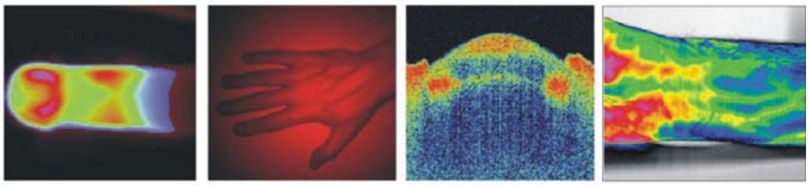
Applied Optoelectronics in Medicine

Aplikovaná optoelektronika v lékařství

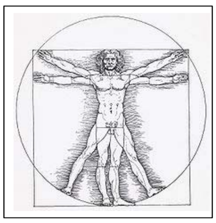
Interdisciplinary course at the CTU Prague (P317APL-E, W, 4 credits)

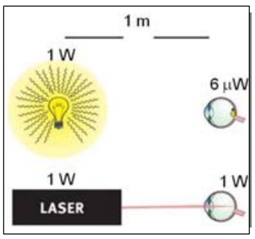


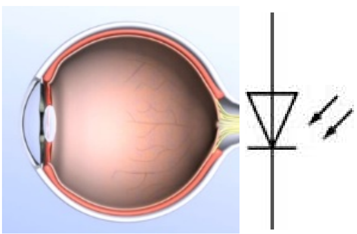
3. Metrological aspects in optoelectronics, light perception
3. Metrologické aspekty optoelektroniky, biofyzika vnímání světla

Learning aims of the third AOM lecture

- Metrology, optoelectronics, photonics - definitions
- Radiation intensity, optical power, radiometry, photometry
- Light perception, sensitivity of the human eye, objective and subjective color valuation
- Eyes in animal kindom





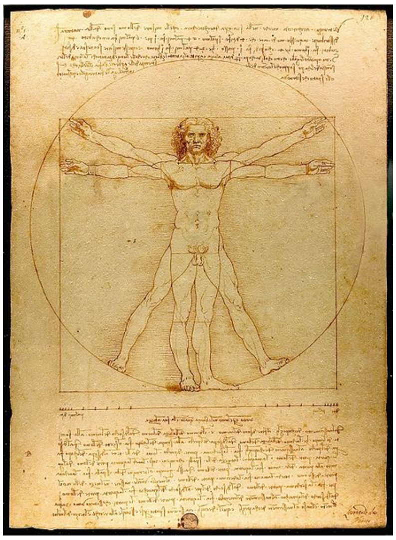


What is metrology ?

Metrology is defined by the International Bureau of Weights and Measures (BIPM) as "the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology”.

Metrology includes also all aspects of measurement. The word comes from Greek μέτρον (*metron*), "measure“ and "λόγος" (*logos*), amongst others meaning "speech, oration, discourse, quote, study, calculation, reason".

In Ancient Greek the term μετρολογία (*metrologia*) meant "theory of ratios".

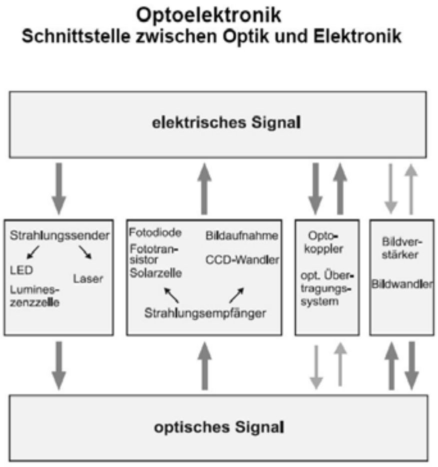


Origin of all dimensions:
The **Vitruvian Man**
(drawing created by Leonardo da Vinci
circa 1490)

What is optoelectronics?

Optoelectronics is the study and application of electronic devices that source, detect and control light, usually considered a sub-field of photonics. In this context, *light* often includes invisible forms of radiation such as gamma rays, X-rays, ultraviolet and infrared, in addition to visible light.

Optoelectronic devices are electrical-to-optical or optical-to-electrical transducers, or instruments that use such devices in their operation. *Electro-optics* is often erroneously used as a synonym, but is in fact a wider branch of physics that deals with all interactions between light and electric fields, whether or not they form part of an electronic device.



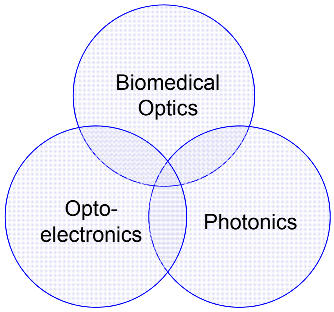
Remember:
The term optoelectronics connotes devices or circuits that comprise both electrical and optical functions.

wikipedia.org/wiki/Optoelectronics

What is photonics?

The word photonics is derived from the Greek word "photos" meaning light; it appeared in the late 1960s to describe a research field whose goal was to use light to perform functions, that traditionally fell within the typical domain of electronics, such as telecommunications, information processing, etc. Photonics as a field began with the invention of the laser in 1960. Though coined earlier, the term photonics came into common use in the 1980s as fiber-optic data transmission was adopted by telecommunications network operators. In a broader sense it is today in use also for “nonclassical optical technologies” (eg biophotonics).

The term **biophotonics** denotes a combination of biology and photonics, with photonics being the science and technology of generation, manipulation, and detection of photons, quantum units of light. It can also be described as the "development and application of optical techniques, particularly imaging, to the study of biological molecules, cells and tissue". One of the main benefits of using optical techniques which make up biophotonics is that they preserve the integrity of the biological cells being examined. Biophotonics has therefore become the established general term for all techniques that deal with the interaction between biological items and photons.

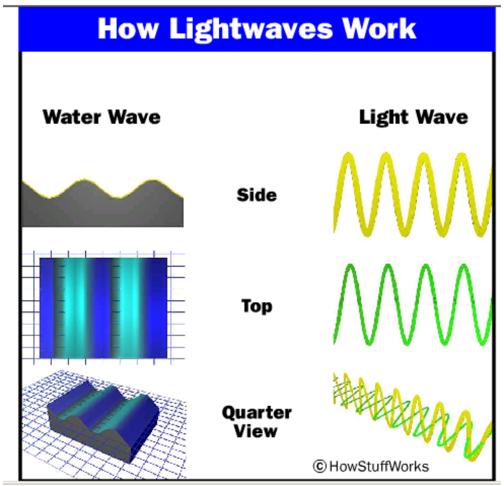


Periodic events in space and time: Vibrations and waves

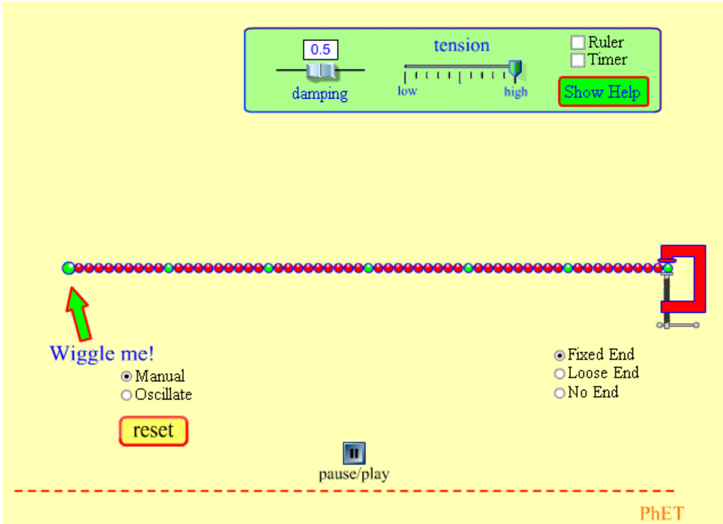
Remember:

- *Oscillations are periodic processes in time (e.g. pendulum, molecular vibration)*
- *Harmonic oscillations are periodic processes, which magnitude follows a sinusoidal function.*
- *Waves are periodic processes in time and space (e.g. water waves, light waves)*

light-waves.swf



Example: Damped / non-damped transverse wave



stringWave.swf

Metrological aspects of optoelectronics

Radiation intensity, radiometry, photometry, physiological optics

Radiant flux

Radiant energy per unit time, also called radiant power.

$$\Phi = \frac{dW}{dt}; \quad [\Phi] = W(watt)$$

Poynting vector

The magnitude of the Poynting vector describes the radiant energy, that is transported perpendicular to the surface unit area per unit time..

$$\vec{S} = \vec{E} \times \vec{H}; \quad \left[\vec{S}\right] = \frac{W}{m^2}$$

Propagation of elektromagnetic waves in vacuum (ε_r=1; μ_r=1) :

$$\left|\vec{S}\right| = \left|\vec{E}\right| \cdot \left|\vec{H}\right| = \sqrt{\frac{\varepsilon_0}{\mu_0}} \cdot \left|\vec{E}\right|^2 = \left|\vec{E}\right|^2 / Z_0$$

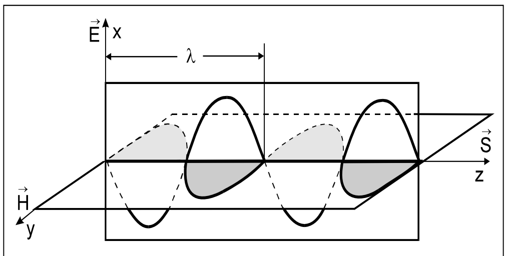
with

$$E = E_0 \cdot \cos(\vec{k}\,\vec{r} - \omega t); \quad [E] = \frac{V}{m}$$

Radiant intensity

For a plane linearly polarized wave, propagating in the +z direction is:

$$E = E_0 \cos(kz - \omega t)$$



Linearly polarized plane wave

For the high optical frequencies (from practical reasons) we introduce a scalar, time-averaged magnitude: the **radiation intensity I**. (Irradiance or radiant flux density.)

$$I = \left\langle \left|\vec{S}\right| \right\rangle; \quad [I] = \frac{W}{m^2}$$

Relation between the radiation intensity and the electric field strength:

$$I = \left\langle \left|\vec{S}\right| \right\rangle = \frac{1}{T}\int_0^T \left|\vec{S}\right| dt; \quad T = \frac{2\pi}{\omega}$$

$$I = \sqrt{\frac{\varepsilon_0}{\mu_0}} \left\langle \left|\vec{E}\right|^2 \right\rangle = \frac{1}{T}\sqrt{\frac{\varepsilon_0}{\mu_0}} \int_0^T E_0^2 \cos^2(kz - \omega t)\, dt$$

After performing integration for z = 0, we obtain an expression, where the radiation intensity is proportional to the square of the amplitude of the electric field strength..

$$I = \frac{1}{2} E_0^2 \sqrt{\frac{\varepsilon_0}{\mu_0}} = \frac{1}{2} c_0 \varepsilon_0 E_0^2; \quad c_0 = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

c_0 ... Light speed in vacuum

Fill in the values of permittivity and permeability of vacuum:

$$\varepsilon_0 = 8{,}854 \cdot 10^{-12} \frac{As}{Vm} \quad und \quad \mu_0 = 1{,}2566 \cdot 10^{-6} \frac{Vs}{Am}$$

it gives the light speed in vacuum:

$$c_0 = 2{,}998 \cdot 10^8 ms^{-1}$$

In all matter other than vacuum, light propagates slower

Remember: *The product of ε_0 and μ_0 has purely mechanical dimension (reciprocal value of velocity).*
The „quotient“ of μ_0 mit ε_0 has purely electrical dimension (resistance).

Speed of light c, frequency f, wave number ρ

$$c = \frac{1}{\sqrt{\varepsilon_0 \varepsilon_r \mu_0 \mu_r}}; \quad \mu_r = 1$$

$$\lambda = \frac{c}{f} = \frac{1}{\rho}$$

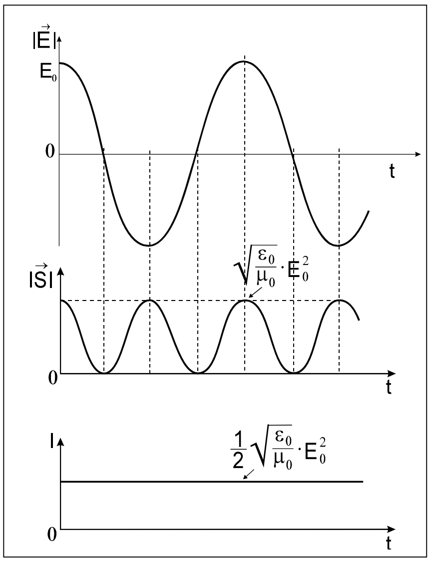
Absolute refraction-index:

$$n = \frac{c_0}{c} = \sqrt{\varepsilon_r}$$

Radiation intensity in optically dense matter (mit $\varepsilon_r > 1$ and $\mu_r = 1$) and applying the rule:

$$\vec{E} = \mathrm{Re}\{\dot{\vec{E}}\}$$

$$I = \frac{1}{2} c_0 \varepsilon_0 n E_0^2 = \frac{1}{2} c_0 \varepsilon_0 n \langle \dot{\vec{E}} \dot{\vec{E}}^* \rangle$$



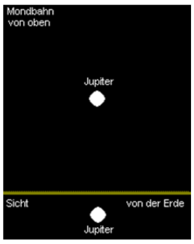
History of measuring the speed of light

1) **Galileo Galilei** attempted in 16th century to measure the speed of light, in which he positioned two men with lanterns on mounds at 100 meters distance to each other...

(1564 – 1642)

2) **Ole Roemer** discovered in 1676, by observing the moons of Jupiter, that the time between the eclipses grew up, when the Earth became more distant ...

(1644 – 1710)



Increased accuracy of *c* and redefinition of the meter and second

In the second half of the 20th century much progress was made in increasing the accuracy of measurements of the speed of light, first by cavity resonance techniques and later by laser interferometer techniques. These were aided by new, more precise, definitions of the meter and second. In 1960, the meter was redefined in terms of the wavelength of a particular spectral line of krypton-86, and, in 1967, the second was redefined in terms of the hyperfine transition frequency of the ground state of caesium-133.

In 1972, using the laser interferometer method and the new definitions, a group at NBS in Boulder, Colorado determined the speed of light in vacuum to be c = 299 792 456.2 ± 1.1 m/s. This was 100 times less uncertain than the previously accepted value. The remaining uncertainty was mainly related to the definition of the meter.[1] As similar experiments found comparable results for c, the 15th Conférence Générale des Poids et Mesures (CGPM) in 1975 recommended using the value 299 792 458 m/s for the speed of light.

A beam of light is depicted travelling between the Earth and the Moon in the time it takes a light pulse to move between them: 1.255 seconds at their mean orbital (surface-to-surface) distance. The relative sizes and separation of the Earth–Moon system are shown to scale. From: http://en.wikipedia.org/wiki/Speed_of_light

For real light sources

(inhomogeneous distribution of radiation intensity over an area perpendicular to the propagation, time-dependent intensity variation (modulation)) is:

$$I = I(x,y,t); \quad z = konst.$$

$$\Phi(t) = \int_{S_\perp} I(x,y,t)\,dS_\perp$$

$$\bar{I}(t) = \frac{\Phi(t)}{S_\perp}$$

Remember: *The time dependence of the radiation intensity and the radiation flux in the formula does not mean the optical carrier frequency. Optical detectors (including the eye) evaluate the radiant flux.*

Radiant energy quantities

Radiant energy

$$W = \int_{\Delta t} \Phi dt; \quad [W] = J$$

Radiant energy volume density:

$$w = \frac{dW}{dV}; \quad [w] = \frac{J}{m^3}$$

$$w = \frac{dW}{dS_\perp cdt} = \frac{I}{c}$$

$dS_\perp$ is a cross-section of an elementary cylinder of length cdt

Spectral radiant density of volume V:

$$W = \int_v w \cdot dV$$

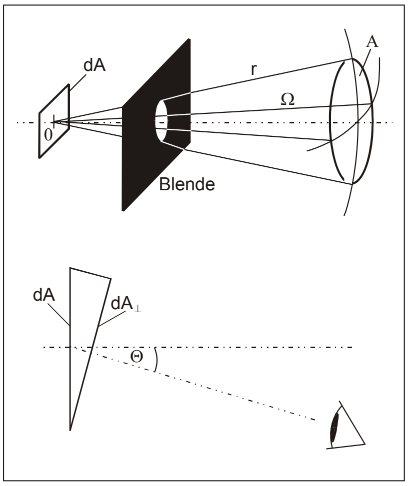
Spectral radiant energy:

$$W_\lambda = \frac{dW}{d\lambda}; \quad [W_\lambda] = \frac{J}{m}$$

Remember: *All radiometric and photometric quantities based on unitary wavelength interval are referred to as "spectral".*

Radiant energy in a wavelength interval:

$$W = \int_{\lambda_1}^{\lambda 2} W_\lambda(\lambda) d\lambda.$$



Irradiance E and radiant exitance M

$$M \;\; oder \;\; E = \frac{d\Phi}{dA}; \quad [M \;\; oder \;\; E] = \frac{W}{m^2}$$

Radiant intensity

$$I_i = \frac{d\Phi}{d\Omega}; \quad [I_i] = \frac{W}{sr}$$

Solid angle Ω

$$\Omega = \frac{A}{r^2} \cdot \Omega_0$$ mit

$\Omega_0 = 1$ sr (Steradian) ... unit solid angle

Radiation in all directions: $\Omega_G = 4\pi$ sr

Effective radiant area:

$$dA_{\perp} = dA \cdot \cos\Theta$$

Radiance L:

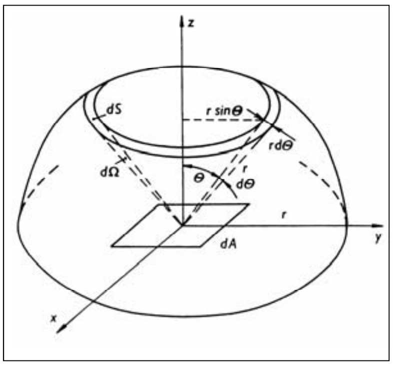
$$L = \frac{d^2\Phi}{dA\, d\,\Omega \cos\Theta} = \frac{dI_i}{dA \cos\Theta};\ [L] = \frac{W}{m^2 sr}$$

Specific case: Lambert-Area

$$I_i(\Theta) = I_i(0)\cos\Theta$$

$$L(\Theta) = \frac{dI_i(0)}{dA} = konst.$$

$$M = \pi L$$



Spectral sensitivity:
Evaluation of optical radiation by a reciever

(DIN 5031, Blatt 2)

Input variable x with $dx = x_\lambda \cdot d_\lambda$ (e.g. radiant flux)
output variable y with $dy = y_\lambda \cdot d_\lambda$ (e.g. photocurrent of the detector)
(Index λ means: "spectral density of the variable")

Absolute spectral sensitivity:

$$s(\lambda) = \frac{dy}{dx};\ s(\lambda) = \frac{y}{x}$$

Relative spectral sensitivity:

$$s(\lambda)_{rel} = \frac{s(\lambda)}{s(\lambda_0)}$$

Remember: *Most of the optical radiation detectors have a nonlinear receiver characteristics (spectral sensitivity curve)*

Spectral sensitivity of a silicon photodiode

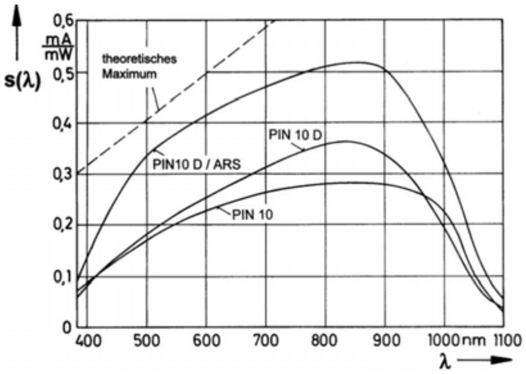
Theoretically maximal absolute spectral sensitivity (one received photon generates exactly one electron) is:

$$\frac{s(\lambda)_{max}}{\frac{mA}{mW}} = \frac{I_{ph}}{\Phi} = \frac{e}{h \cdot c}\lambda = \frac{\frac{\lambda}{nm}}{1240}$$

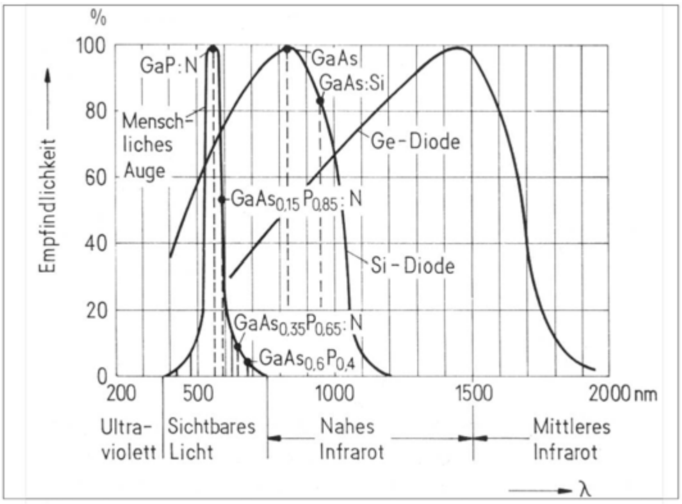
with e=1,6·10^{-19} As, c=3·10^{8} ms^{-1} u. h=6,626·10^{-34} Js

Absorption edge of Silicon (with E_{Si} = 1,1 eV):

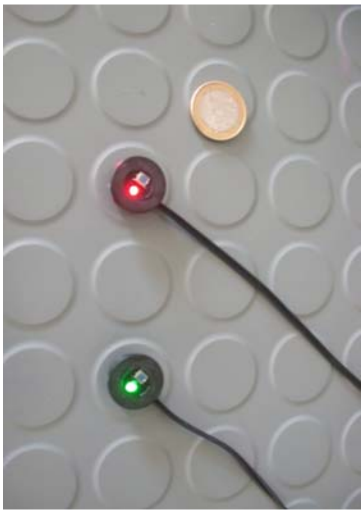
$$\lambda_{\max,Si} = \frac{c \cdot h}{E_{Si}} = 1127{,}17\ nm$$



Different light detectors (photodiodes) and their spectral sensitivity

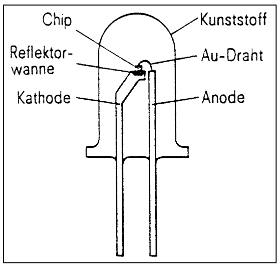


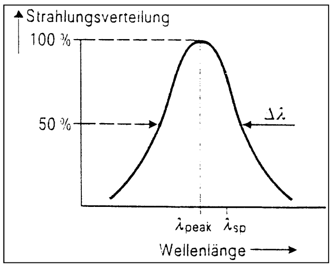
Different light detectors (photodiodes) for optoelectronic sensors



Different light emitters (LEDs) for optoelectronic sensors

Typical “hardware” form and radiation characteristic





Farbe	Wellenlänge nm	Substrat	E_g eV	Aktive Schicht
Infrarot	950	GaAs	1,4	GaAs:Si
Infrarot	800 bis 900	GaAs	1,4	GaAlAs
Rot	700	GaP	2,3	GaP:ZnO
Standardrot	660	GaAs	1,4	$GaAs_{0,6}$ $P_{0,4}$
Superrot	635	GaP	2,3	$GaAs_{0,35}$ $P_{0,65}$:N TSN
Gelb	590	GaP	2,3	$GaAs_{0,15}$ $P_{0,85}$:N TSN
Grün	565	GaP	2,3	GaP:N
Blau	480	SiC	2,8	SiC

TSN steht für Transparent Substrate Nitrogen (doped)

Basics of physiological optics

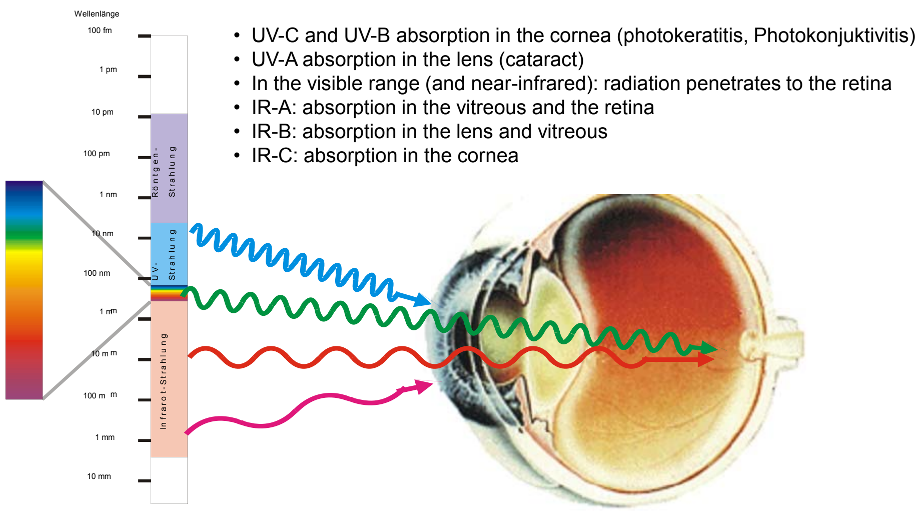
Optical radiation spectra bands

		Wavelength range [nm]	Frequency range [THz]
Ultraviolet radiation	**UV-A**	100 - 280	3000 - 1071
	UV-B	280 - 320	1071 - 937,5
	UV-C	320 - 380	937,5 - 789,5
Visible radiation (light)	**violet**	380 - 430	789,5 - 697,6
	blue	430 - 485	697,6 - 618,5
	green	485 - 560	618,5 - 535, 7
	yellow	560 - 585	535,7 - 512,8
	orange	585 - 615	512,8 - 487,8
	red	615 - 780	487,8 - 384,6
Infrared radiation	**IR-A**	780 - 1400	884,6 - 214,3
	IR-B	1400 - 3000	214,3 - 100,0
	IR-C	3000 - 1.10^6	100,0 - 0,3

The human eye as a high sensitivity photodetector

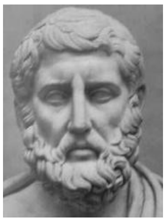
From optical point of view is our eye a transparent imaging device, with favored interactions on the **retina**

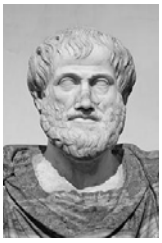
- UV-C and UV-B absorption in the cornea (photokeratitis, Photokonjuktivitis)
- UV-A absorption in the lens (cataract)
- In the visible range (and near-infrared): radiation penetrates to the retina
- IR-A: absorption in the vitreous and the retina
- IR-B: absorption in the lens and vitreous
- IR-C: absorption in the cornea



First documented speculations on the nature of light perception

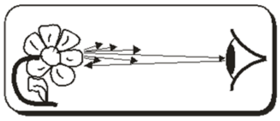
The optics developed initially out of the natural philosophical issues in Greek antiquity about the nature of vision and color perception





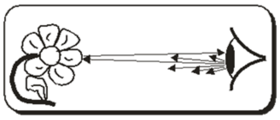
EMPEDOKLES (490 - 435 v. Chr.):
Theorie der Entwicklung des Lebens

"Objekt sendet Licht aus, erreicht Auge und kehrt zurück"



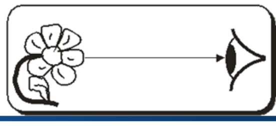
ARISTOTELES (384 - 322 v. Chr.):
Theorie der größtmöglichen Vollkommenheit

"Lichtstrahlen werden vom Auge gesendet, beleuchten Objekt und kehren zurück"

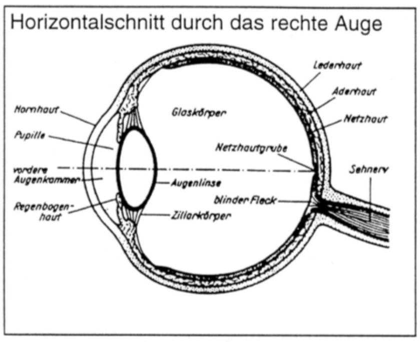


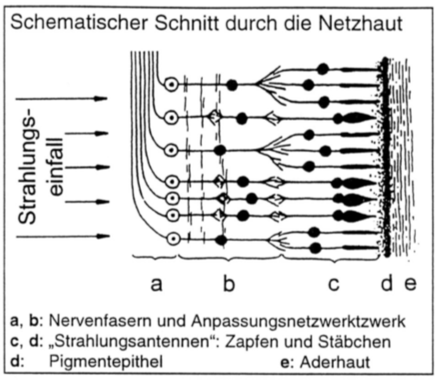
ALHAZEN (Ibn Al Haitham; 965 - 1039):
Theorie der Augenfunktion als Lichtdetektor

"Lichtstrahlen haben ihren Ursprung im Objekt, nicht im Auge"



The human eye as a photodetector array



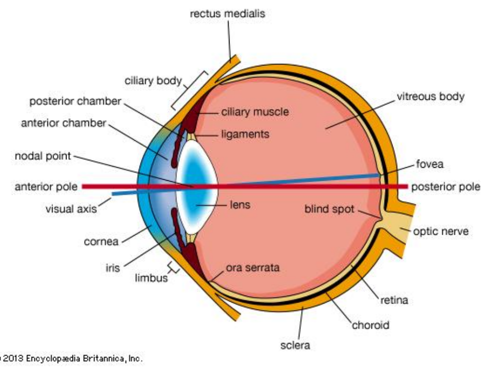


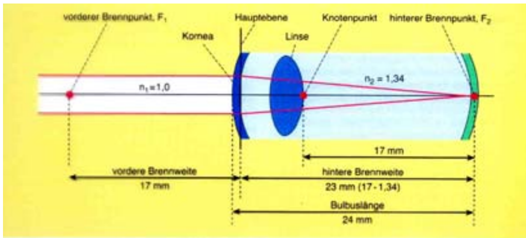
The human optic/visual organ works like a computer system. The eye acts as a radiation detector, the brain as a calculator. The light and color perception is the output.

The retina is a receiver with multiple detectors on the surface. With 110 to 125 million **rods** (diameter 3 mm) and 4-7 million **cones** (diameter 4 mm) in the middle.

The human eye as a optical device

horizontal section through the right eye





Something remarkable to our eyes ....

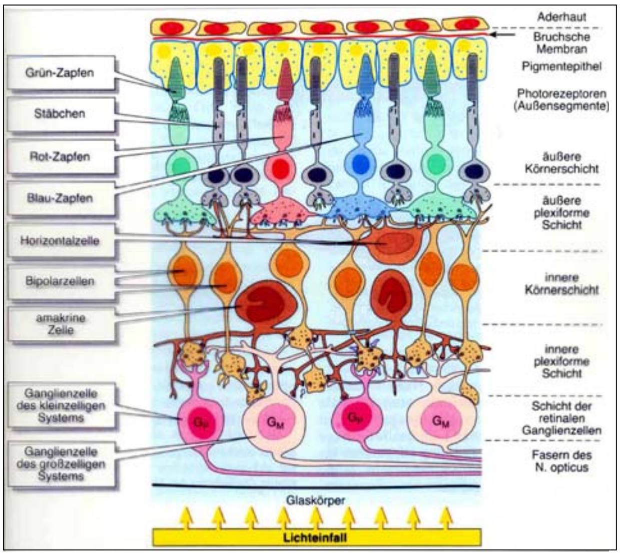
Hermann von Helmholtz (08.31.1821 - 08.09.1894)
German physiologist and physicist, once said he would fire an optician, who would bring him an instrument like the human eye, and yet not being able to recreate one.

The contouring and centering of the image-forming surfaces (cornea and lens) are even worse than a cheap camera, the aberrations are not adequately optically corrected..., but all these weaknesses are excellently compensated by sophisticated neuronal control mechanisms.

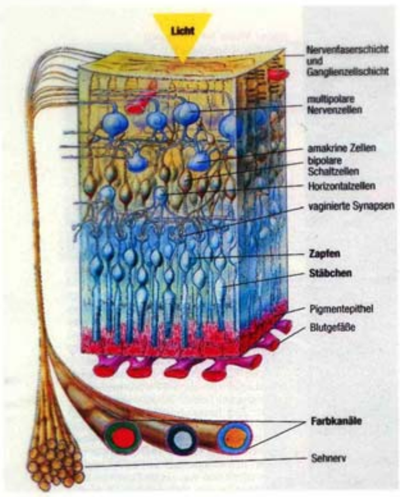
Together with the exceeding sensitivity range (brightness range) which is greater than those of any physical device (15%).

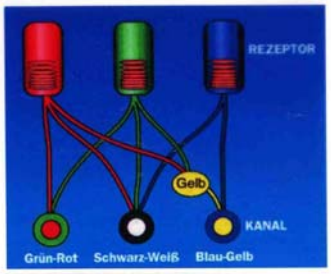
The eye is constantly listening and adopts its sensitivity and angular-dependent reception characteristics through the endogenous accommodative function automatically - like a Polaroid color film pack with a few milliseconds development time that switches automatically from 10 to 40 DIN

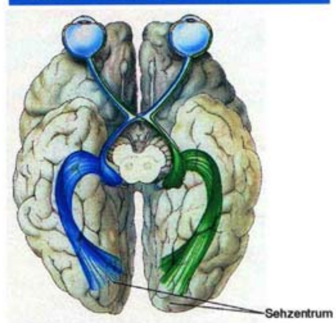
Schema of the complex neuronal network in retina



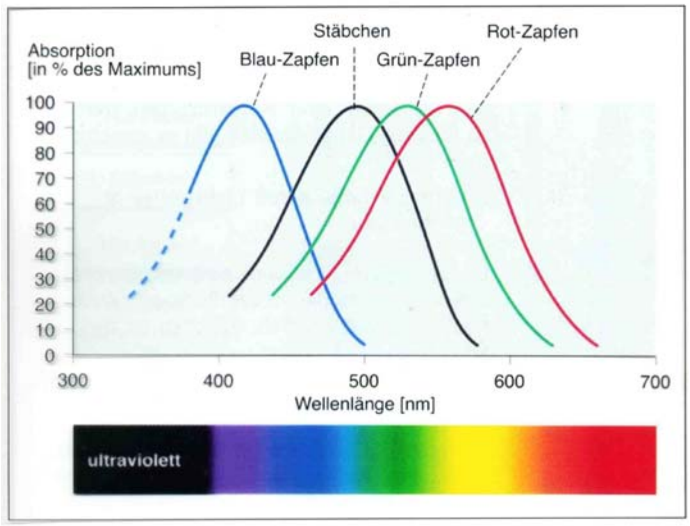
Signal & color coding and data transfer in human neural system



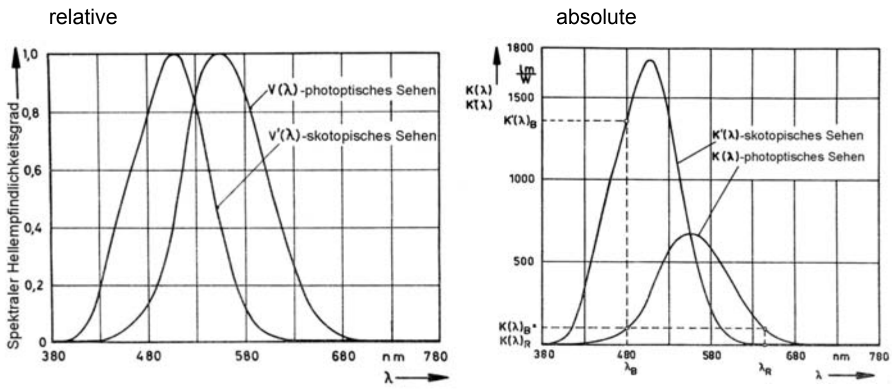




Spectral sensitivity of retina detectors (rods and cones)



Light sensitivity characteristics of the human eye
(so called standard observer according to DIN 5033)

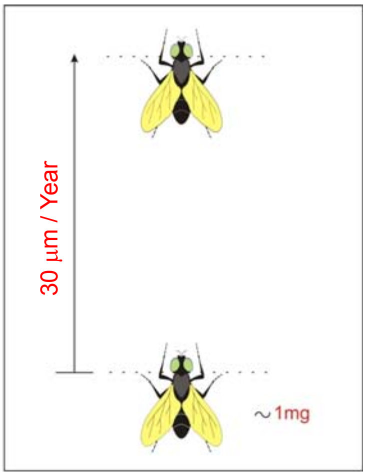


Ultimate sensitivity of the human eye

Three conditions:

10 aW:

- 5 photons of the same wavelength 500 nm,
- absorbed at exactly the same place on retina
- within 1ms



~ 4 x 10^{-16} W

In technical world, such sensitivity can be achieved only with special and expensive SPAD detectors.

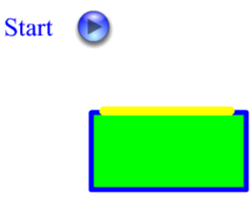
Predecessor models of the human eye in the animal kingdom:

from light-dark perception of individual sensory cells to the eye

In the animal kingdom, there are many different types of eyes. Some are quite sophisticated, others in a very low development stage. Here we present some examples of these sense organs. According to their construction, they are well suited to different perception tasks. The highly developed eye of vertebrates seems to be a meaningful development of the precursors.

According to the theory of Nilsson and PELG (1994), the eye has developed from a flat light-sensitive Layer. The initial structure consists of a flat light-sensitive layer (green), which is located above a pigment layer (dark blue). The photosensitive layer is protected by a transparent cover (yellow).

The adjacent animation presents, in simplified manner, the transition to the lens-eye.



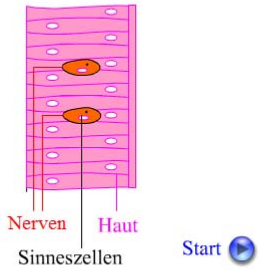
auge2.swf

NILSSON, D., PELGER, S: A pessimistic estimate of the time required for an eye to evolve. Proc. R. Soc. Lond. B 256 (1994), 53-58
Quelle: http://leifi.physik.uni-muenchen.de/web_ph07_g8/umwelt_technik/02augen/tieraugen.htm

Predecessor models of the human eye in the animal kingdom:
Earthworm

Many invertebrates are capable of light-dark perception only. The earthworm, for example, has many photoreceptor cells incorporated into the skin-layer. On this way, it can determine whether it is exposed to light or not.
One could believe that the earthworm, which is normally under ground, does not need to see at all. But if its photoreceptor cells respond, it is a signal of danger. It means to it, an exposure to daylight and there is a risk of being eaten by birds. **The light sense of the earthworm is comparable to the human heat perception.**

regenwurm.swf

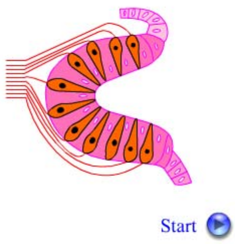


Quelle: http://leifi.physik.uni-muenchen.de/web_ph07_g8/umwelt_technik/02augen/tieraugen.htm

Predecessor models of the human eye in the animal kingdom:
Limpet

In higher developed animals, the light-sensitive cells can be found concentrated at certain spots together. This increases sensitivity to light.
For better protection these spots, they converted to kind of grooves. The limpets are for example equipped with such grooves. The spots can be excited with light from certain direction only. This is controlled by arrangement of these Photo-cells. (See animation).
On this way, **the sense of direction** could develop. Since there is no projection of a point on surface the "groove" eye (Napfauge), there is **no image impression possible**.

napfschnecke.swf



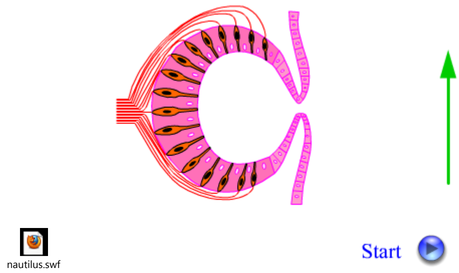
Quelle: http://leifi.physik.uni-muenchen.de/web_ph07_g8/umwelt_technik/02augen/tieraugen.htm

Predecessor models of the human eye in the animal kingdom:
Nautilus

By tentacle marine creatures e.g. the Nautilus, the grooves(foveae) are grown almost to a ball. There is an image projection on the photo-senstive tissue in the groove through the small opening, similar to a simple pinhole camera.

If the hole opens, the image becomes brighter, if the opening closes the image gets sharp but dark.

Beside the **light-dark** perception and **direction** sense, the pinhole-eye enables a simple **image projection**.



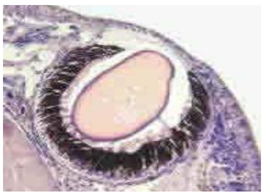
Quelle: http://leifi.physik.uni-muenchen.de/web_ph07_g8/umwelt_technik/02augen/tieraugen.htm

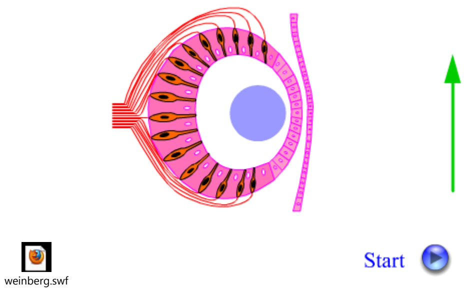
Predecessor models of the human eye in the animal kingdom:
Burgundy snail (*Helix pomatia*)

The pinhole-eye creates a sharp image only if the hole is very small. But this decreases the image brightness.

Here the natural needed a trick: Development of a **lens**, probably through thickening of the fluid located in the groove. Now, despite large aperture, with the lens it was possible to get **a sharp and bright image** projection.

The Burgundy snail has such a lens eye.



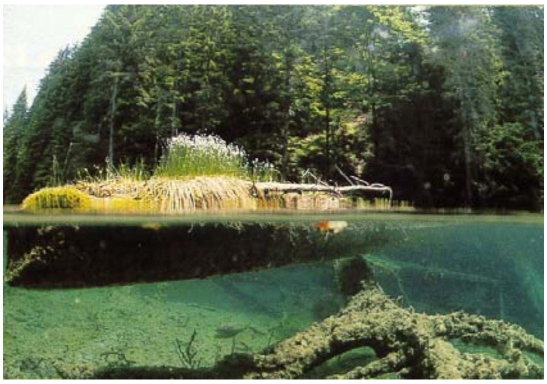


Quelle: http://leifi.physik.uni-muenchen.de/web_ph07_g8/umwelt_technik/02augen/tieraugen.htm

Is the human eye an optimal imaging system?

Examples from the animal kingdom:

Four eyes for two worlds



Is the human eye an optimal imaging system?

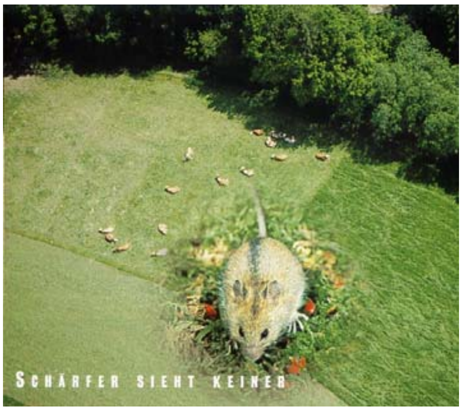
Examples from the animal kingdom:

Eight eyes can see more

Is the human eye an optimal imaging system?

Examples from the animal kingdom:

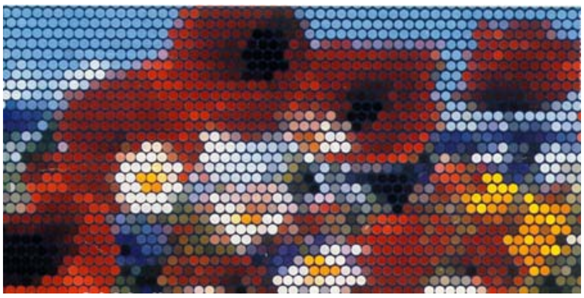
Proverbial eagle eyes



Is the human eye an optimal imaging system?

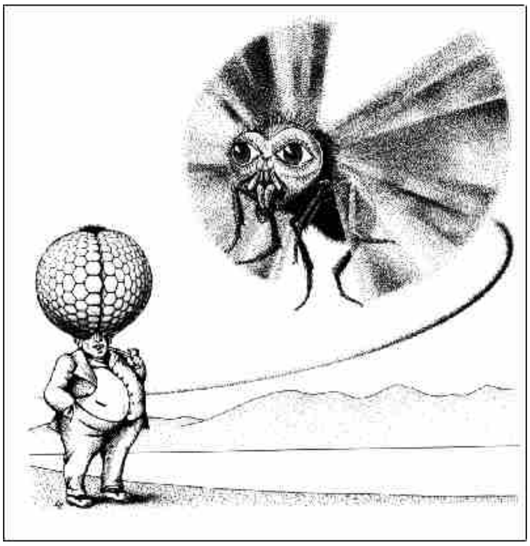
Examples from the animal kingdom:

Panoramic view of insects



Performance comparison of the human lens – eye and the complex eye of a fly

Should we preserve the aspect ration…



Aus: Kuno KIRSCHFELD, Naturwissenschaftliche Rundschau 9 (1984), 352-362

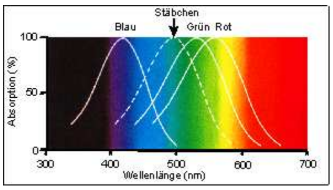
Colour comparison human / bee / fish

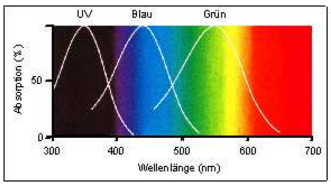
Human:
3 cones –photoreceptors with maximal absorption at 419, 531 und 559 nm

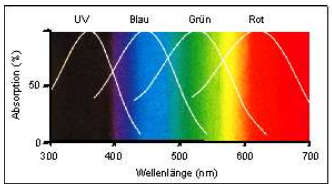
Bee:
3 cones –photoreceptors with maximal absorption at 340, 440 und 540 nm

Fish:
4 cones –photoreceptors with maximal absorption at 360, 450, 530 und 620 nm (**tetrachromatic vision**)

> *Remember:*
>
> *The ability of color perception is mostly examined by drill experiments*







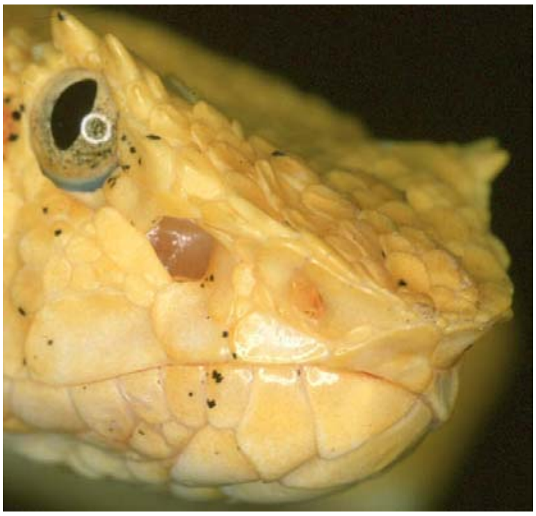
By the way …
How good can snakes see?

Snakes are cold-blooded animals and take the body temperature of their surroundings.
The strongest sense is the smell. The "nose" of snakes is built up from the tongue and so-called Jacob's bodies (sense pits in roof of the mouth).
Thus.. snakes "smell" with their tongues.
Snakes are almost deaf - they have an external ear and no eardrum - and they can badly see.
Usually they "locate" with a pit organ as an infrared sensor.

Physically: Temperature resolution 0,003° C (!)
Biologically: Identification even in total darkness

http://www.sgipt.org/galerie/tier/schlang/schl_ueb.htm

Structure and morphology of pit organs of pit vipers (Crotalinae)

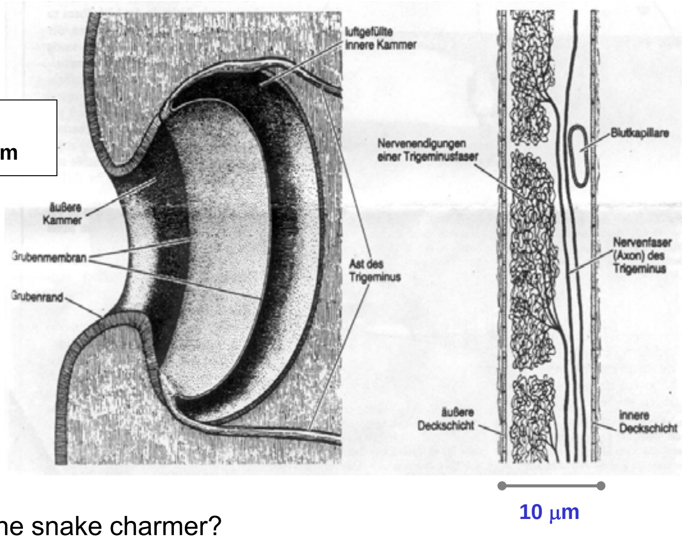


- Paired organ located between the nostril and eye
- Principle of a pinhole camera
- Two-chamber (Bicameral) system
- integrated cooling system

http://www.sgipt.org/galerie/tier/schlang/schl_ueb.htm

Fine structure of the pit organ of a snake

Cooling, two chamber system



And what about the snake charmer?

From: Newman and Hartline, 1982

Citát pro třetí přednášku / Quotation of the lecture 3:

„Mehr Licht“

„More light“

Johann Wolfgang von GOETHE
(22. 3. 1832)