Farbe

Physics of Color
visible light is electromagnetic radiation in a particular region of the entire spectrum
distinguishing criterion: its frequency
normally, a ray of light contains many different waves with individual frequencies

the associated distribution of wavelength intensities per wavelength is referred to as the *spectrum* of a given ray or light source.
Light – Particles or Waves?

- Light waves usually propagate according to the laws of geometric optics (as photons).
- However, certain properties can only be described by taking their wave nature into account.
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Light – Particles or Waves?

- a photon (from Greek φῶς, phos = light) is the elementary particle responsible for electromagnetic phenomena, the carrier of electromagnetic radiation
- photons have wave and particle properties („wave-particle-duality“)
- energy of a photon: $E = h \cdot f$
  - $h$ ... Planck constant [Planck‘sches Wirkungsquantum]
    ( $h = 4,13566\ldots \cdot 10^{-15}$ eVs )
  - $f$ ... frequency (in Hertz)
Wave Types

- **longitudinal wave** = compression wave
  - vibrations *parallel* to direction of travel
  - example: sound

- **transverse wave** = swinging wave
  - vibrations *perpendicular* to direction of travel
  - example: water, *light*
Light – Coherence

- light is a transverse wave
- its frequency alone is sometimes not sufficient to describe a given wave train
- *temporal* coherence: how monochromatic?
- *spatial* coherence: cross-correlation between points in a wave
- *polarization* coherence
polarization describes the oscillation direction of a transverse wave.

light is called polarized if all waves oscillate the same way.

in 2 dimensions → oscillation distribution
  can be linear, circular, elliptical
Linear, Circular and Elliptical Polarization
Circular Polarization
Polarization Examples

normal photo

photo with polarization filter
Polarization Examples

circular polarized glasses for 3D cinemas

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Polarization Examples

reflections are often polarized:
window seen without/with polarized sunglasses
reflections are often polarized:
photo without/with polarization filter
Causes for Light Color

- for directly viewed emitters, only their characteristics have to be considered.
- in all other cases, the interaction of light with the objects in a scene is at least partially responsible for the perceived color of an object.
a light frequency corresponds to a wavelength and has an energy level \( E = \text{const}/\lambda = h \cdot f \)
- \( h \)…Planck constant \([\text{Plancksches Wirkungsquantum}]\)
- \( f \)…frequency (waves/sec)
Quantum Properties of Matter

- atoms & molecules have stable ground states
- by inserting energy (e.g. by heat, electricity or photons) they can reach an excited state
- several excitation levels are possible
- excited states are usually not stable: by emission of a quantum of energy (e.g. a photon or heat) the system returns to a lower energy state (decay)
Example Hydrogen Atom

- **ground state:**
  - single electron in lowest possible orbit (1s)

- **excited state:**
  - electron moves to higher orbit (e.g. 2p)

- **decay:**
  - atom emits photon to return to lower energy state

energy absorption

photon emission

Multiple Decays

- **ground state:**
  - electron in a stable orbit
- **excited state:**
  - electron moves to higher orbit
- **2 decays:**
  1. atom emits photon to return to lower energy state
  2. atom emits another photon to return to stable state
- photon energies characterize the matter (spectrum)
quantum systems such as molecules can only exist in certain discrete states

only certain transitions between these states are allowed

the states correspond to energy levels

\[ E = \text{const}/\lambda = h \cdot f \]
Laser-Light

- Light Amplification by Stimulation of Emitted Radiation
- produces temporal and spatial coherent light
  - all photons are in phase
  - is monochromatic
- main difference to „ordinary“ light: it propagates in almost perfectly straight line

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Light and Biology

- bond-dissociation energy \([\text{Bindungsenergie}]\) of most molecules > 3 eV
  - 750 nm wave has 1,65 eV
  - 380 nm wave has 3,26 eV

\[
E = h \cdot f \\
( E = h \cdot f \quad \text{with} \quad \begin{align*} 
    h &= 4,13566\ldots \cdot 10^{-15} \text{ eVs} \\
    750 \text{ nm} &\approx 0,40 \cdot 10^{15} \text{ Hz} \Rightarrow \\
    750 \text{ nm} &\text{ has 1,65 eV} \end{align*} )
\]

- atmosphere absorbs higher energy waves
- rhodopsine and iodopsines have to be able to react chemically
  - no vision beyond 780 nm possible