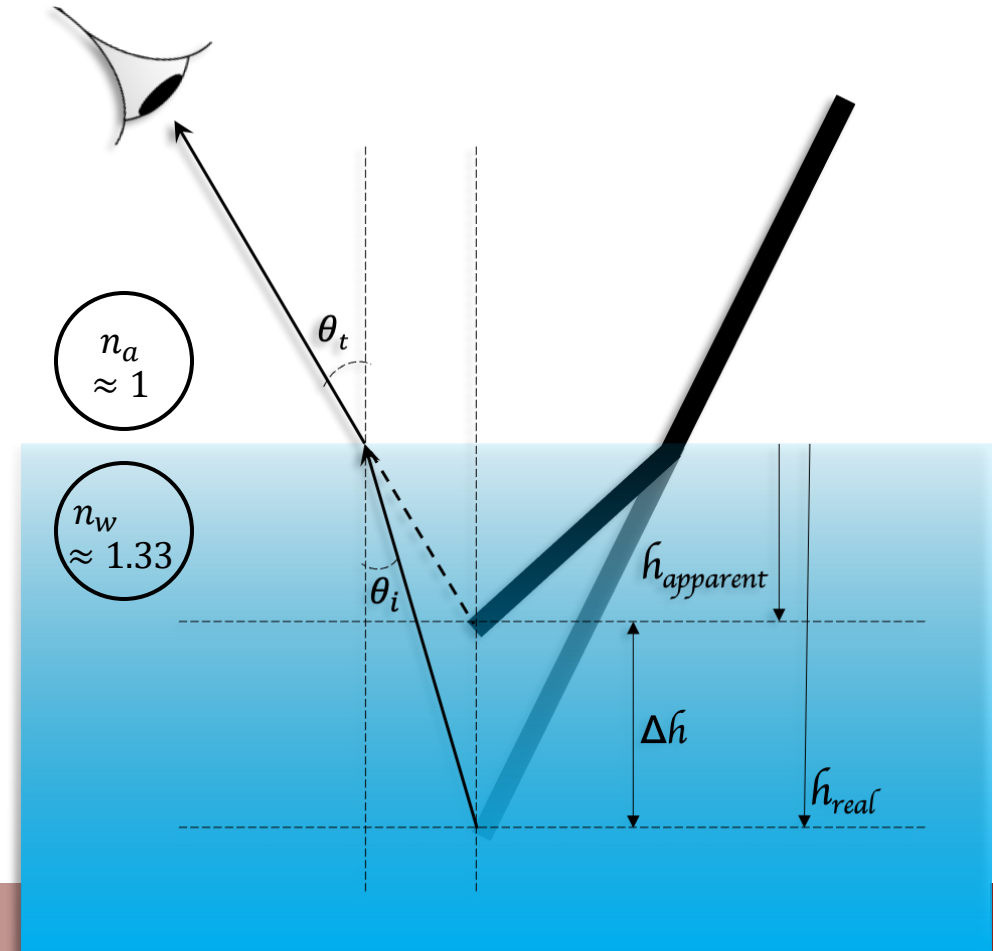
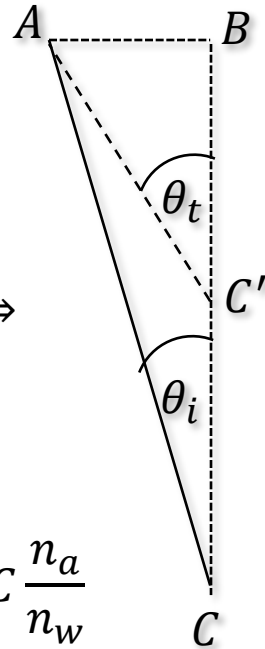
Light interactions with media

- Apparent shape distortion due to refraction

$$\left. \begin{aligned} \sin \theta_i &= \frac{AB}{AC} \\ \sin \theta_t &= \frac{AB}{AC'} \Rightarrow AC' = \frac{AB}{\sin \theta_t} \end{aligned} \right\} \Rightarrow$$

$$AC' = AC \frac{\sin \theta_i}{\sin \theta_t} \xrightarrow{\frac{\sin \theta_t}{\sin \theta_i} = \frac{n_w}{n_a}} AC' = AC \frac{n_a}{n_w}$$

$$h_{\{apparent\}} = \frac{n_a}{n_w} h_{\{real\}} \left(= \frac{h_{\{real\}}}{1.33} \approx 75\% h_{\{real\}} \right)$$



Apparent curiosities

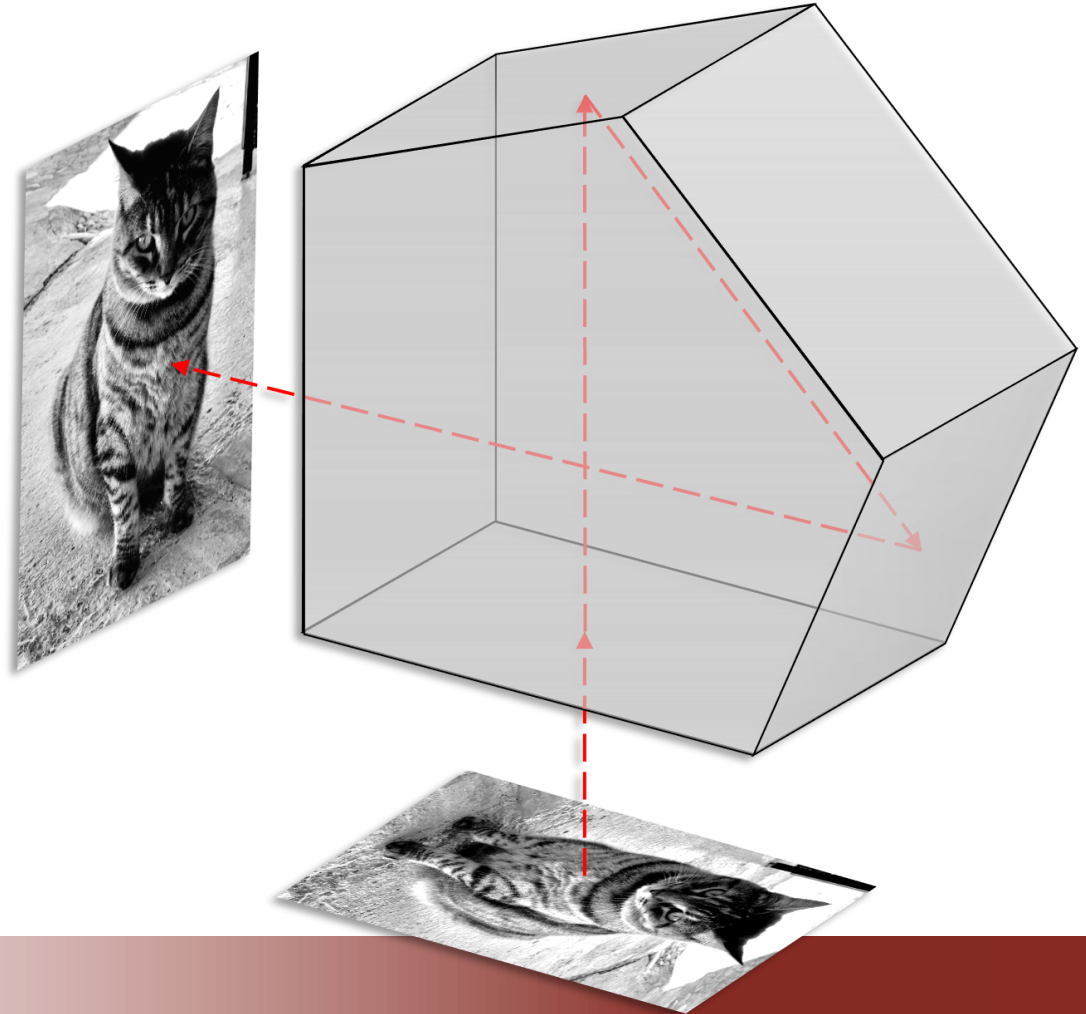
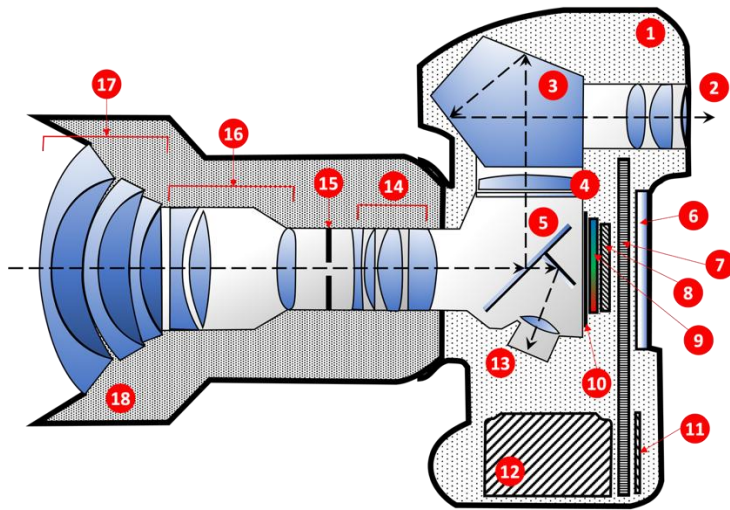


- Reflection on convex and concave/hollow surfaces



Apparent curiosities

- Total internal reflection
 - Application in cameras



Measurement of light



• Radiometry

Transition from radiometry to photometry requires the eye sensitivity.

$$K = \frac{\Phi_v}{\Phi_e} = \frac{\int_0^\infty K(\lambda) \Phi_{e,\lambda} d\lambda}{\int_0^\infty \Phi_{e,\lambda} d\lambda}$$

$$K(\lambda) = K_{max} V(\lambda)$$

$K(\lambda)$ is the eye sensitivity as a function of the wavelength:
luminous efficacy function
**described later*

inverse square law for point source

$$E_v = \frac{\Phi_v}{A} \xrightarrow[A=4\pi s^2]{\Phi_v=4\pi I_v} E_v = \frac{I_v}{s^2}$$

Quantity	Radiometry		Photometry
Energy	Radiant energy (J)	Q_v	Luminous energy (lm·sec=talbot)
Power/Flux (energy per unit time)	Radiant flux/power (W)	Φ_v	Luminous flux/power (lm=cd·sr=talbots·sec ⁻¹)
Sterance/Angular flux density (flux per unit solid angle per unit projected source area)	Radiant sterance Radiance (W·m ⁻² sr ⁻¹)	L_v	Luminous sterance Luminance (nit=lm·m ⁻² sr ⁻¹)
Areance/Flux density (exitance-flux emitted by a surface)	Radiant exitance/Radiosity (W·m ⁻²)	M_v	Luminous exitance/ Luminosity (lux=lm·m ⁻²)
Areance/Flux density (flux incident on a surface)	Irradiance (W·m ⁻²)	E_v	Illuminance (lux=lm·m ⁻²)
Pointance (flux per unit solid angle)	Radiant intensity (W·sr ⁻¹)	I_v	Luminous intensity (cd=lm·sr ⁻¹)

$$\Phi_v = \int_{\Omega} I_v(\vec{\omega}) d\omega$$

$$L_v = \frac{\Phi_v}{\omega(A \cos \theta)} = \frac{I_v}{A \cos \theta}$$

$$M_v = \frac{\Phi_v}{A}$$

$$E_v = \frac{\Phi}{A}$$

$$I_v = \frac{\Phi_v}{\omega} \xrightarrow[\text{point source}]{\text{omnidirectional}} I_v = \frac{\Phi_v}{4\pi}$$

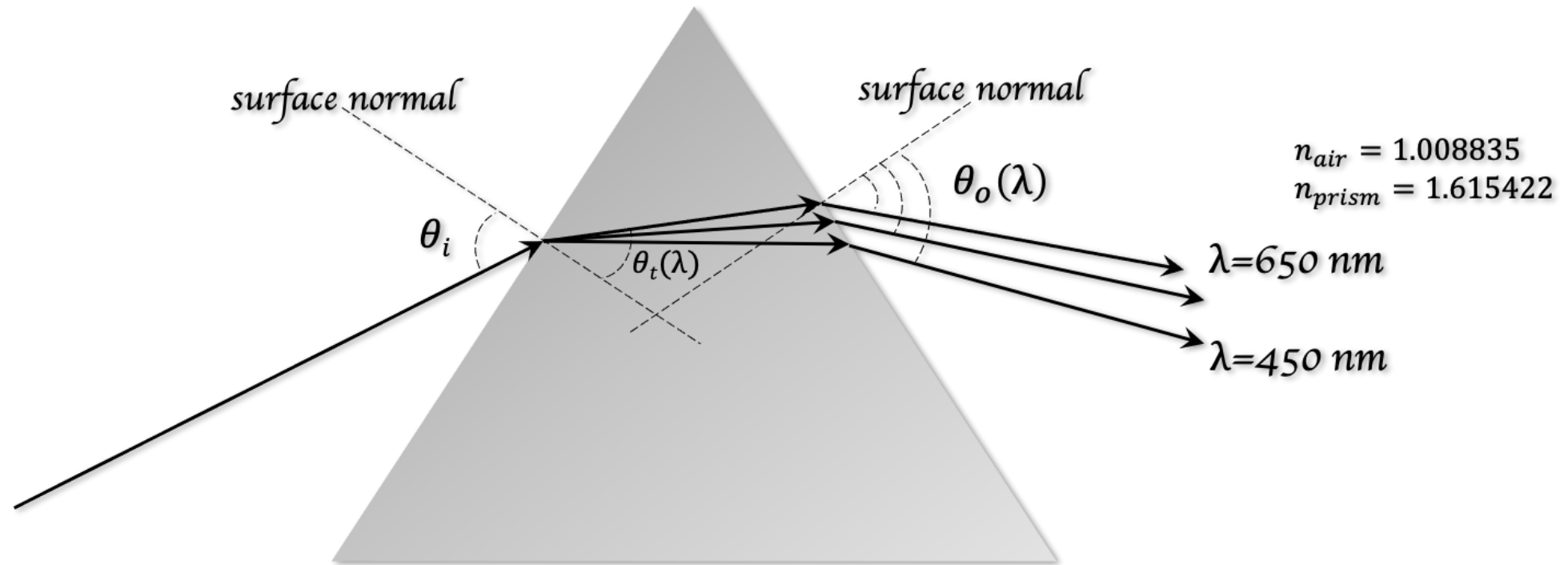
A : area of the emitting surface

$$\text{Solid angle } \omega = 2\pi \left(1 - \cos \frac{\theta}{2}\right)$$

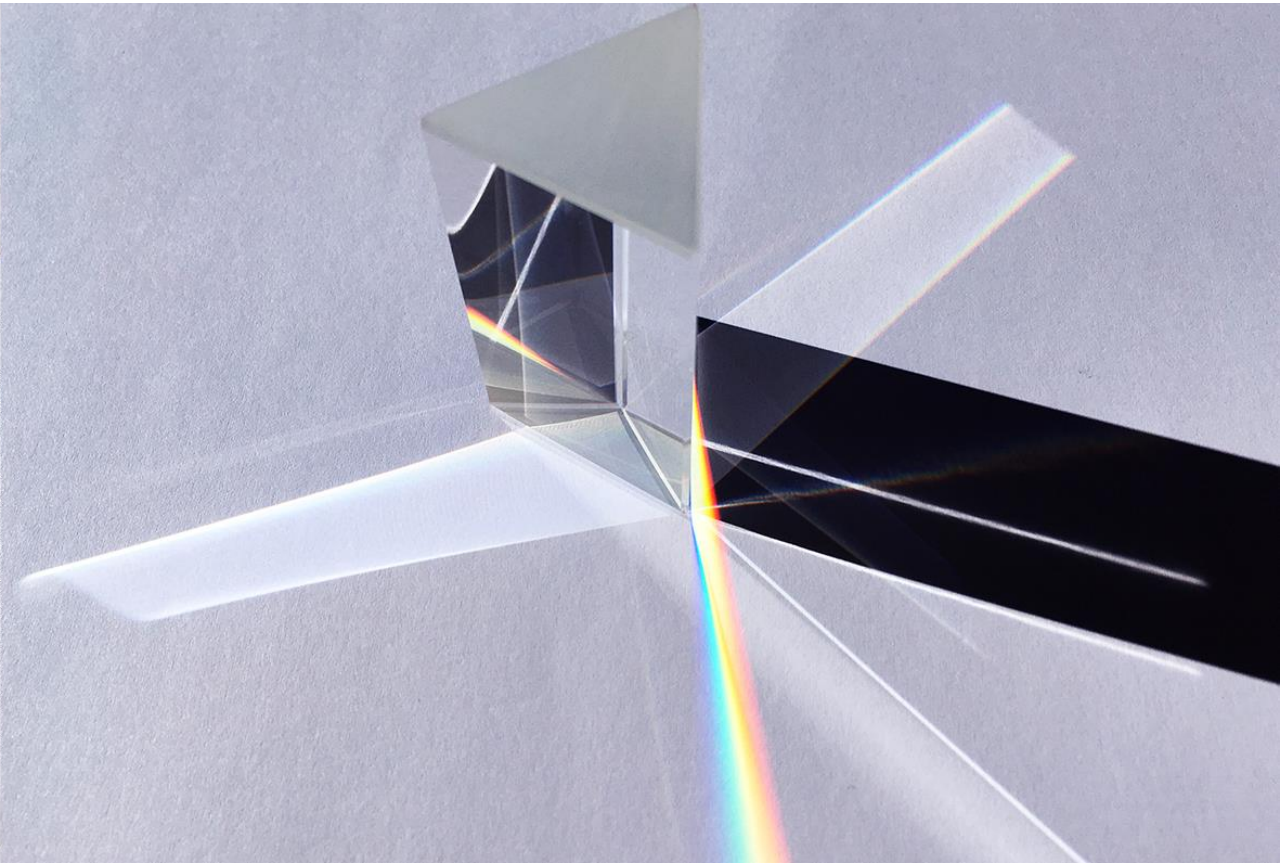
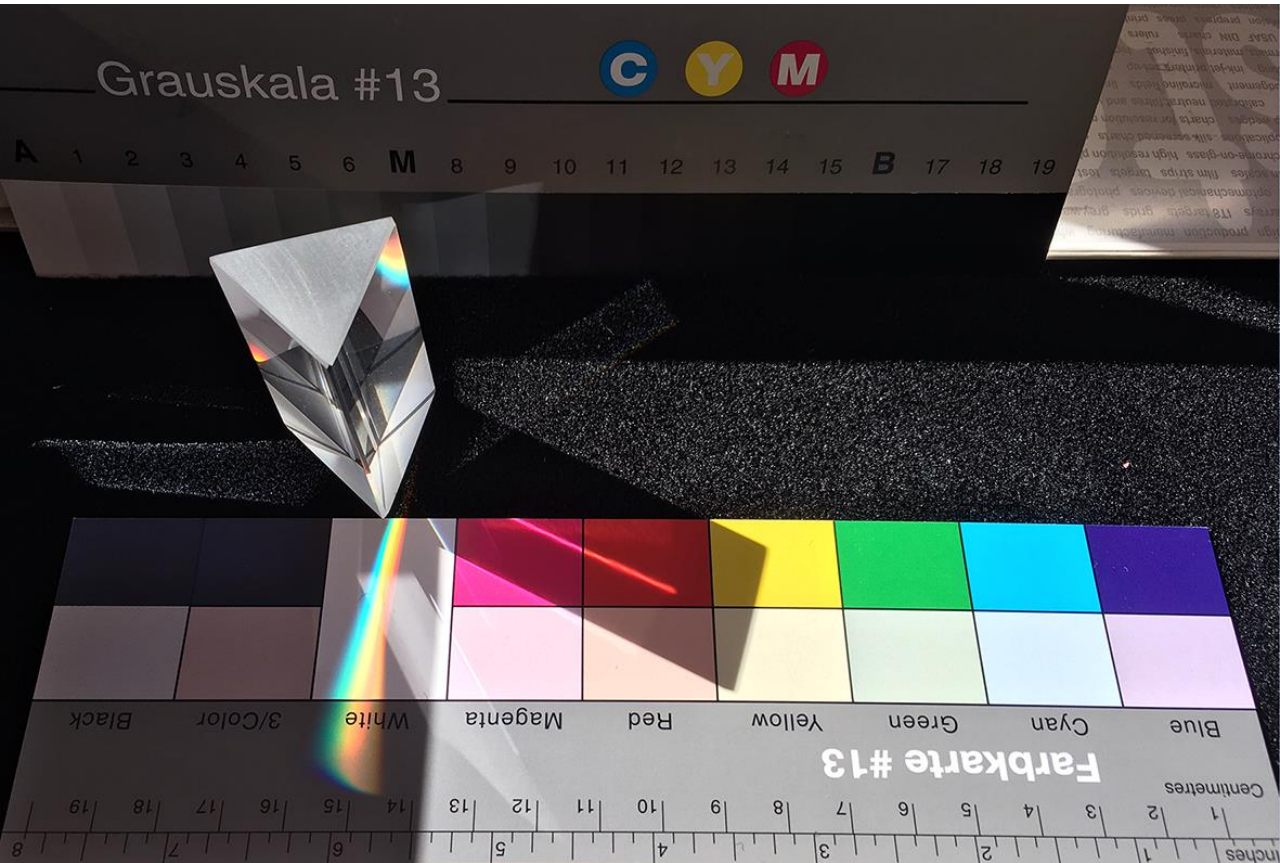
The emergence of colors



- Refraction and dispersion



The emergence of colors



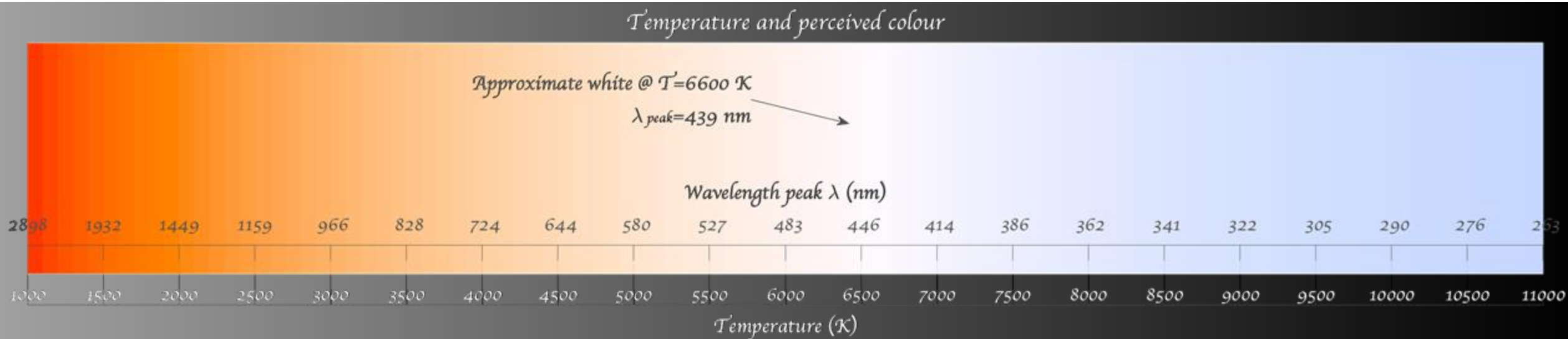
The emergence of colors



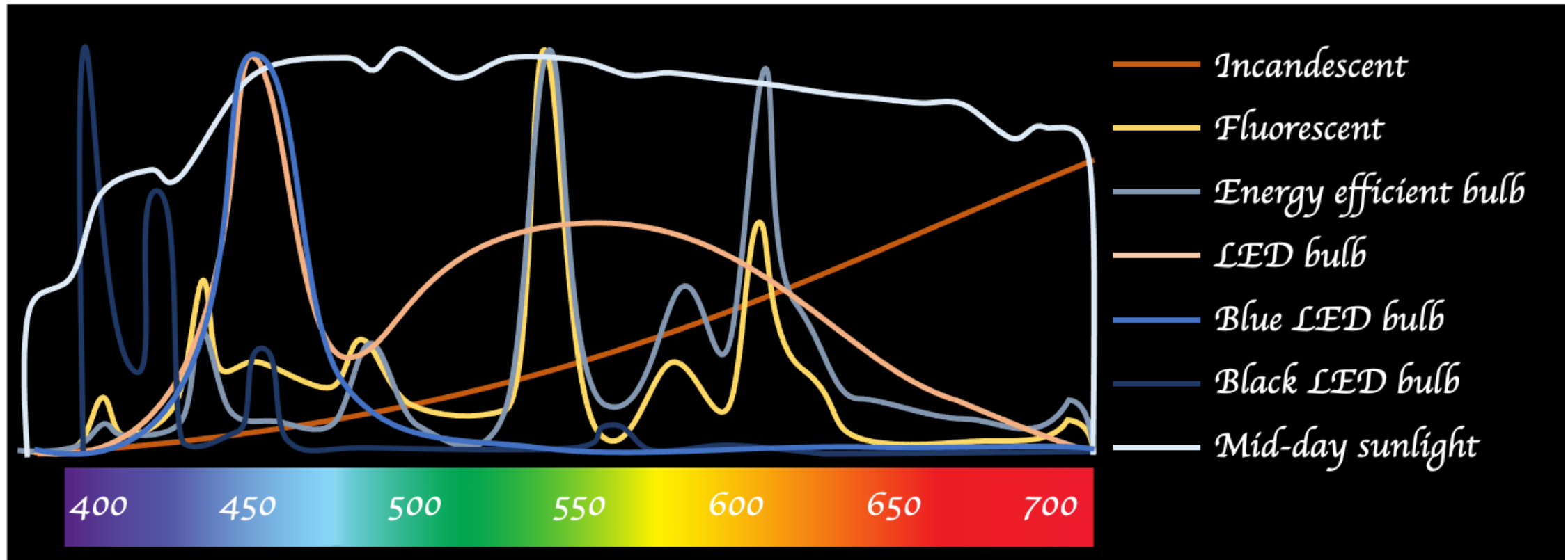
All perceived light sources



- Color perception of light of all possible sources
 - Temperatures range 1000–11000 K
 - Wavelengths of maximum power through Wien's Law, 2898–263 nm



Artificial light sources

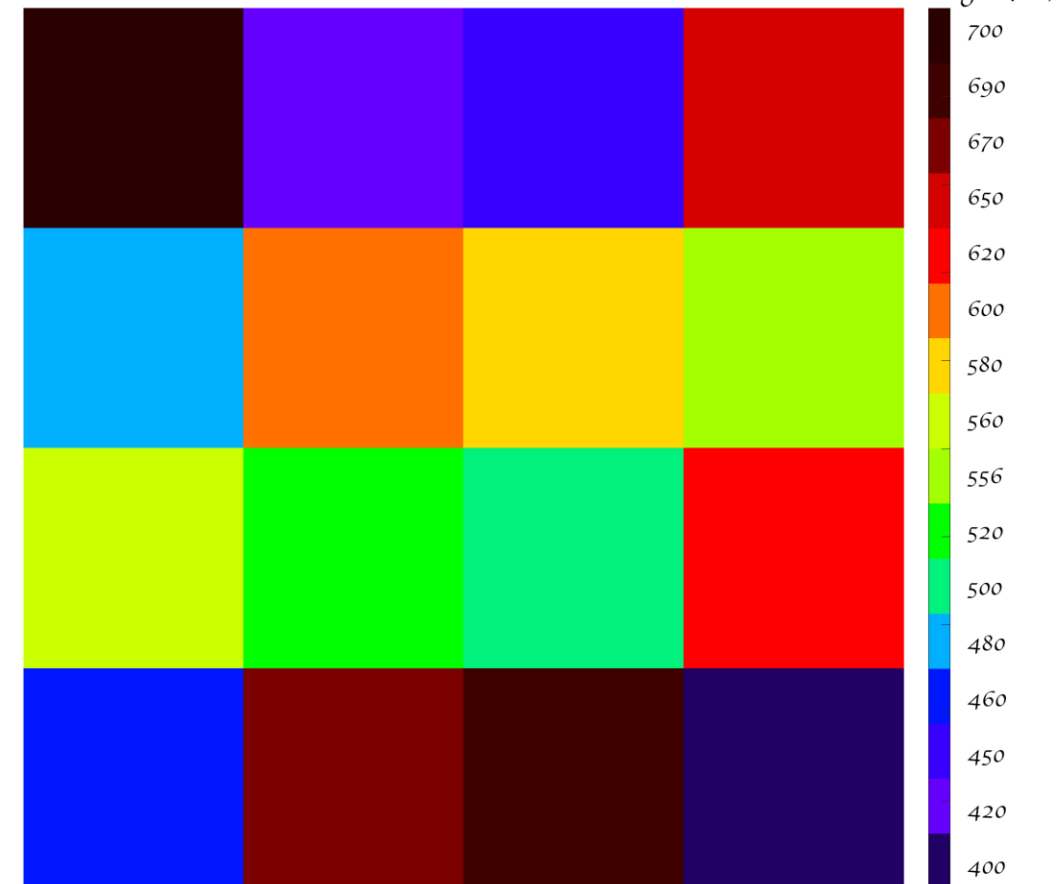


Biological image formation

- The eye-brain system which includes
 - the system of sensing
 - the system of perception
- Example of spectral colors
 - Single wavelength light



Spectral colours example image (sRGB rendering)

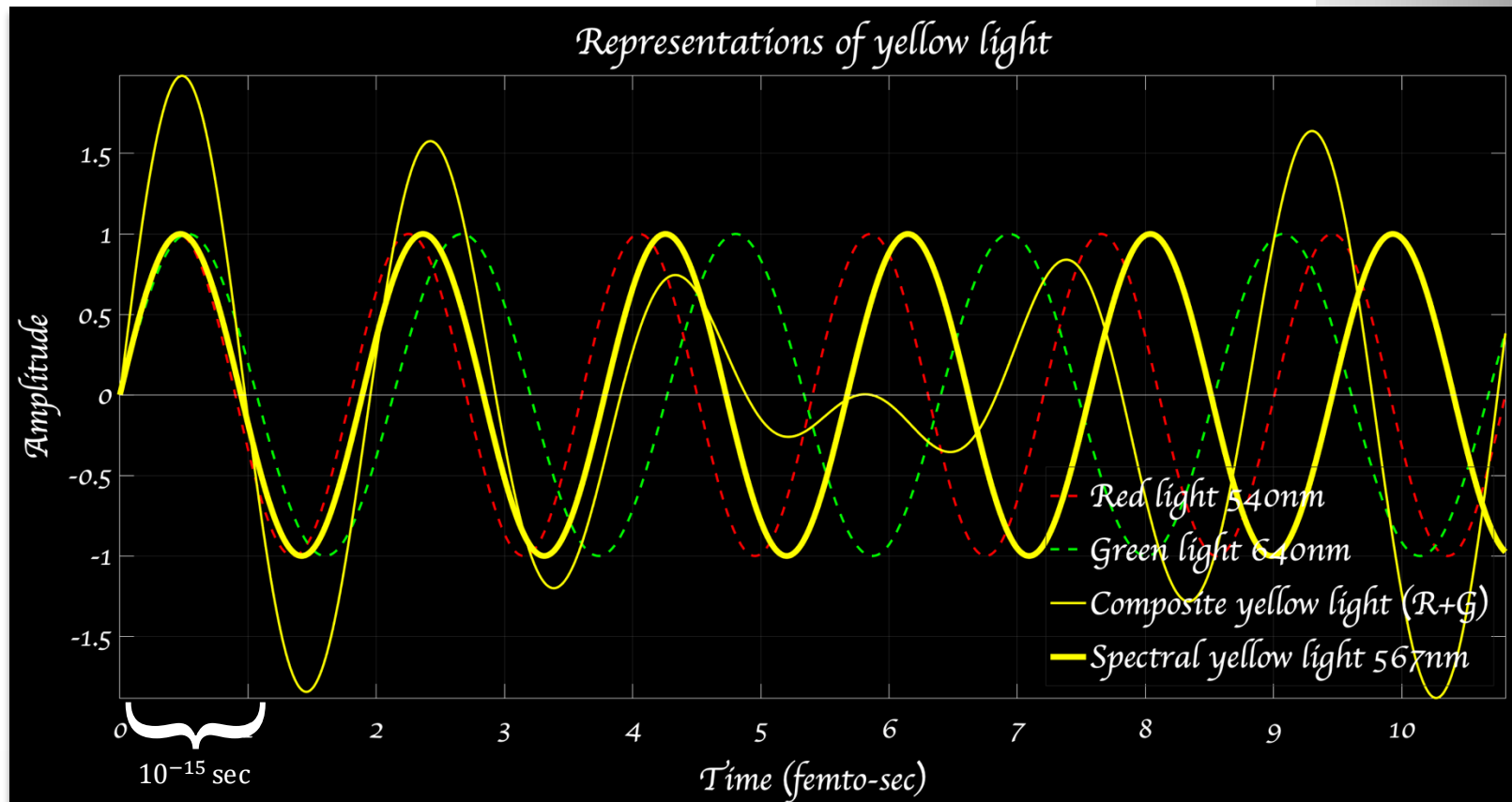


Biological image formation



- The yellow light “issue”

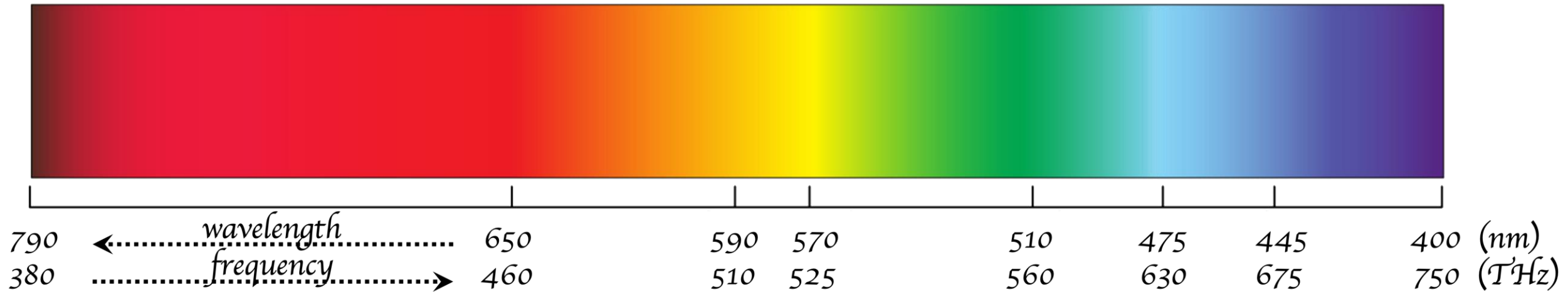
the yellow light issue
the yellow light issue

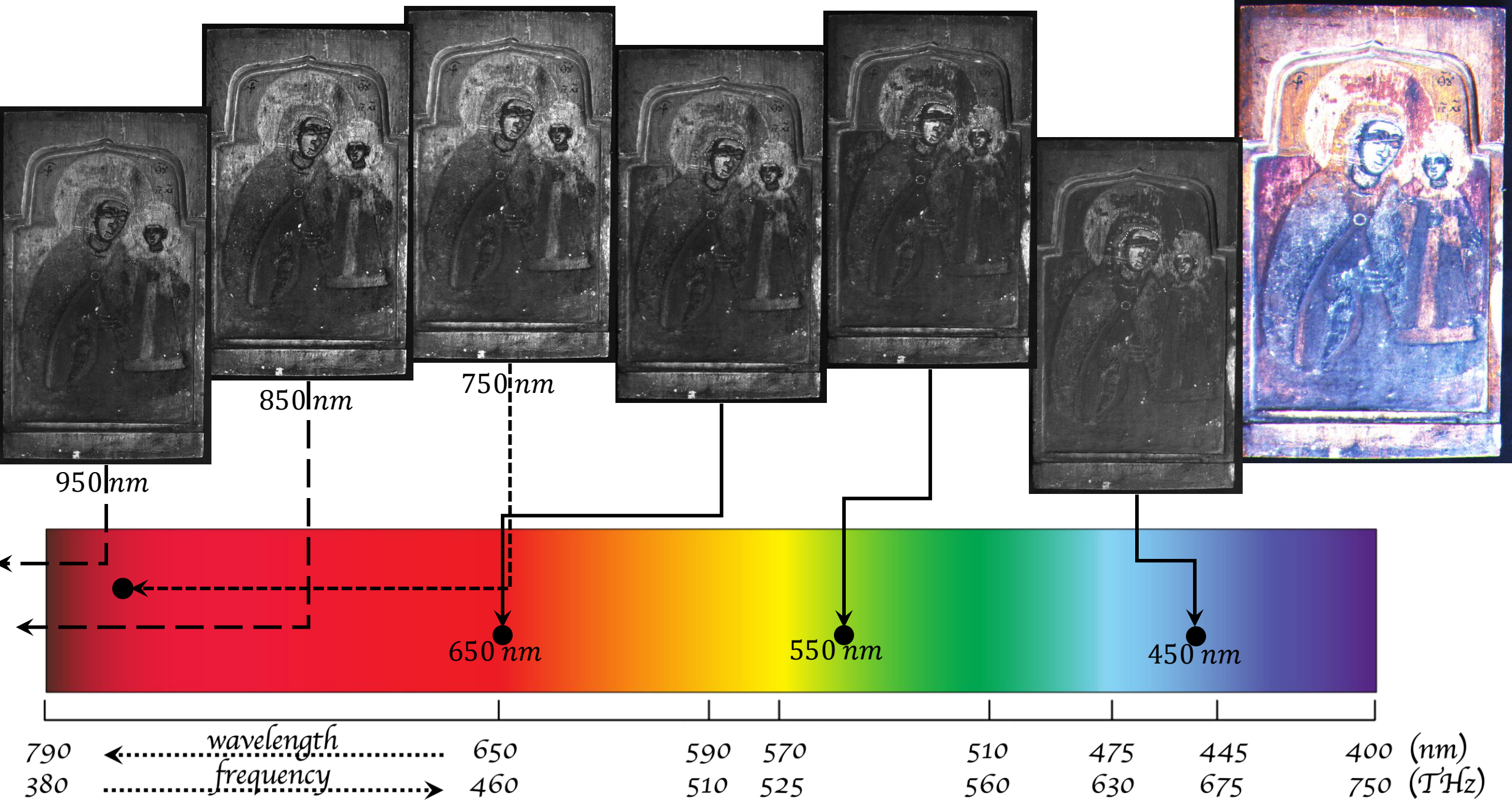


Biological image formation



- So what's color after all?
 - Colors for a specific observer are the apparent variations or mixtures of light, which on average extend between 380 nm (790 THz, in what appears as “purple”) and 740 nm (400 THz, in whatever appears as “red”)





Biological image formation



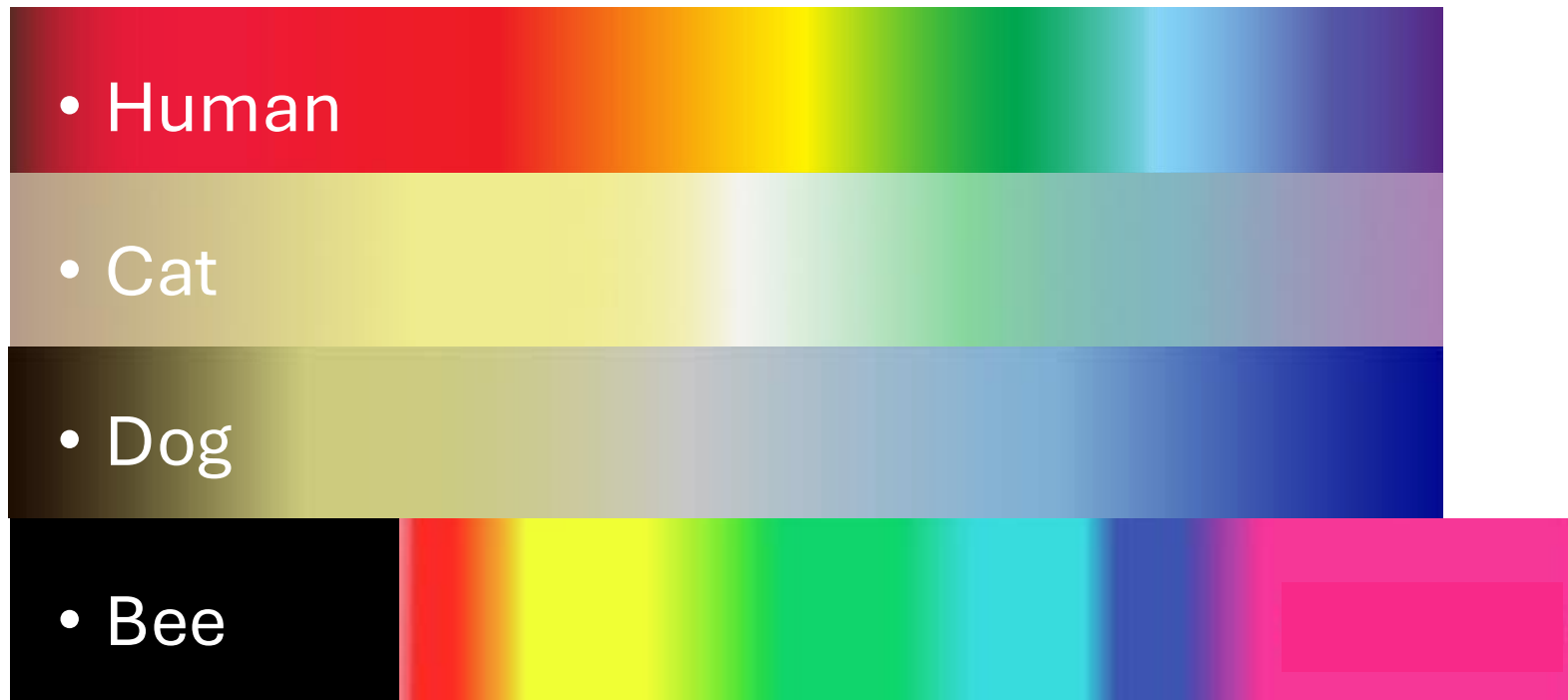
- How would a landscape appear in 1000 nm?



Biological image formation



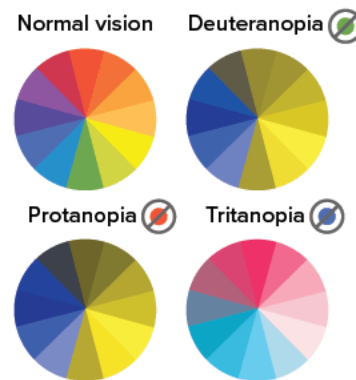
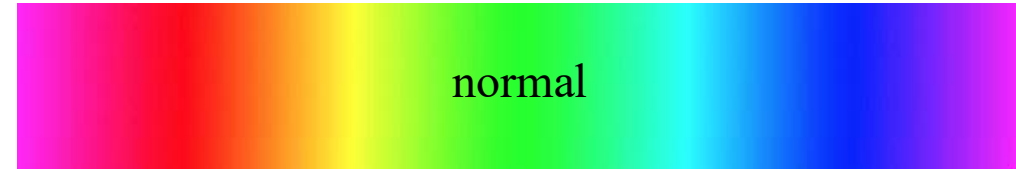
- Do all biological organisms see the same?



Biological image formation



- Do (at least) all humans see the same?
 - Nope!
 - And here lie the first successes in the relevant advances in research



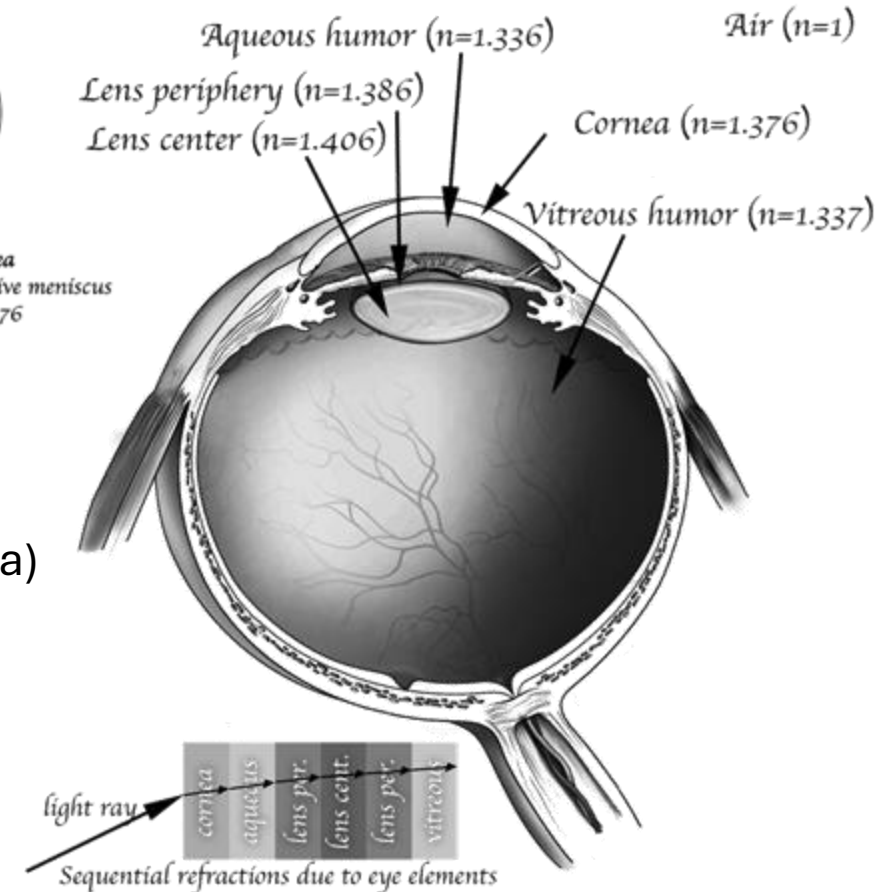
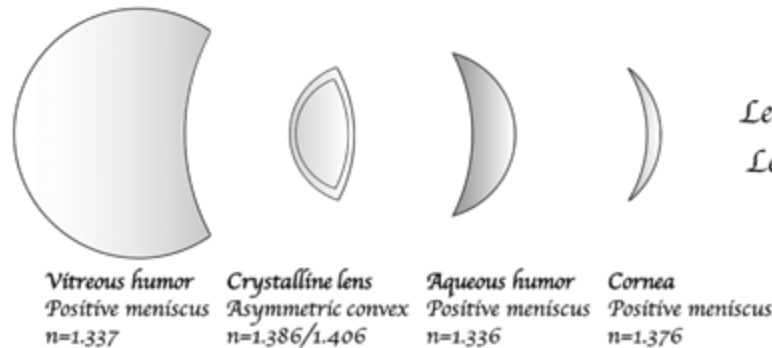
Biological image formation

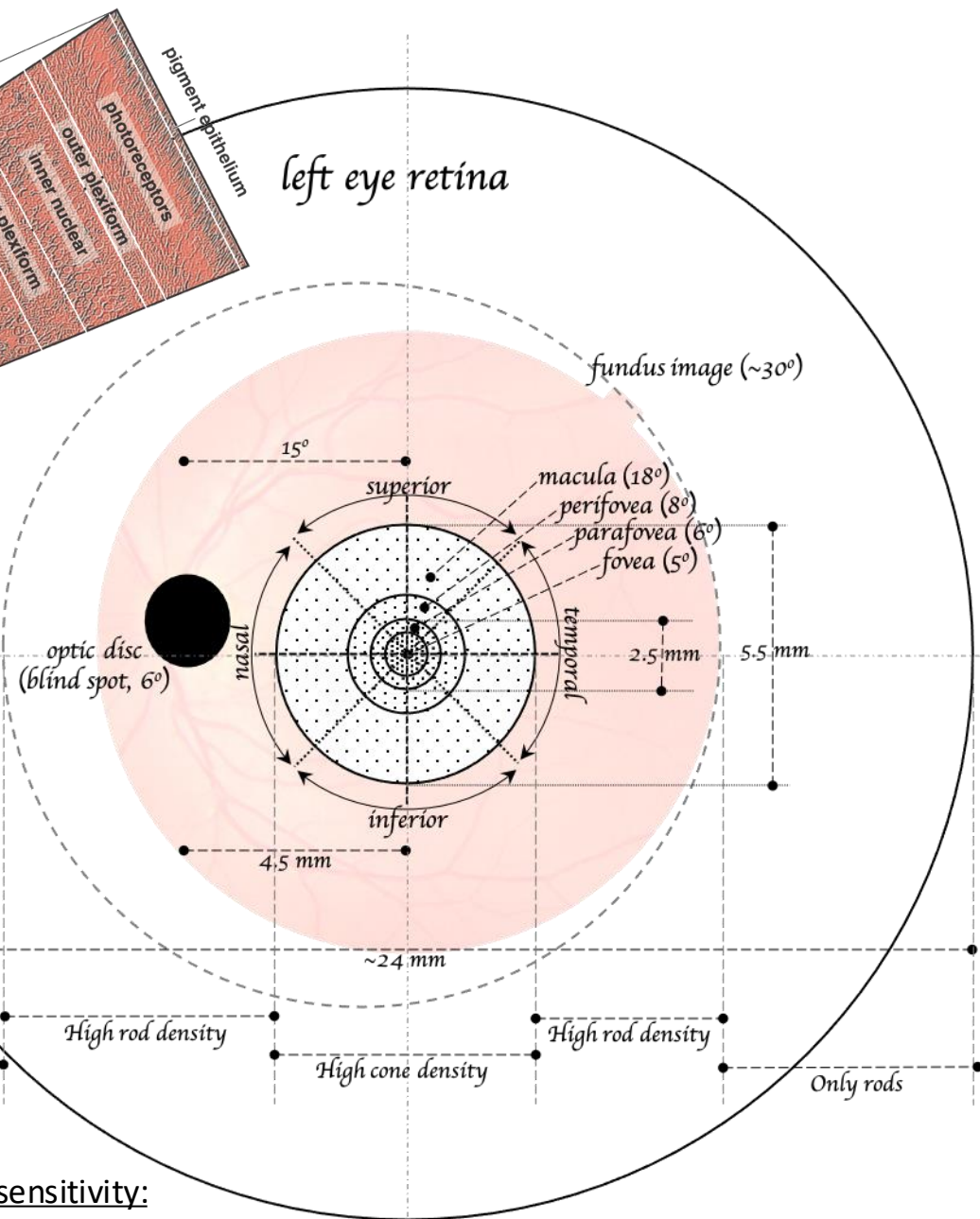
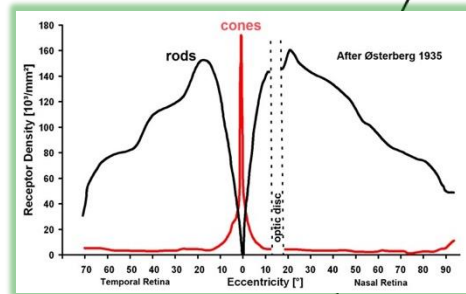
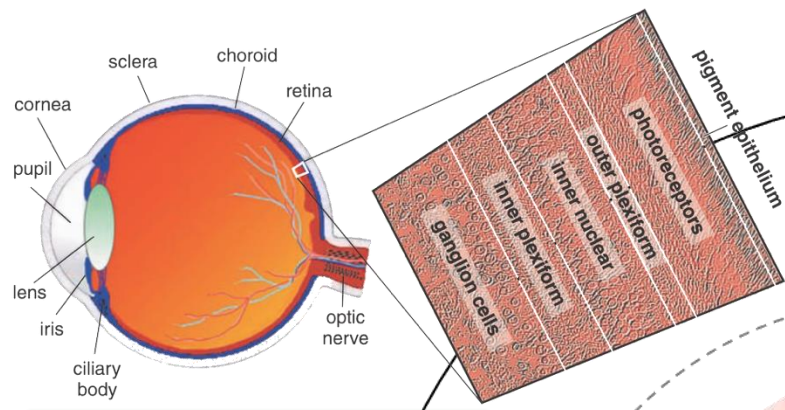
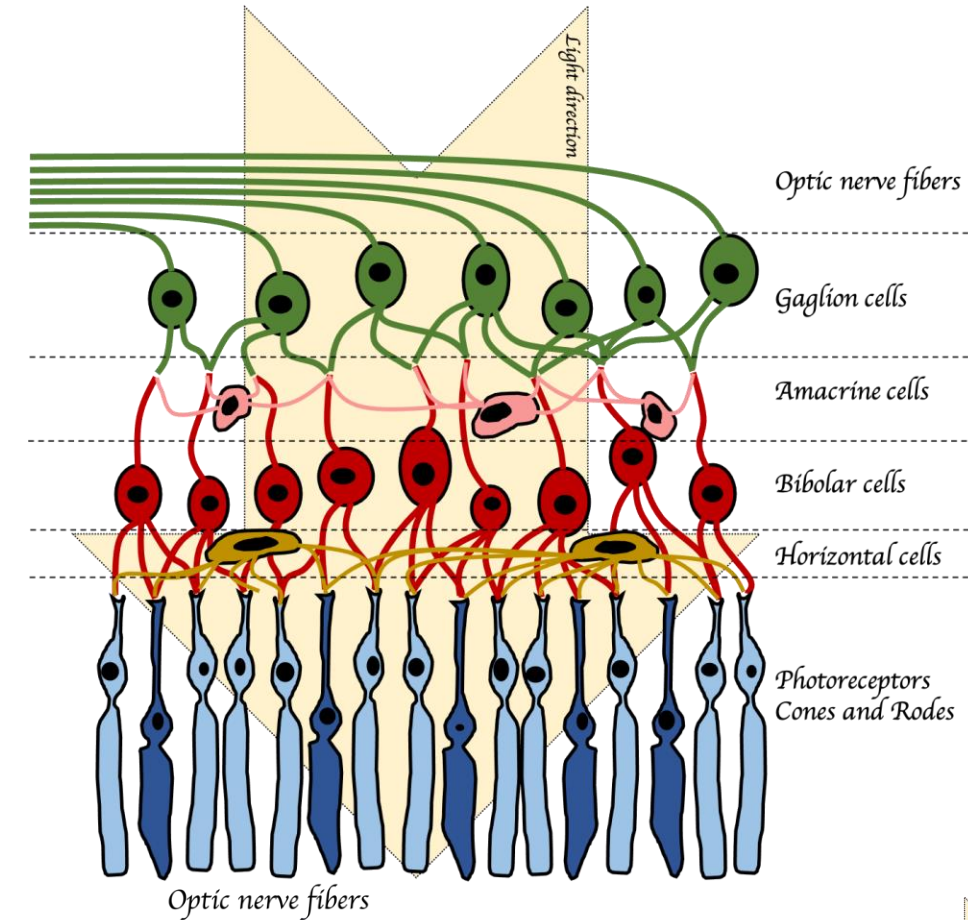


- How is it done?

- The lens

- typically a bubble-shaped tissue
- ~ 10mm diameter, no nerves and vessels
- pale yellow color
- absorbs ~8% of incoming light
- blocks ultraviolet at 300–400nm, (shorter lengths absorbed by cornea)
- provides standard focal distance ~22 mm
 - with large changes while adapting (accommodation)
 - focus 5 cm – infinity
(power 20 dioptries [= $1/0.05 \text{ m}^{-1}$])





More than 100 million
photosensitive cells in the retina

Photoreceptors
Cones only

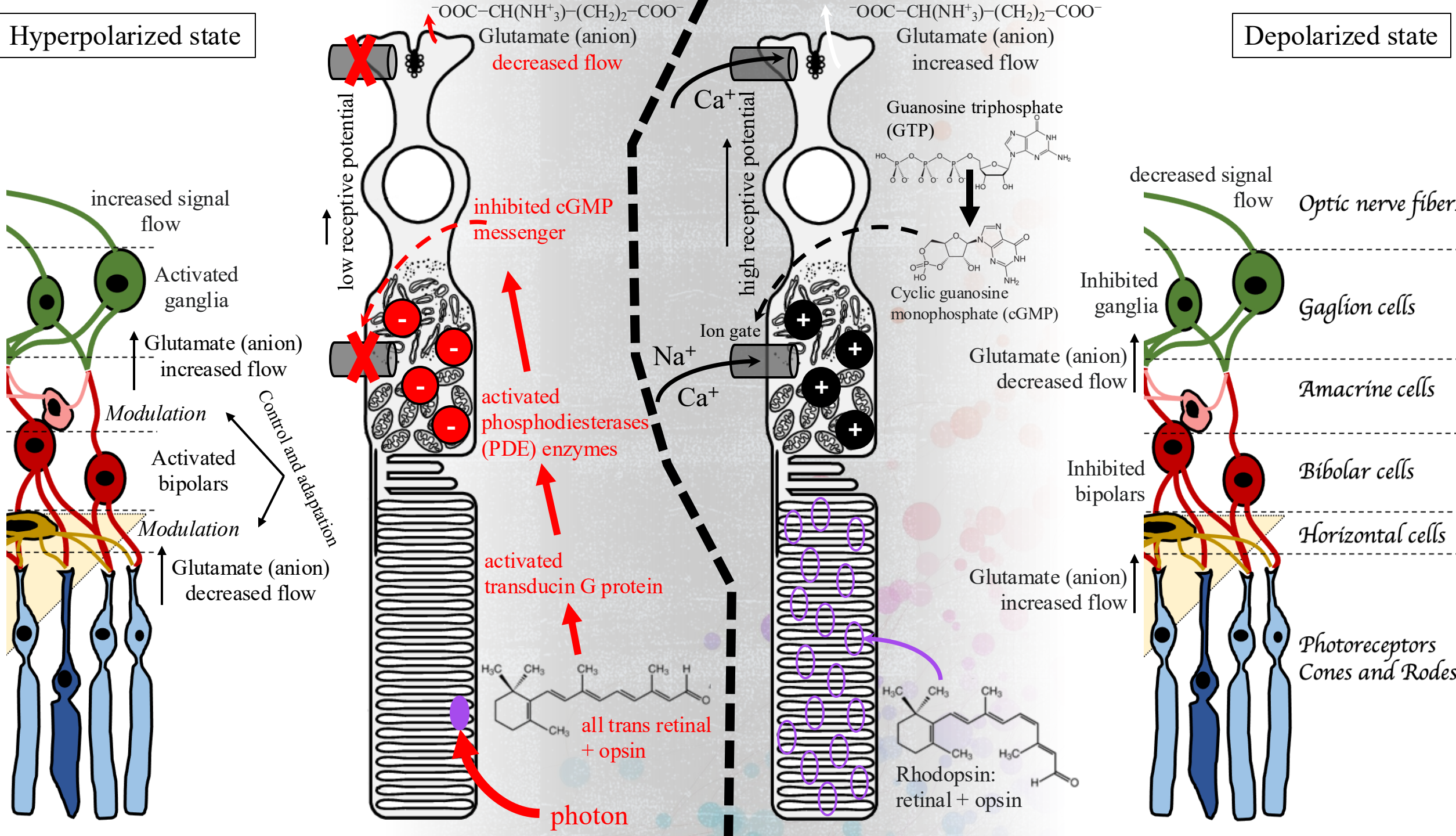
Maximum sensitivity:

Rods: (R) 500 nm (green)

Cones: (S) 420 nm (purple), (M) 530 nm (green), (L) 560 nm (yellow)

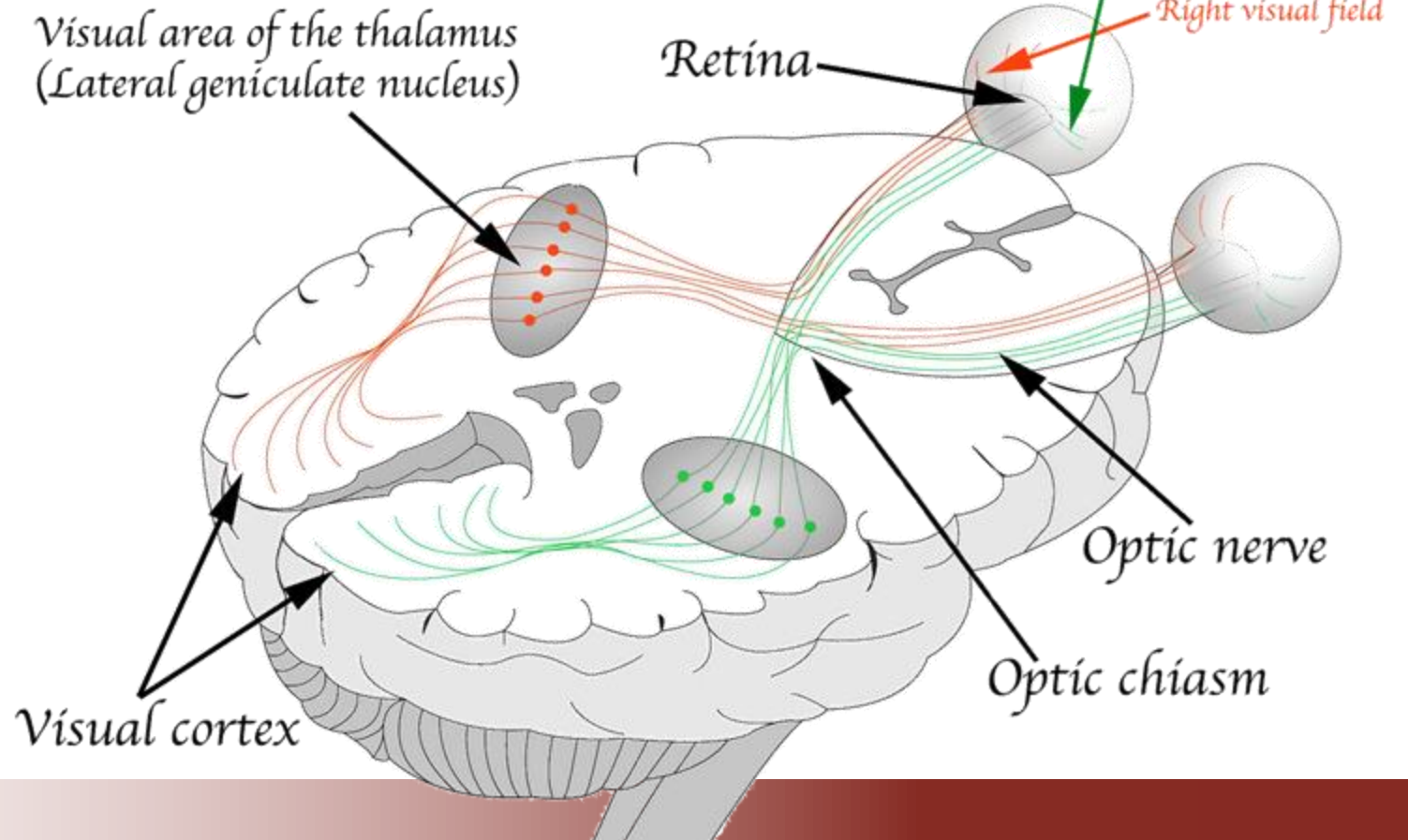
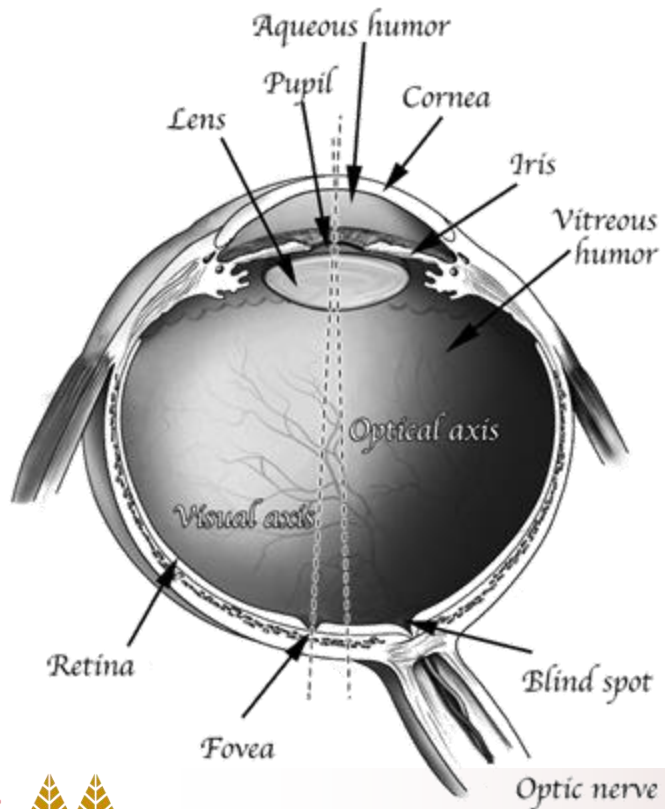
Hyperpolarized state

Depolarized state



Biological image formation

- How is it done?



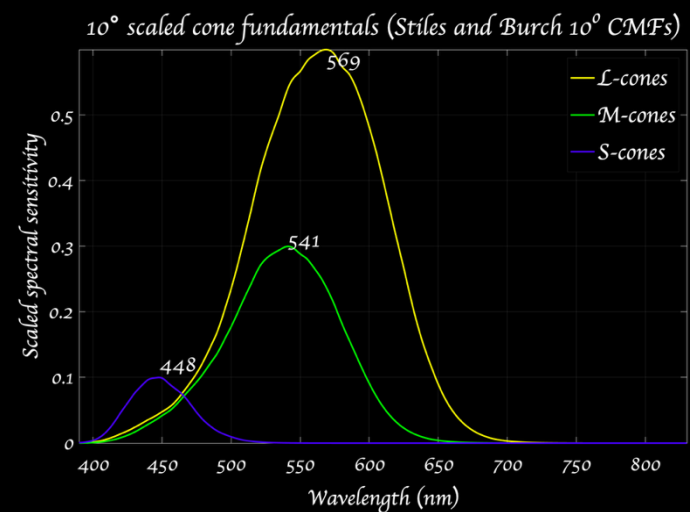
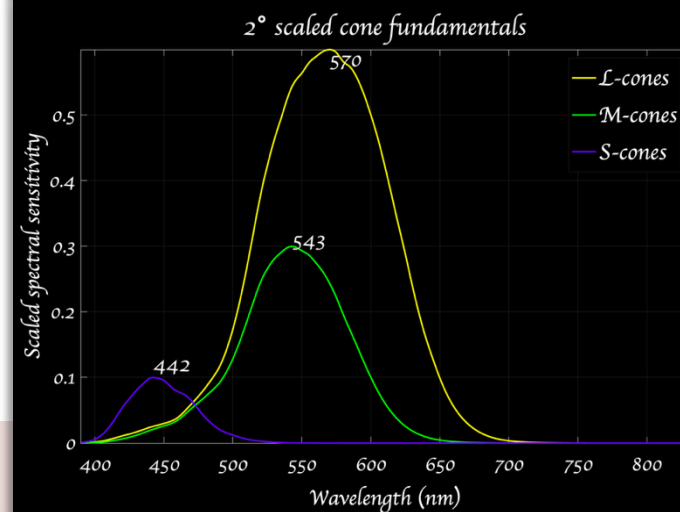
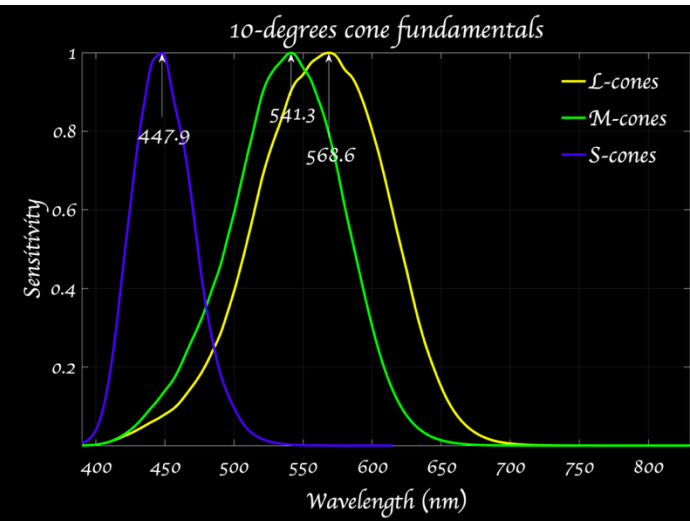
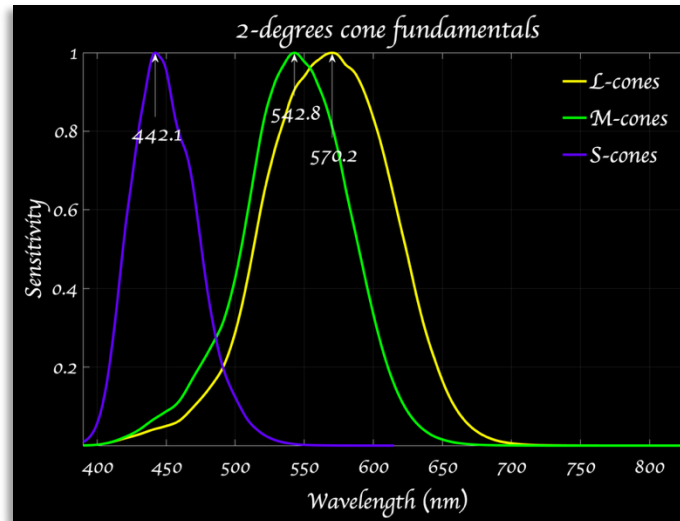
Biological image formation



- Energy footprint
 - Requires the metabolism of large amounts of energy
 - One of the most energy-efficient processes in the human body
 - Estimated to require ~20% of brain energy
 - When...the brain is estimated to consume
 - ~20% of oxygen and ~25% of glucose used for body energy production (~ 20% total energy)
- Communication footprint
 - Study in guinea pigs in 2006 showed
 - a bandwidth of ~875 kbps for $\sim 10^5$ ganglion cells in the eyes
 - Matching for the 10^6 ganglion cells of human
 - a bandwidth of 8.75 Mbps (ethernet of that period) was estimated
 - Estimation of the response speed of each neuron was
 - ~1 kHz, although the overall response is much slower (4 Hz)

Human vision specifications

- Spectral sensitivity
- L:M:S=60:30:10



Human vision specifications



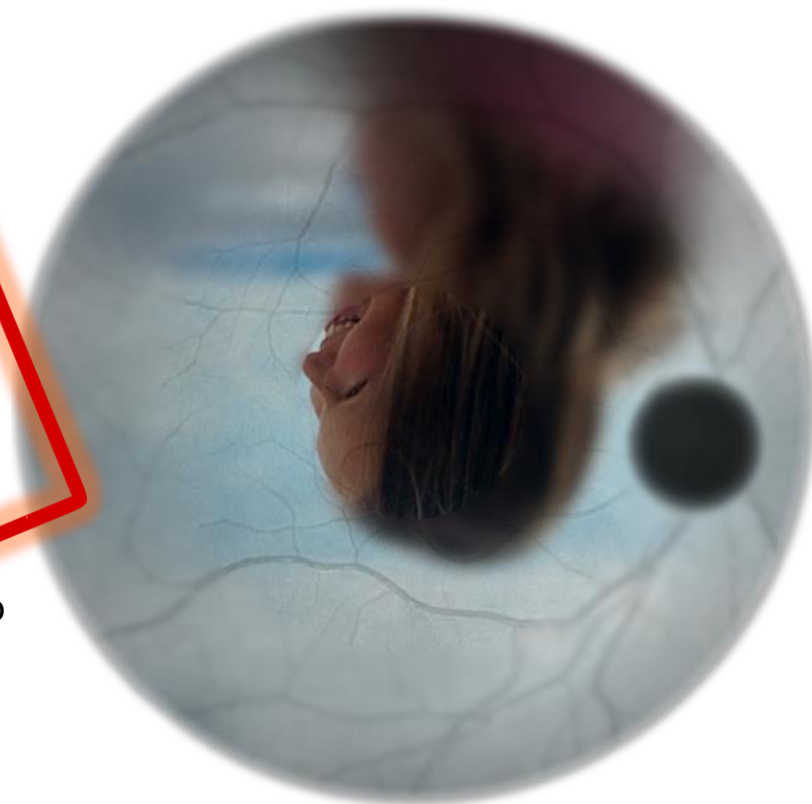
- Assuming only cones in the central area
- For an eye with a viewing angle of 170° horizontal and 150° vertically

$$R = a_{\text{horiz. degrees}} \times \frac{60 \text{ arc-minutes per degree}}{\text{arc-minutes per pixel}} \times a_{\text{vert. degrees}} \times \frac{60 \text{ arc-minutes per degree}}{s \text{ arc-minutes per pixel}} \Rightarrow$$

- For two eyes at the same time, that viewing angle 120° horizontal and 150° per vertical

$$R = 120 \times \frac{60}{0.39} \times 150 \times \frac{60}{0.39} \Rightarrow$$

$$R \approx 426.035.500$$



Human vision specifications

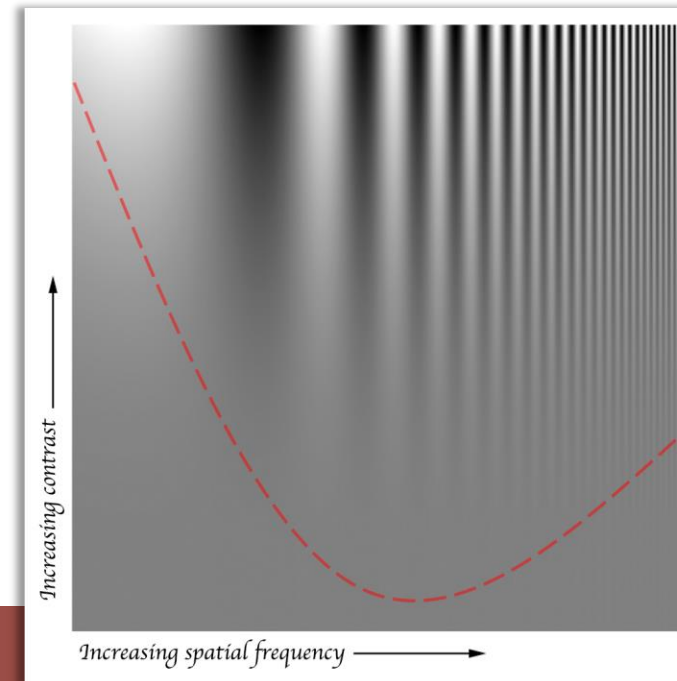
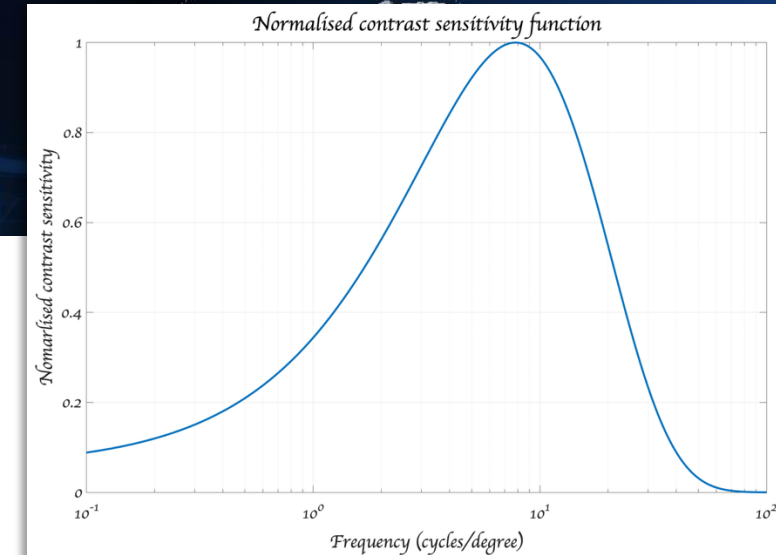
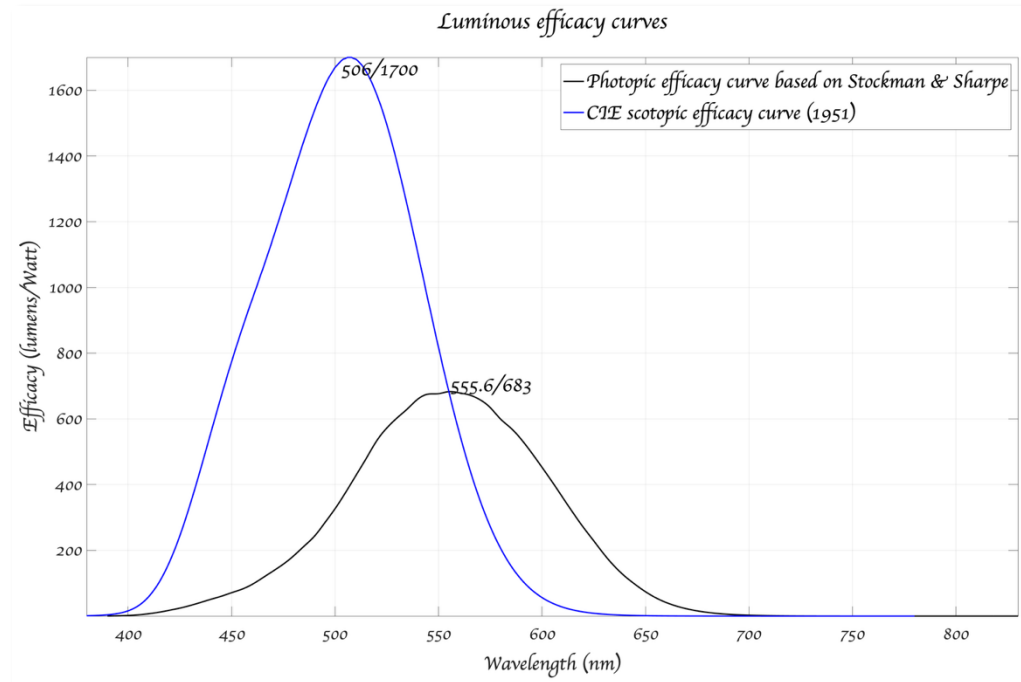
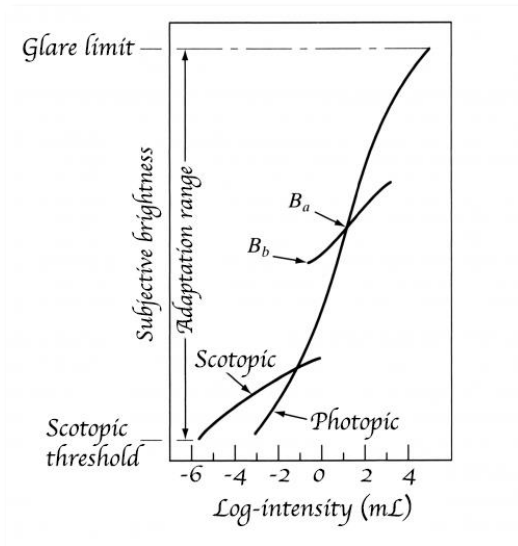


- Initially
 - L, M, S color parameters
- Further codification
 - (L+M) color parameter
 - brightness
 - (L-M) color parameter
 - red-green contrast
 - S-(L+M) contrast color parameter
 - blue-yellow contrast



Human vision specifications

- Sensitivity to intensity and wavelength
- Sensitivity to contrast



Human vision specifications



- **Luminous efficacy function**

- Quantification of the average spectral sensitivity of human vision
- First standardized in CIE 1931 standard
 - Improved since then many times
- Day-time vision maximum sensitivity is
 - at 555 nm with a value of 683 lm.W⁻¹
- Night-time vision maximum sensitivity is
 - at 506 nm with a value of 1700 lm.W⁻¹
- Practically the luminous flow is resulting

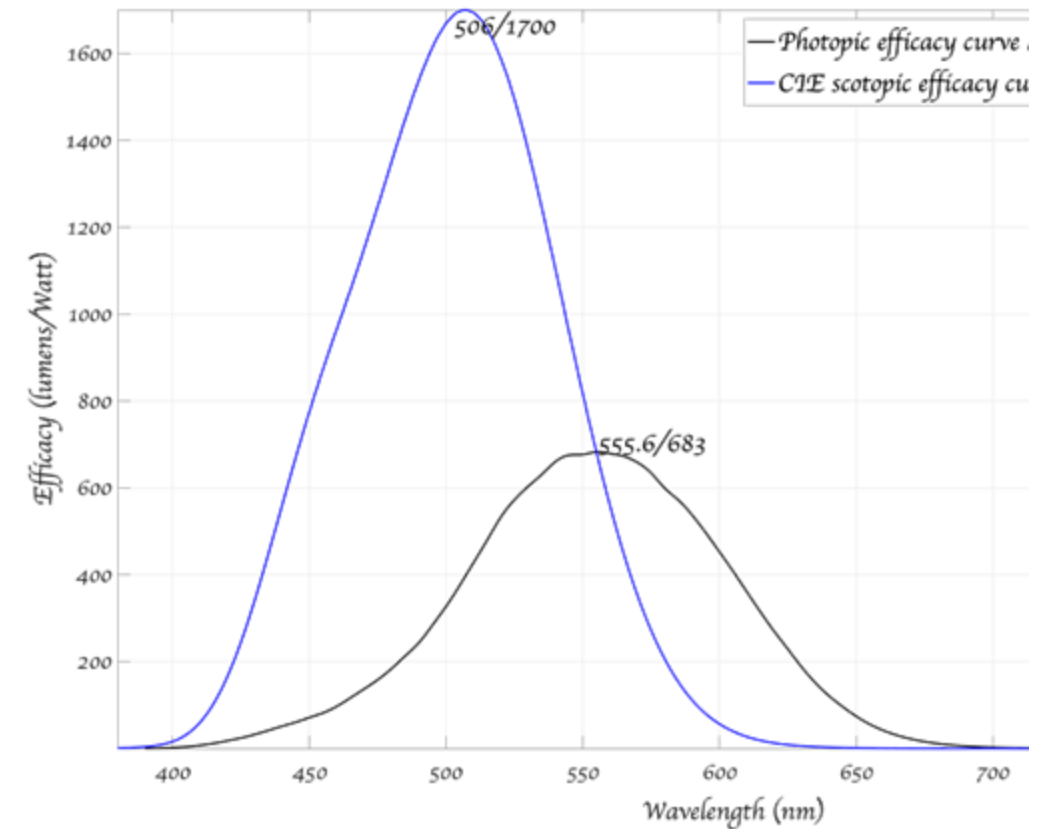
$$\Phi_v = 683 \cdot \int_0^\infty V(\lambda) \Phi_{e,\lambda} d\lambda$$

- For a monochromatic source

$$\Phi_v = 683 \cdot V \cdot \Phi_e$$

- Overall, the response of a viewer R to a light with spectral power distribution S(λ) is

$$R = \int_{\lambda_{min}}^{\lambda_{max}} V(\lambda) S(\lambda) d\lambda$$

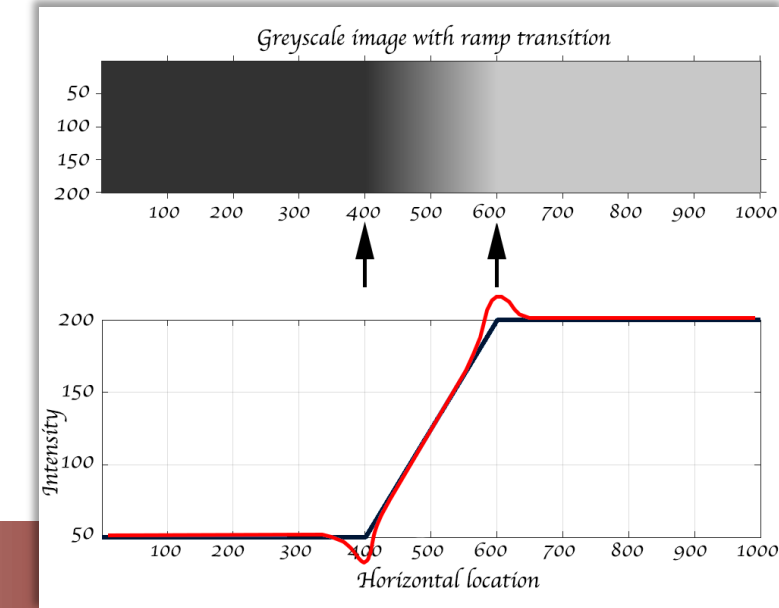
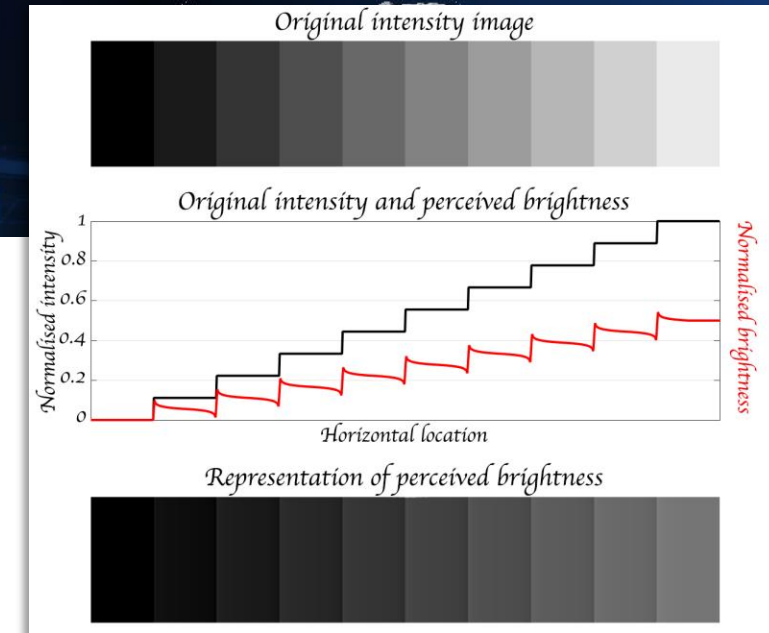
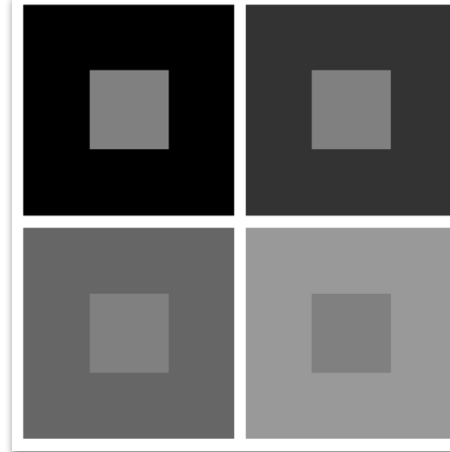
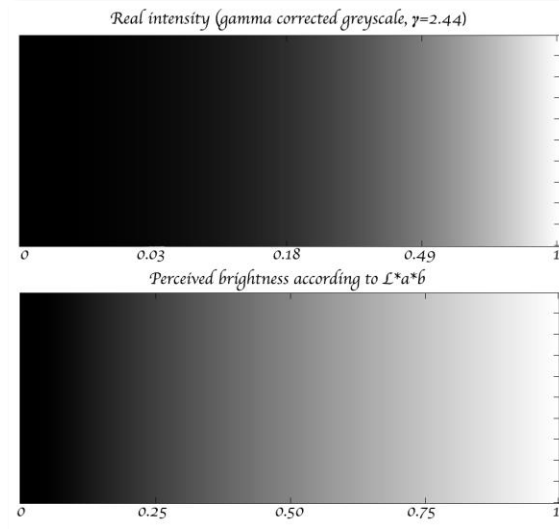
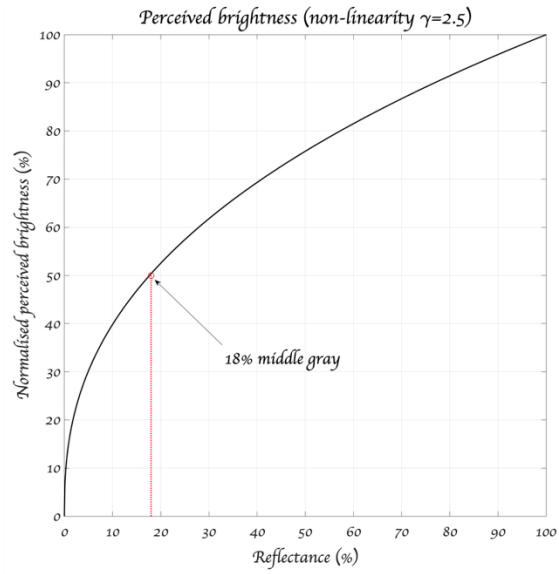


Example 1: 10 mW red laser pointer at 680 nm produces a luminous power of $0.010 \times 0.0163 \times 683 = 0.111$ lm

Example 2: 10 mW red laser pointer at 630 nm produces a luminous power of $0.010 \times 0.275 \times 683 = 1.88$ lm

Human vision specifications

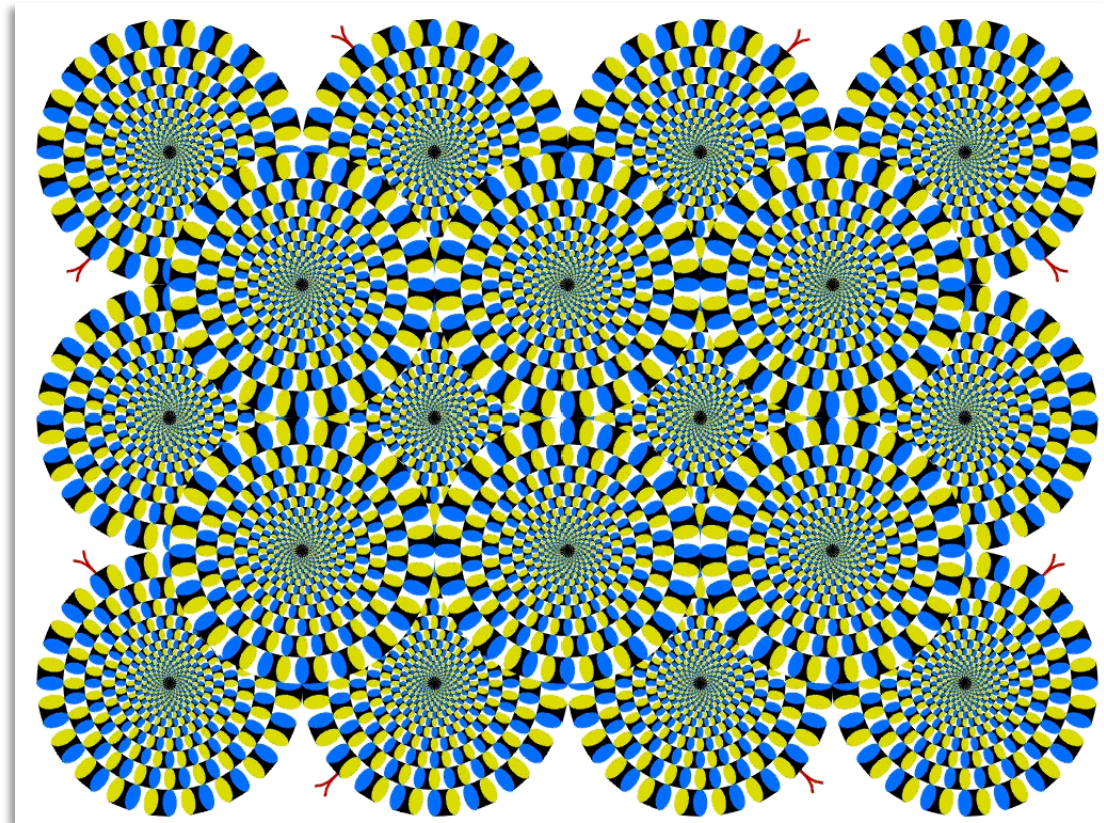
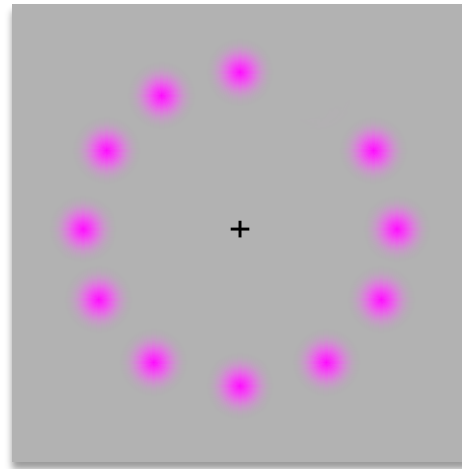
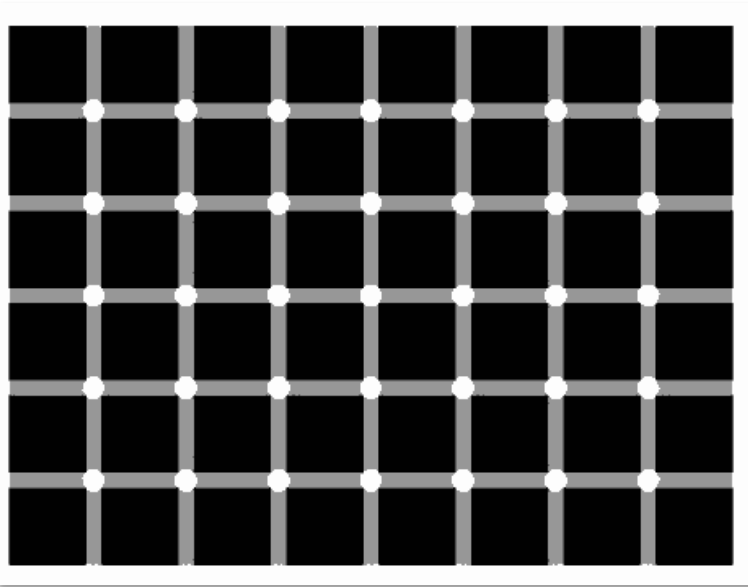
- Response to brightness
- Response to brightness gradations
- Response to relative contrast



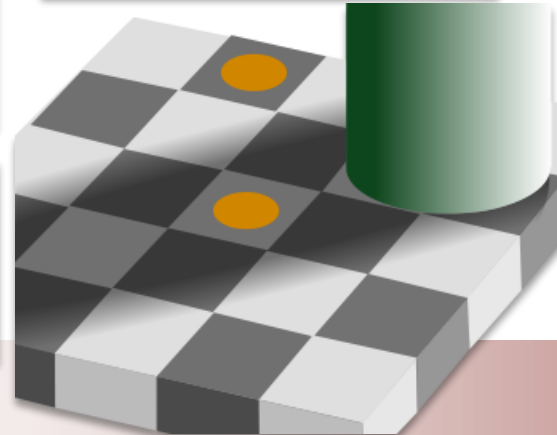
Human vision specifications



- Psychovision – psychology of vision



SCHRÖDINGER'S CAT IS
ALIVE



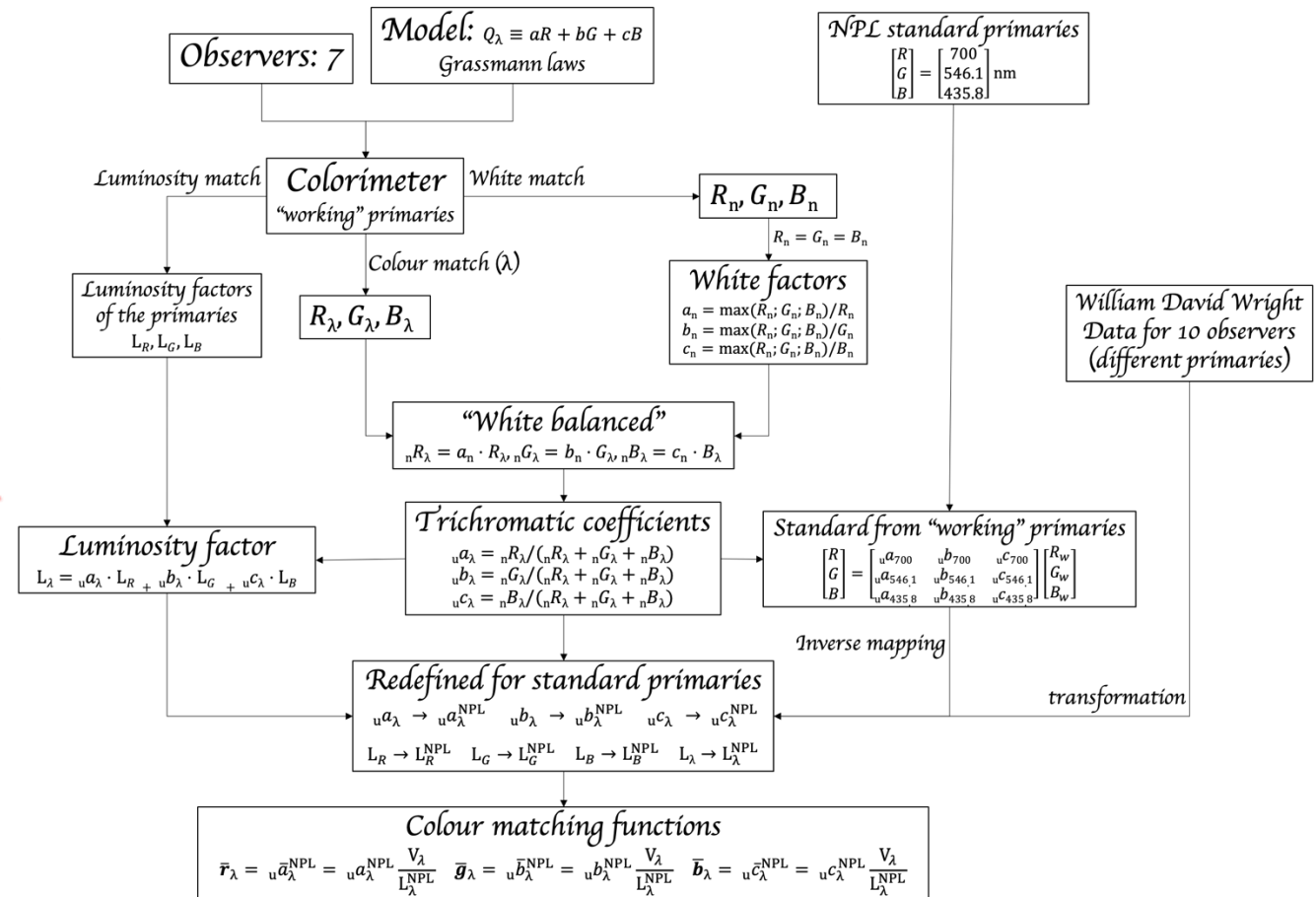
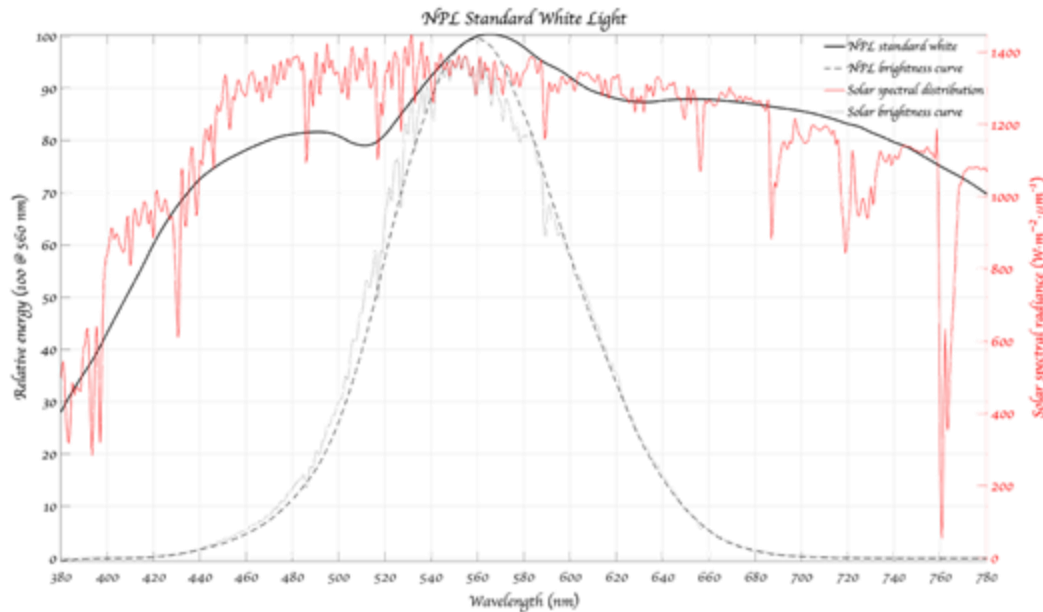
Human vision specifications



- John Guild / CIE color standardization
 - Early 20th century – need for standardization in color theory
 - Standardization of the “standard observer”
 - Standardization of the response to light of the standard observer (“fundamentals”)
 - Standardization of “color matching functions”
 - Standardization of a “standard color space”

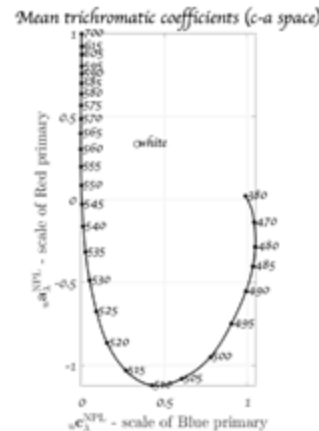
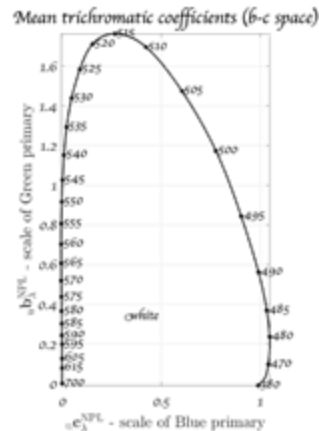
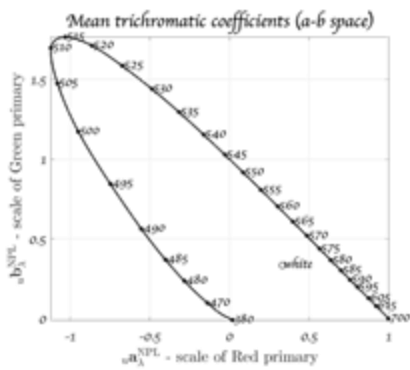
Human vision specifications

- John Guild's intricate setup

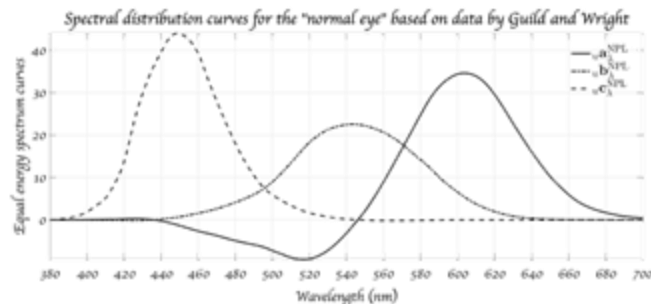
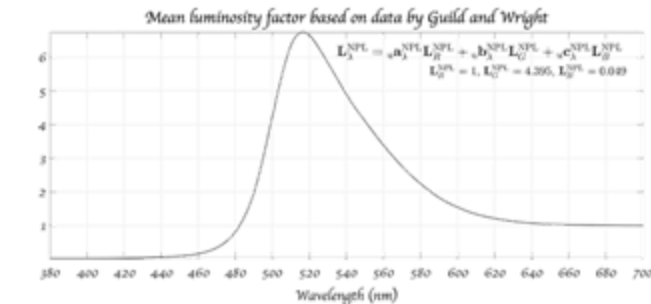
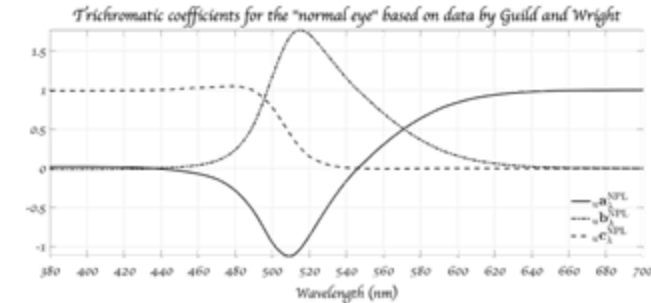
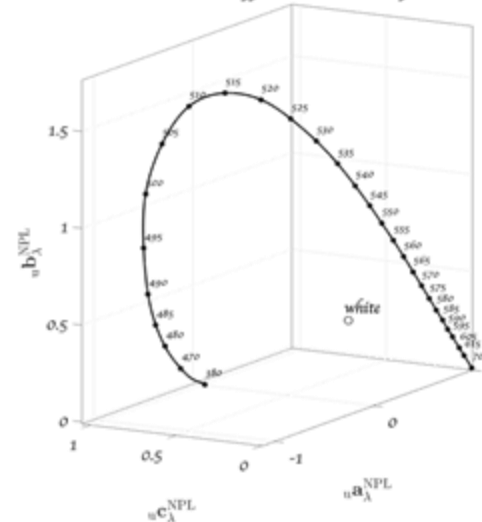


Human vision specifications

- John Guild's results
 - Specification of the standard observer
 - Chromaticity diagrams
 - Spectral distribution curves



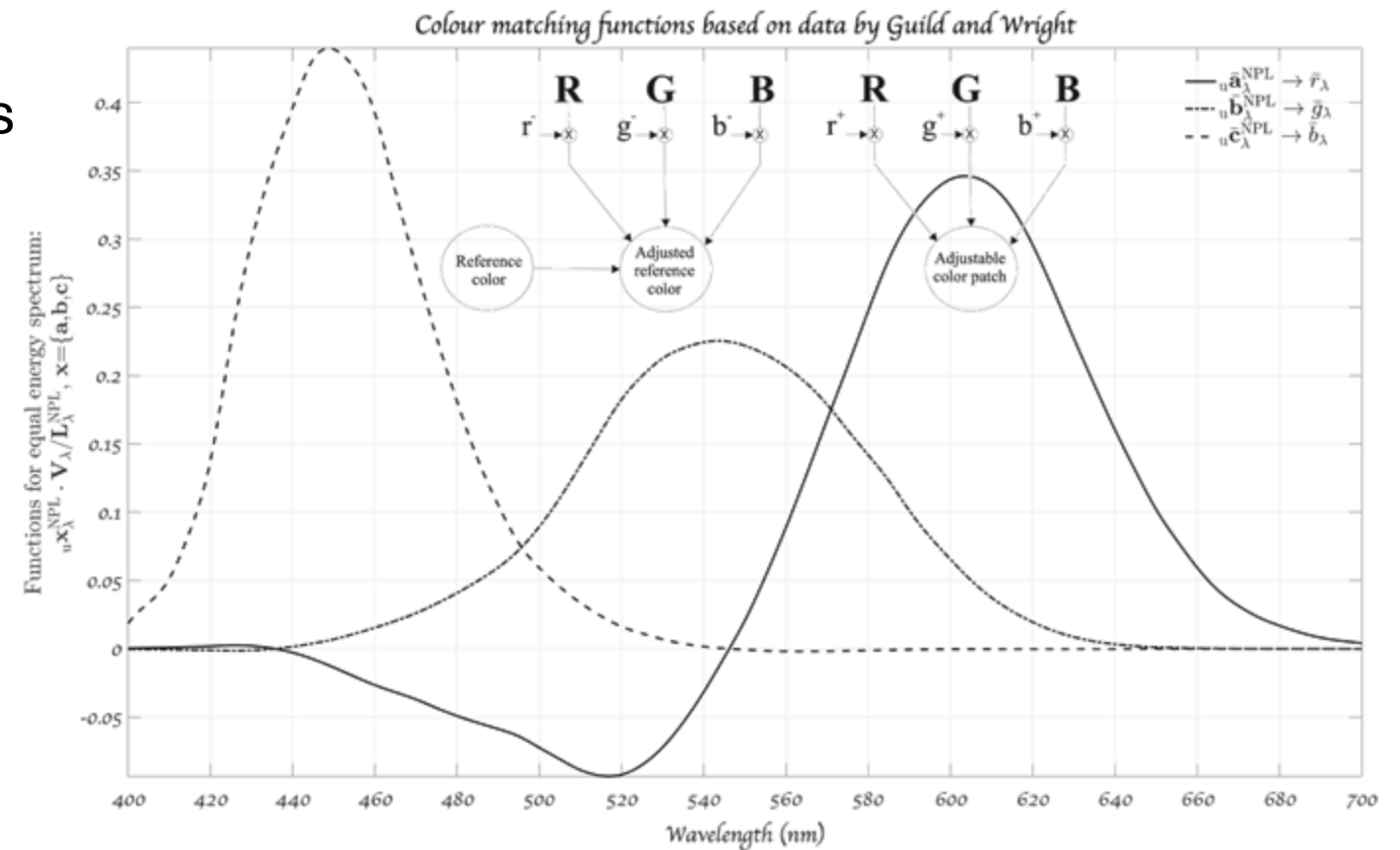
Mean trichromatic coefficients in 3D representation



Human vision specifications



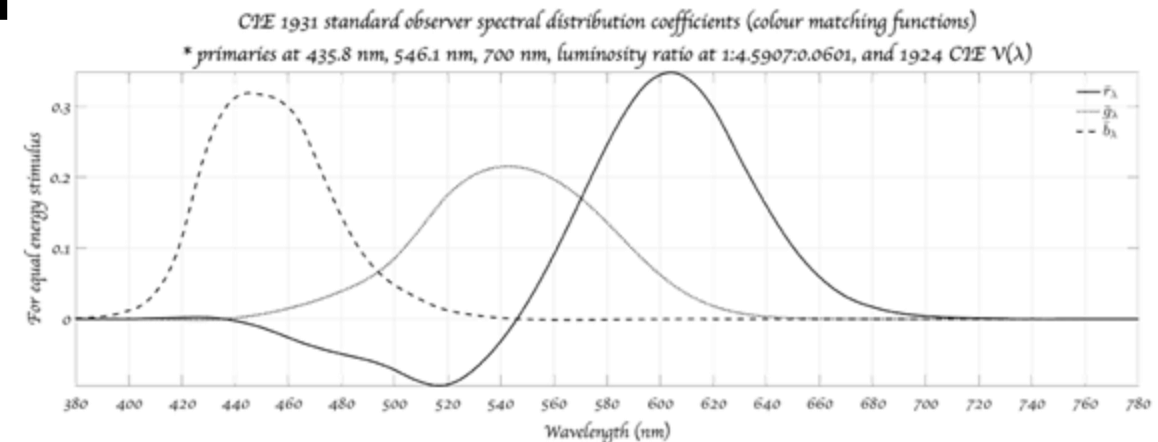
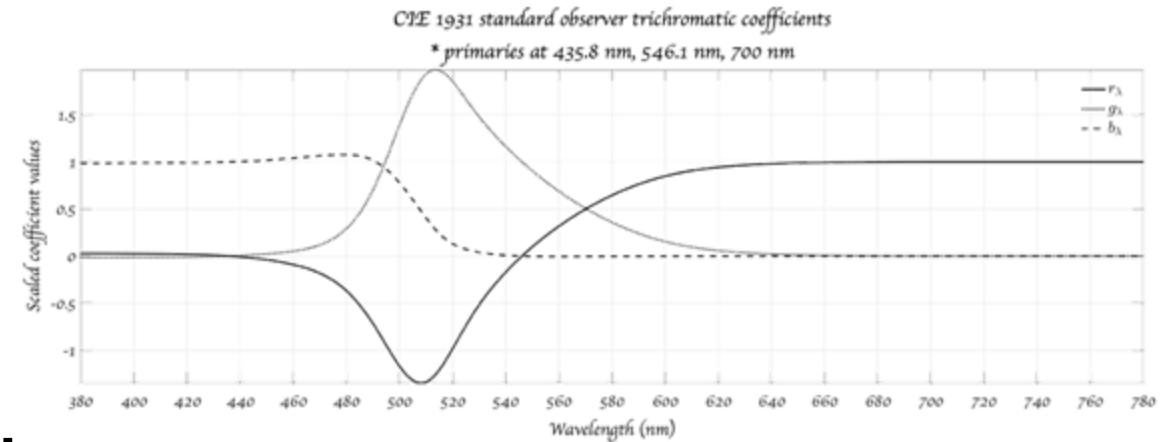
- John Guild's results
 - Colour matching functions for the NPL primaries



Human vision specifications



- John Guild's results
 - Standard observer coefficients
 - Color matching functions
- **The definition of the standard observer in the CIE 1931 standard**

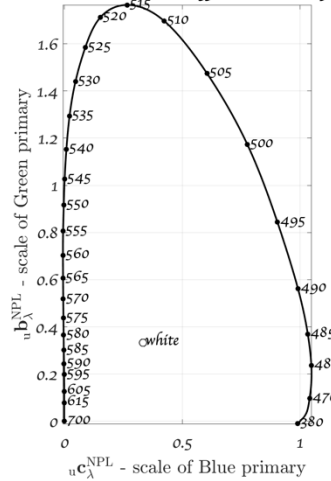


Human vision specifications

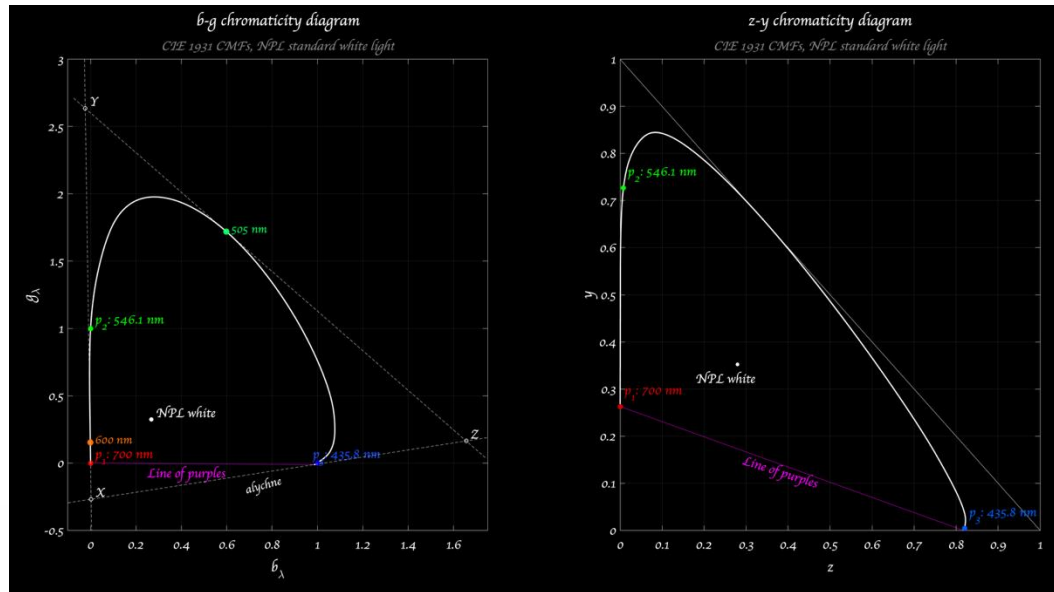
- CIE 1931 XYZ standardization



Mean trichromatic coefficients (*b-c space*)

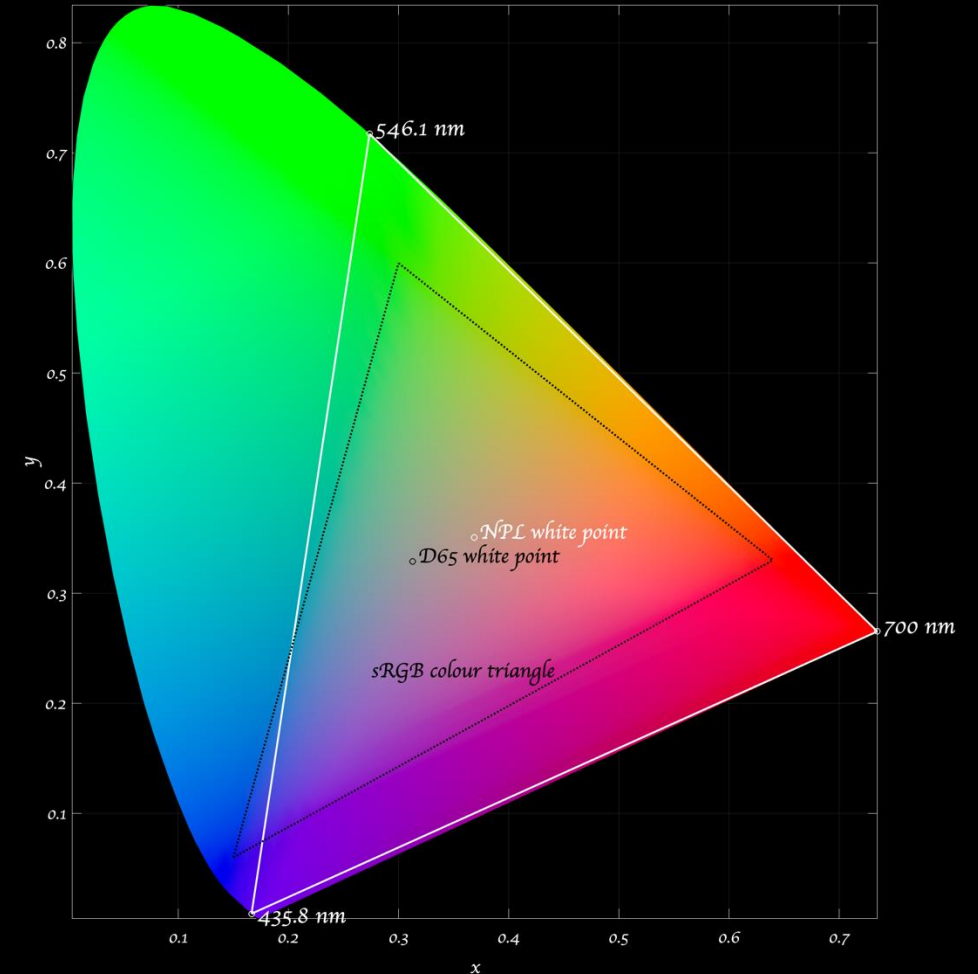


CIE 1931 XYZ

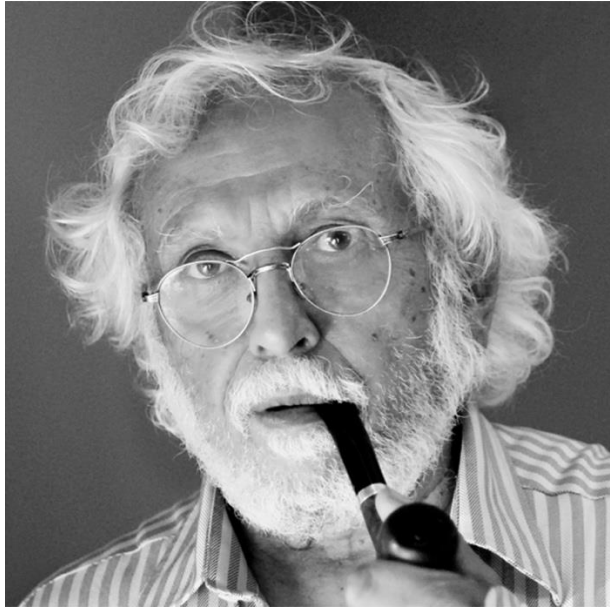


The standard NPL primaries for colorimetric specification

CIE 1931 CMFs, NPL standard white light



Light



Grammatikakis (1939-2023)

“I was born centuries before centuries ago, in a Space where there was no space and in a Time where there was no time. In a strange way, however, I feel that I pre-existed my birth. And while everything has changed since then, I feel that nothing has changed. My presence measures the eternal.”

2005, The Autobiography of Light

Image



Hermann Ludwig
Ferdinand von
Helmholtz, 1821-1894

“It is by the eye alone that we know the countless shining worlds that fill immeasurable space, the distant landscapes of our earth, with all the varieties of sunlight that reveal them, the wealth of form and colour among flowers, the strong and happy life that moves in animals. Next to the loss of life itself, that of eyesight is the heaviest.”

Opening of the 1868 lecture on the *Recent progress of the theory of vision*

Digital image

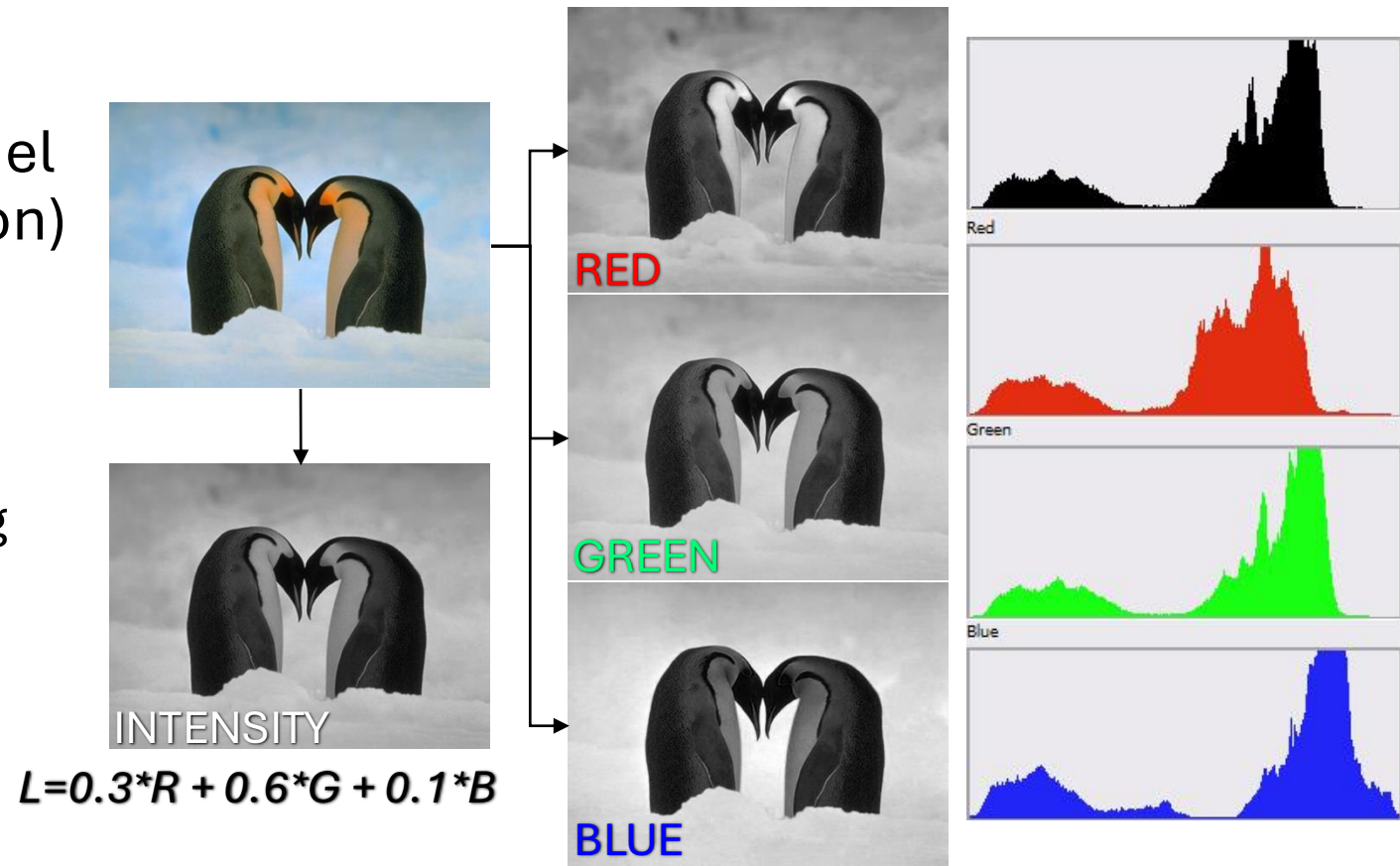
Introduction to digital imaging



A model for digital images



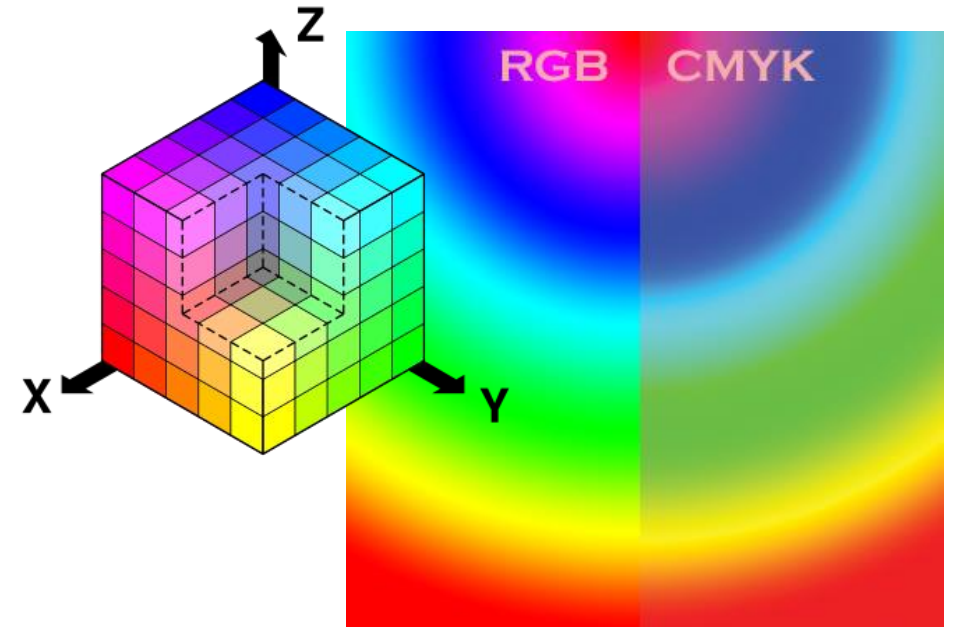
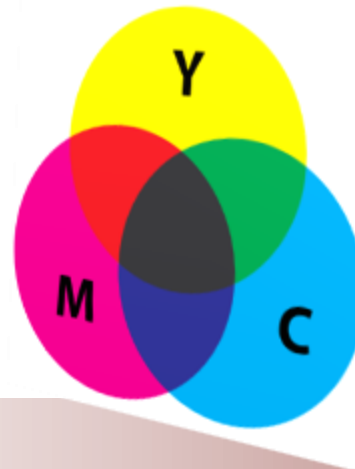
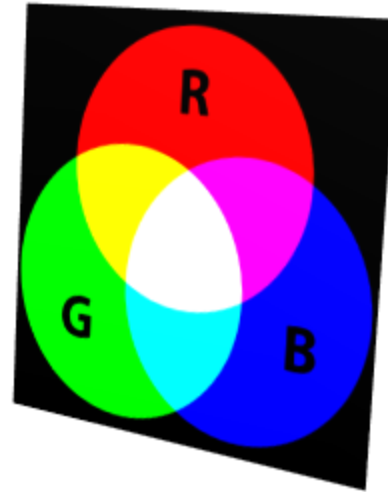
- Following vision research
 - Adopted a trichromatic model (three channel representation)
 - RGB additive color system
 - Red, Green, Blue primaries
 - For each channel (typical)
 - Information content encoding
 - (Pict)ure (El)ement $\rightarrow$ Pixel
 - 8 bits (1 byte) per pixel



A model for digital images



- Color systems
 - Additive RGB
 - Suitable for displays
 - Subtractive CMYK
 - Suitable for printers



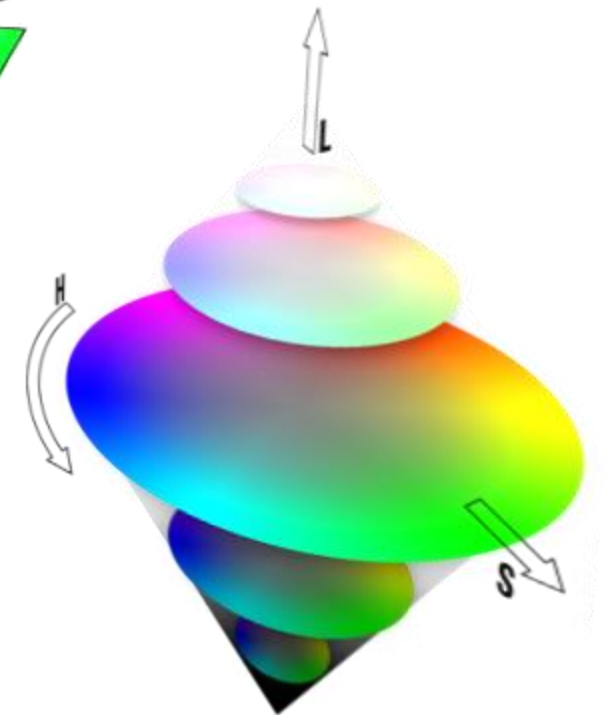
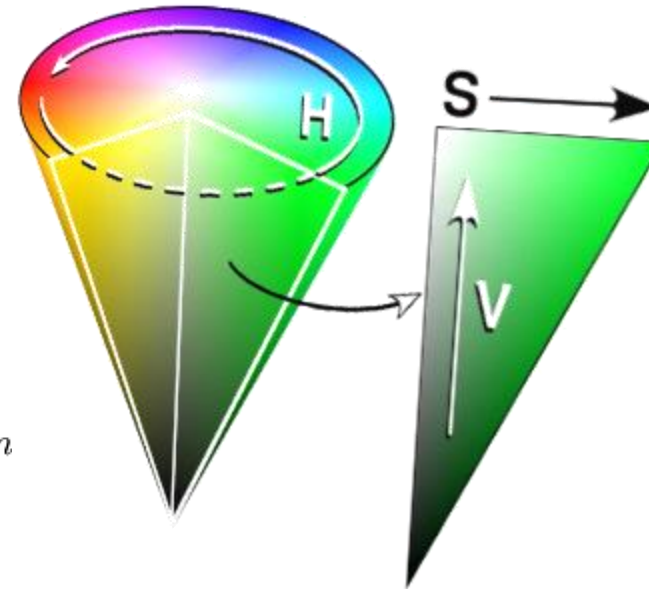
A model for digital images



- Color systems

- HSV (Hue, Saturation, Value)

$$h = \begin{cases} \text{undefined} & \text{if } \max = \min \\ 60^\circ \times \frac{g-b}{\max-\min} + 0^\circ, & \text{if } \max = r \text{ and } g \geq b \\ 60^\circ \times \frac{g-b}{\max-\min} + 360^\circ, & \text{if } \max = r \text{ and } g < b \\ 60^\circ \times \frac{b-r}{\max-\min} + 120^\circ, & \text{if } \max = g \\ 60^\circ \times \frac{r-g}{\max-\min} + 240^\circ, & \text{if } \max = b \end{cases}$$
$$l = \frac{1}{2}(\max + \min)$$
$$s = \begin{cases} 0 & \text{if } l = 0 \text{ or } \max = \min \\ \frac{\max-\min}{\max+\min} = \frac{\max-\min}{2l}, & \text{if } 0 < l \leq \frac{1}{2} \\ \frac{\max-\min}{2-(\max+\min)} = \frac{\max-\min}{2-2l}, & \text{if } l > \frac{1}{2} \end{cases}$$



- HSL (Hue, Saturation, Luminance)

$$s = \begin{cases} 0, & \text{if } \max = 0 \\ \frac{\max-\min}{\max} = 1 - \frac{\min}{\max}, & \text{otherwise} \end{cases}$$
$$v = \max$$

A model for digital images



- Broadcast color systems
 - YUV (PAL), YCbCr
 - YIQ (NTSC)

$$Y = \left\lfloor \frac{R + 2G + B}{4} \right\rfloor$$

$$U = B - G$$

$$V = R - G$$

$$\begin{pmatrix} Y \\ Cb \\ Cr \end{pmatrix} = \begin{pmatrix} 0,299 & 0,587 & 0,114 \\ -0,16875 & -0,33126 & 0,5 \\ 0,5 & -0,41869 & -0,08131 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$



R



Y



G



U/Cb



B



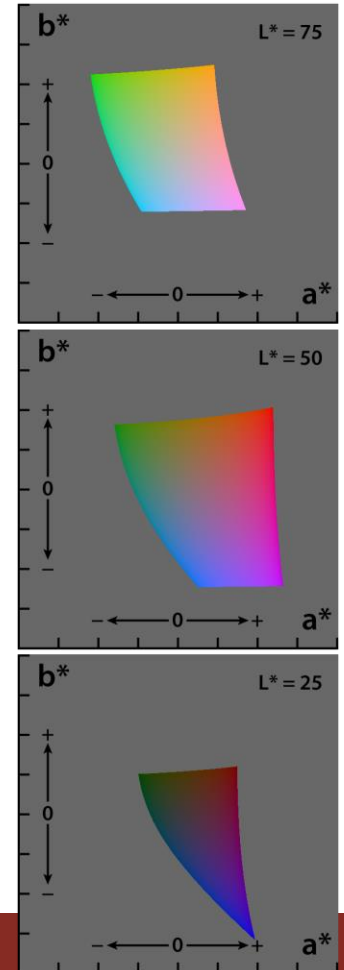
V/Cr

A model for digital images

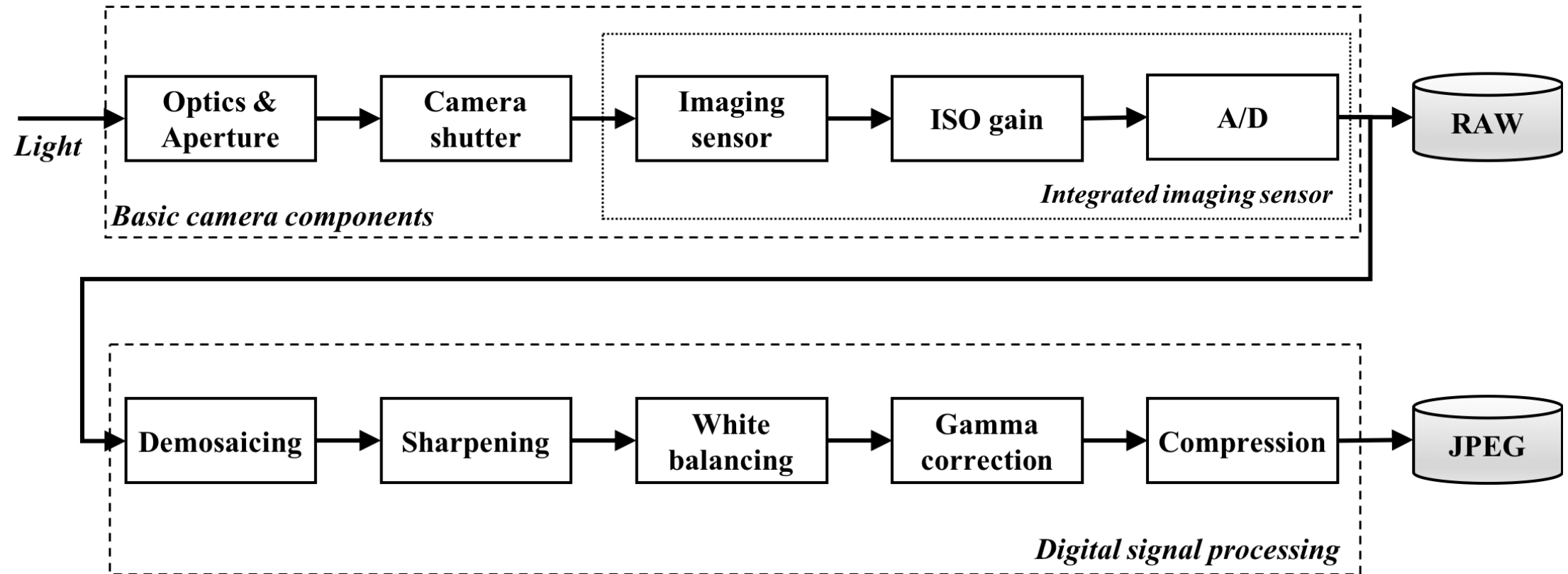


- Advanced color systems to match human performance
 - CIE L*a*b* / LUV / sCIE Lab
 - Transformation through CIE 1931 XYZ

$$\begin{aligned}L^* &= 116 f(Y/Y_n) - 16 \\a^* &= 500 [f(X/X_n) - f(Y/Y_n)] \\b^* &= 200 [f(Y/Y_n) - f(Z/Z_n)]\end{aligned}$$



A camera model for digital photography

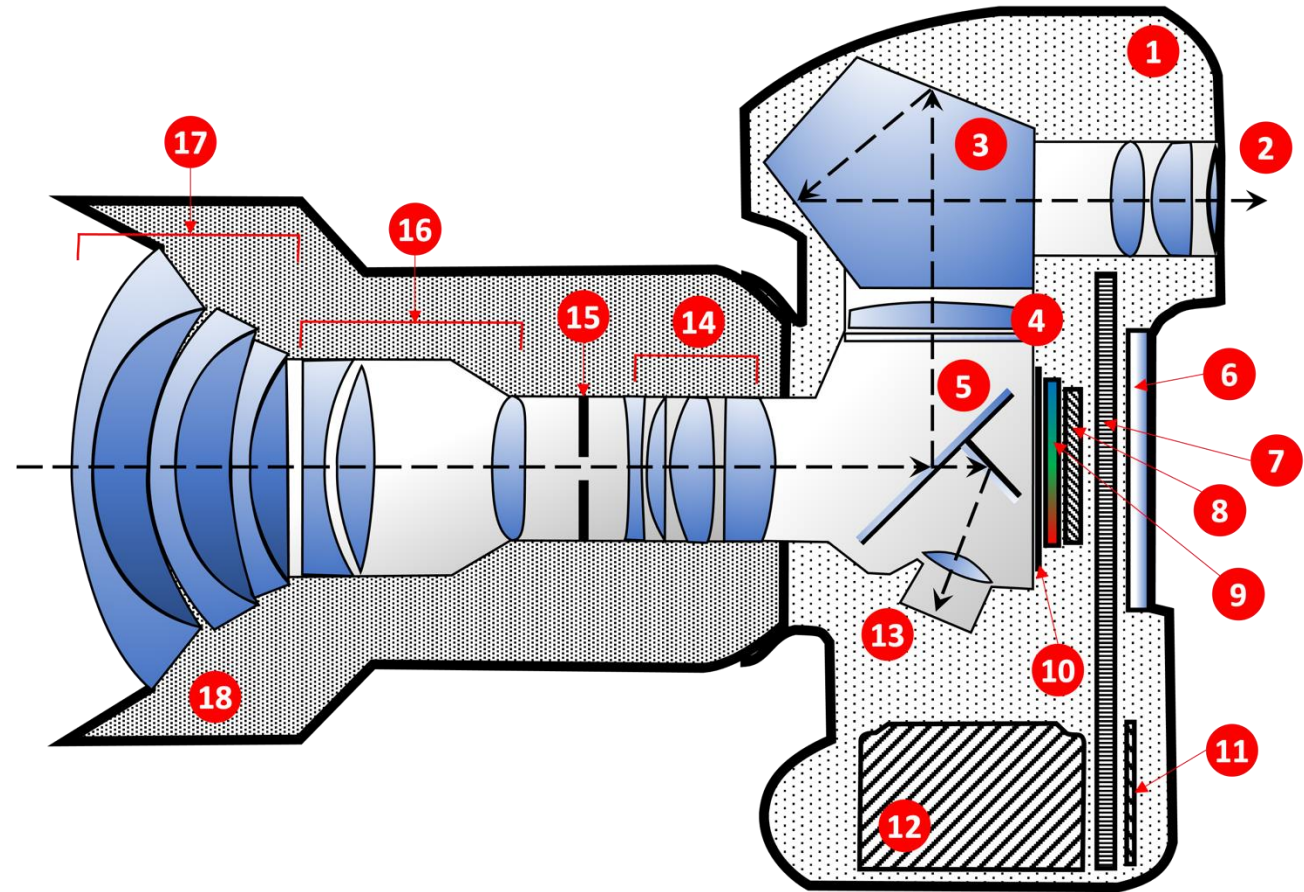


Capturing digital images



- Involves
 - Optics
 - Quantum mechanics / photoelectric effect
 - Signal processing
 - demosaicing, amplification, white balancing, gamma correction, data conversion, noise reduction, data compression and imaging standards
 - Digital file management
 - Mechatronics
 - Encoded knowledge of the standard observer
 - Encoded knowledge of color representation models

Capturing digital images



Bibliography

