
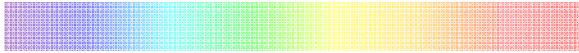


# Einführung in die Farbwissenschaft

## Causes of Color





## (15) Causes of Color


- **made light**
  - ◆ lightbulbs, fire, lightning, aurora, glowing
- **lost light**
  - ◆ water, plants, gold, emerald [Smaragd]
- **moved light**
  - ◆ rainbow, sky&sunset, butterfly, opal

[www.webexhibits.org/causesofcolor](http://www.webexhibits.org/causesofcolor)

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## Causes of Color: Made Light




### Lightbulbs

- light color depends on technology




normal bulb    daylight bulb    mercury lamp [Quecksilber]    low pressure sodium lamp [Natrium]    high pressure sodium lamp [Natrium]

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## Causes of Color: Made Light #1




### Color from Incandescence


- „blackbody radiation“
- when heated, a blackbody emits energy
  - ◆ wavelengths in visible area  $\Rightarrow$  light
  - ◆ it “glows”
- heating source
  - ◆ electricity (lightbulb, lightning)
  - ◆ chemical reactions (fire, sun)




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## Blackbody Radiation




- a **blackbody** has no color
- looks black because it absorbs all light
- no radiation at  $-273^{\circ}\text{C} = 0^{\circ}\text{K}$  [Kelvin]
- when heated, a blackbody emits energy
  - ◆ i.e. it becomes luminous
  - ◆ radiance depends on temperature
  - ◆ wavelengths depend on temperature
  - ◆ wavelengths in visible area  $\Rightarrow$  light, **color**
  - ◆ it “glows”



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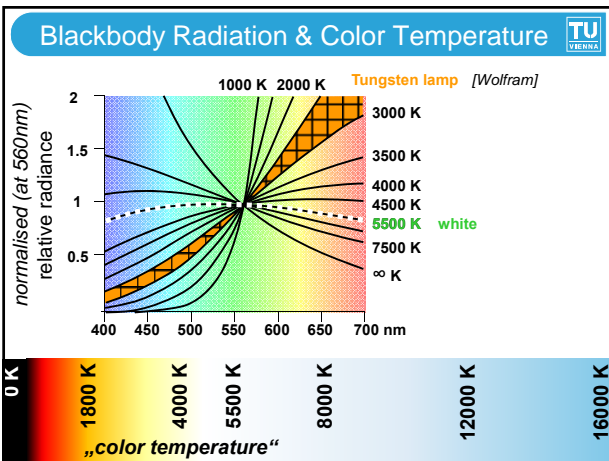
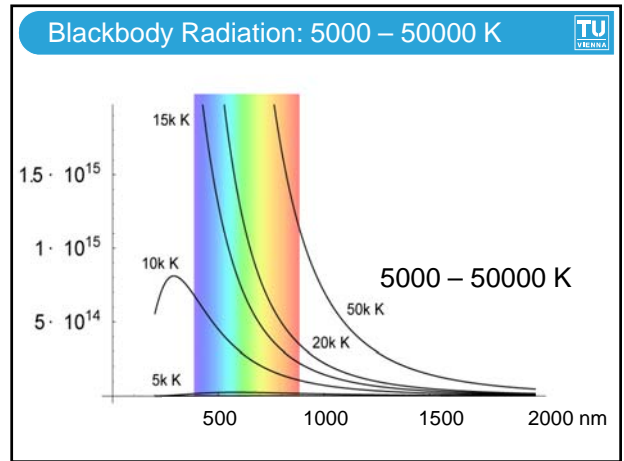
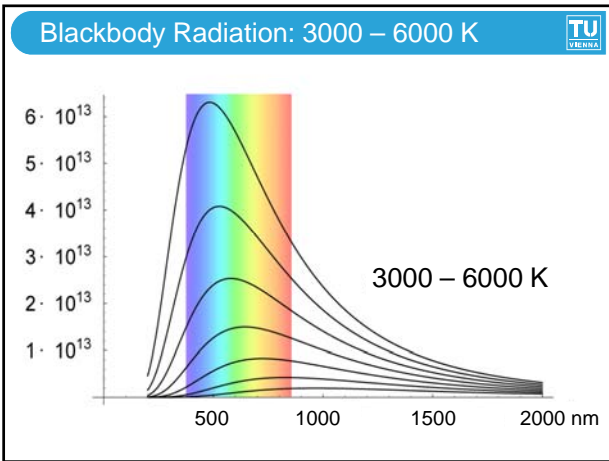
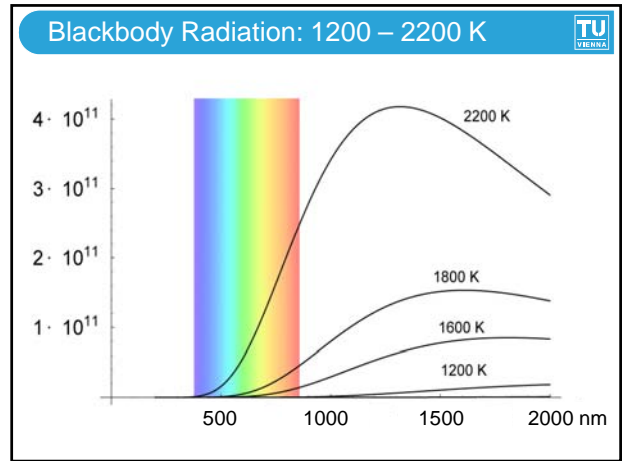
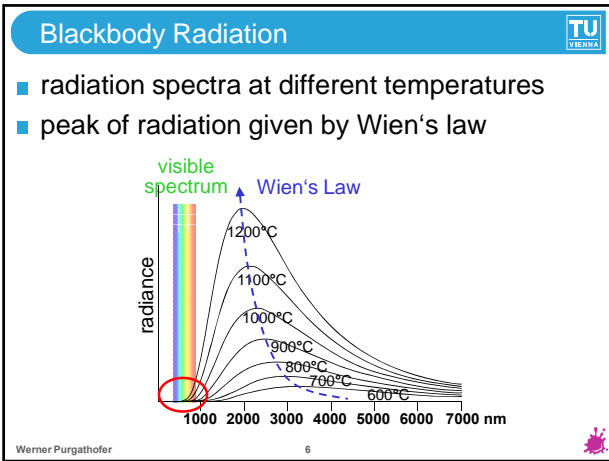
## Blackbody Radiation



- BR = electromagnetic radiation spectrum of an object at a certain temperature
- **all matter (regardless of composition) emits exactly the same spectrum at a given temperature**
- at around 500 K objects start to glow red
- extremely hot iron furnaces [Ofen] can glow almost white
- plasma can glow blue at about 20.000 K (very bright and hot stars)

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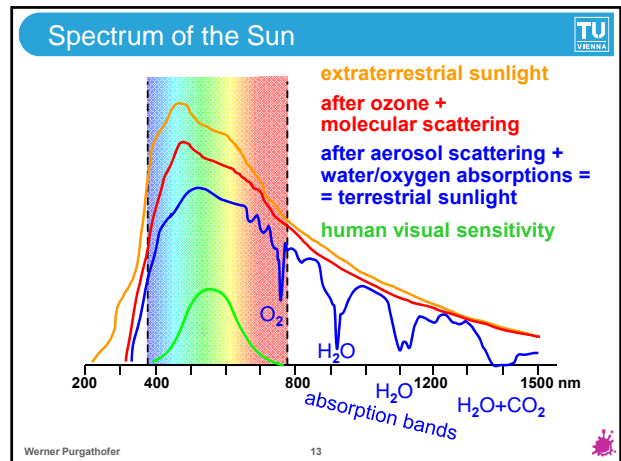
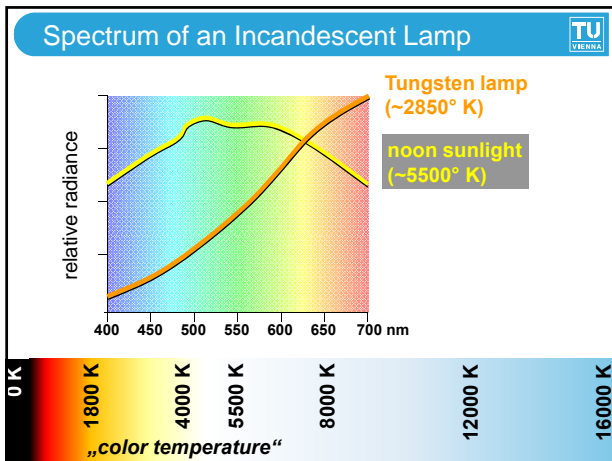




### Tungsten Lamp [Wolfram-Glühlampe]

- also called **incandescent light** [Glühlicht]
- tungsten is heated by electricity  
⇒ blackbody radiation
- temperature  
~ 2500° C = ~ 2800° K
- higher temperature would rapidly destroy the tungsten
- ⇒ yellowish light

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### Causes of Color: Made Light #2

#### Color from Gas Excitation

- emission of light by a chemical element present as a gas (e.g. neon) or vapor (e.g. of sodium [Natrium] or mercury [Quecksilber])
- electrical excitation raises atoms into higher energy states
- they decay back to ground state with the emission of photons
- fluorescent lamps
- aurora borealis

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### Gas Excitation – Sodium

- several different excitation paths exist
- the existence of the two „twin“ steps at the bottom is responsible for the double emission line spectrum of sodium lamps

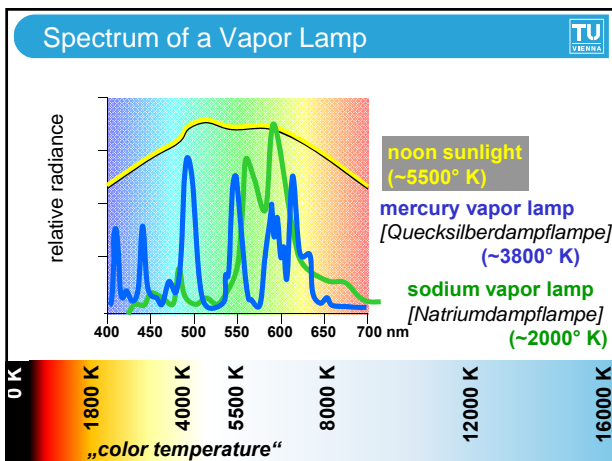
IONIZED Na<sup>+</sup> at 5.12 eV

ENERGY (eV)

Na GROUND STATE 3s<sub>1/2</sub>

2.008 eV 2.008 eV

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### Color Temperature of some Light Sources

- candlelight 1500 K
- sodium vapor lamp 2000 K
- 100W incandescent lamp 2800 K
- fluorescent lamp 4000 K
- xenon lamp 4500 K
- sun 5500 K
- electronic flashlight 5600 K
- overcast sky 7000 K
- blue sky (without sun) 9000 – 20000 K

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### Causes of Color: Made Light #3

#### Doped Semiconductors

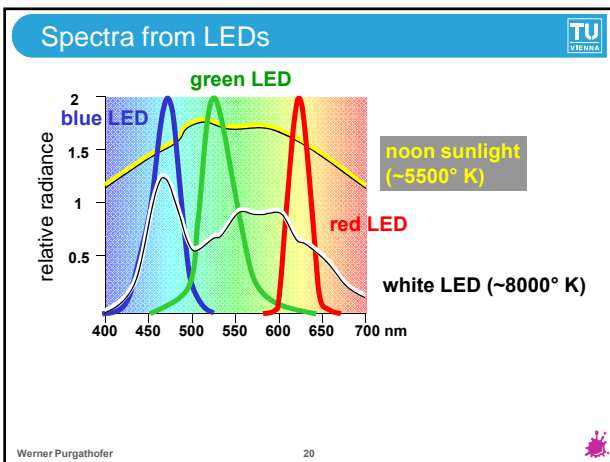
- LEDs, colored diamonds

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### Doped Semiconductors: LEDs

- semiconductor-pairs with impurities (dopes)
- n-side: more electrons, p-side: less electrons
- current sends high energy electrons to holes on other side where they lose energy according to used impurities
- energy loss determines photon wavelength
- only in 1 direction because they are diods

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### Causes of Color: Made Light #4

#### Glowing

- Chemoluminescence**
- emitted as a product of chemical reactions
- unstable products, which then decay in order to form more stable products
- energy is emitted in the form of light

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### Examples for Glowing

- light sticks
- breaking waves at midnight
- deep ocean fish, firefly

© BeecheyPhotography.com

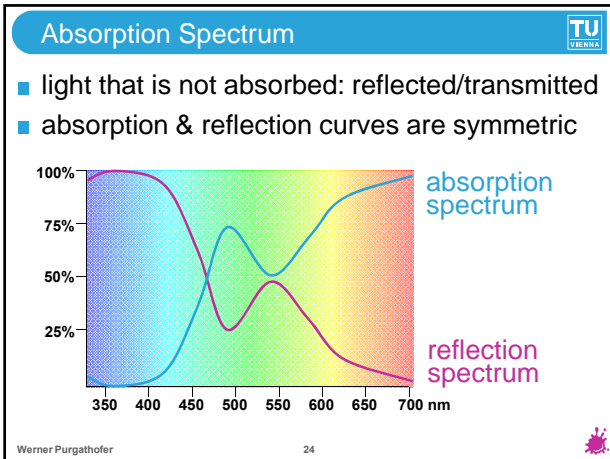
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### Causes of Color: Lost Light

#### Absorption

- molecule excitation changes require a certain amount of energy
- this energy is absorbed from outside influence
- if required energy is in visible interval, this light part is absorbed
  - a 775 nm photon has 1.6 eV
  - a 413 nm photon has 3.0 eV
- normally the energy is re-emitted as heat

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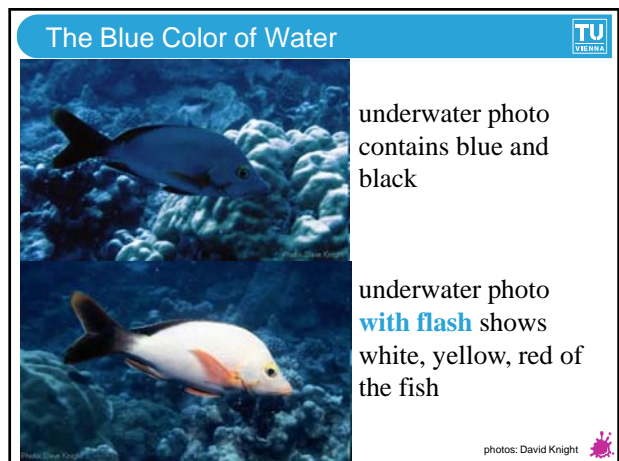
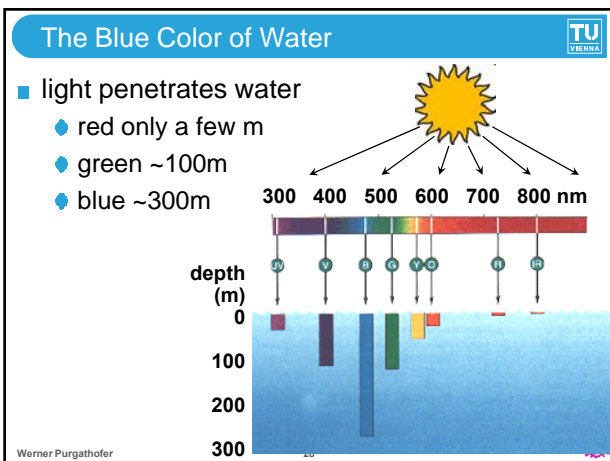
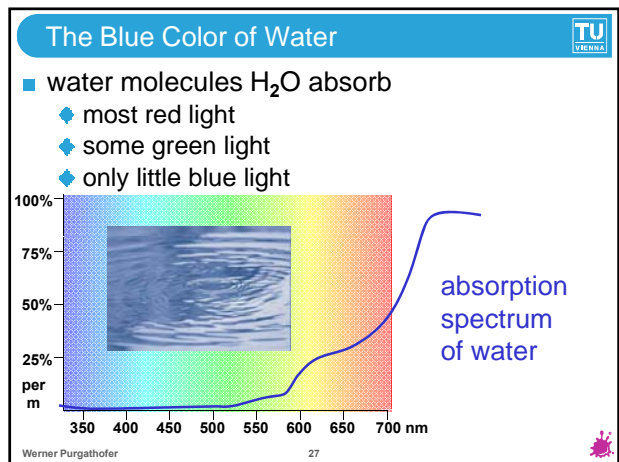
- ### Absorption Reasons
- vibrations and rotations
  - ligand field effects
  - charge transfer
  - band theory: metals & semiconductors
  - color centers
  - absorption by organic compounds
- Werner Purgathofer 25

### Causes of Color: Lost Light #1

#### Color from Vibrations and Rotations

- atoms of a molecule are in constant motion
- motions are called vibrational modes (some motions are rotational modes)
- occur at specific frequencies
- molecules absorb photons with correct energy to excite the vibration to a higher level
- mostly infrared frequencies
- only for water in the visible range

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## Color of Water



- So... what is the color of water?
  - blue in visible light
  - not transparent in IR!



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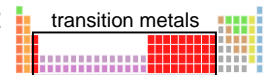
30

## Causes of Color: Lost Light #2



### Ligand Field Effects

- a *ligand* is an atom, ion, or molecule that bonds to a central metal, generally involving formal donation of one or more of its electrons
- 2 forms:
  - color in *transition metal compounds*
  - color from *transition metal impurities*
- transition metals are elements no. 21-48, 57-80, 89-112



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## Color in Transition Metal Compounds



[Übergangsmetall-Verbindungen]

- provides the colors of many minerals & paint pigments
- also called *idiochromatic* ("self-colored")
- examples:
  - chrome green  $\text{Cr}_2\text{O}_3$
  - Thenard's blue  $\text{Al}_2\text{CoO}_4$
  - red iron ore  $\text{Fe}_2\text{O}_3$
  - pink rhodochrosite  $\text{MnCO}_3$
  - ...



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## Color from Transition Metal Impurities



[Übergangsmetall-Verunreinigungen]

- occurs mostly in otherwise colorless minerals and gemstones, such as ruby or emerald
- also called *allochromatic* ("other-colored")
- examples:
  - ruby [Rubin], emerald [Smaragd]
  - aquamarines
  - green jade
  - colors in ceramics, glass, ...
  - ...

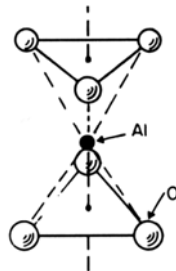
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## Ligand Field Colors



- atoms with paired electrons require high energies to excite
- in complex molecules, the neighbourhood of an atom can influence this situation, especially if the atom is an impurity
- pure  $\text{Al}_2\text{O}_3$  is colorless
- 1% chrome turns it into ruby



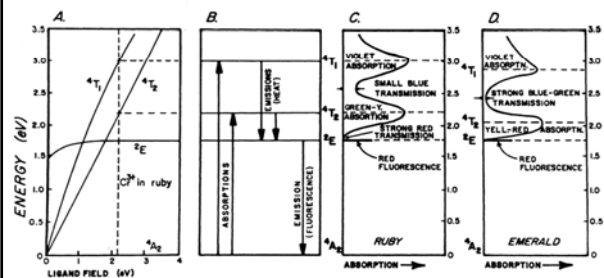
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## Ruby vs. Emerald



- ruby is corundum-based, emerald a beryllium derivative
- both are colored by 1% chrome



### Chrome Ligand Colors: Family Photo

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### Chrome Color: Intermediate

- alexandrite: intermediate crystal lattice between ruby [Rubin] and emerald [Smaragd]
- green under daylight
- red under incandescent illumination

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### Pleochroism [Pleochroismus]

- certain crystals exhibit differing colors according to the observer's position
- specialized form of ligand field effects
- dependent on orientation of crystal lattices
- only occurs in multi-axial crystals

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### Causes of Color: Lost Light #3

#### Color from Charge Transfer [Ladungsverschiebung]

- occurs if two otherwise insignificant impurities in a crystal influence each other, such as in sapphire

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### Charge Transfer: Sapphire

- somewhat similar to ligand field
- $\text{Al}_2\text{O}_3$  + fractions of 1 percent Ti is colorless
- same + similar % of iron: pale yellow
- both: deep blue
- Fe and Ti influence each other by CT

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### Causes of Color: Lost Light #4

#### Metals and Alloys (Band Theory)

- strong reflection of polished metal surfaces
- "white" metals: silver, iron, chromium, ...
- "yellow/red" metals: gold, brass [Messing], copper, ...
- alloys [Legierungen]: bronze, ... - color not predictable

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## Energy Bands



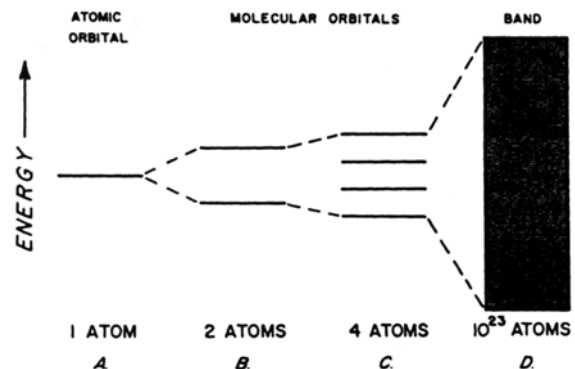
- in non-metals, individual atoms and small molecules have individual electron orbitals
- a piece of metal can be seen as one large molecule with a huge number of electrons
- these electrons together have so many energy levels that the distribution of their energies can be thought of as continuous
- this area of the spectrum is called the **energy band** of the substance

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## Energy Band Illustration



## Colors of Metals



- the energy band absorbs penetrating light and transforms it to current
- strong absorption: light penetrates into a metal solid only a few hundred atoms, typically less than the wavelength
- immediate re-emission of incident photons
- efficiency of this process can be wavelength – dependent: higher energies are less efficient for some materials (copper, gold)



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## Causes of Color: Lost Light #5



### Semiconductors (Band Theory)

- silicon
- pure diamond
- cadmium yellow

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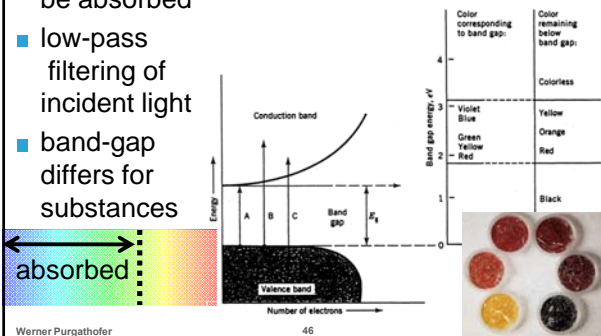
45



## Energy Band Colors – Semiconductors



- only photons of a certain minimum energy can be absorbed
- low-pass filtering of incident light
- band-gap differs for substances



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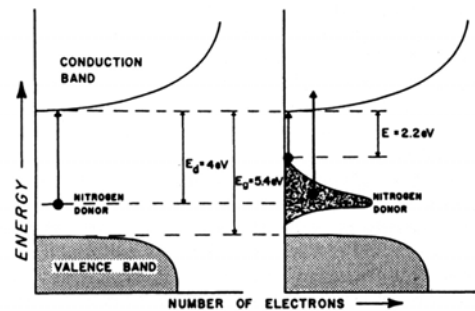
46



## Energy Band with Dope



- dope atoms offer intermediate levels in energy gap



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## Causes of Color: Lost Light #6



### Color Centers [Farbzentren]

- produce color after irradiation
  - ◆ some electrons are trapped in an excited state
  - ◆ absorb visible light in this trap
- lose color when heated
  - ◆ enough energy releases electron from the trap
- examples:
  - ◆ smoky quartz, amethyst, blue topaz

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## Color Center Examples



century-old glass bottle (contains mangan) after intense irradiation: amethyst glass



colorless quartz crystal as grown

irradiated crystal forms smoky quartz

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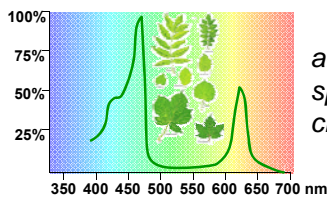


## Causes of Color: Lost Light #7



### Plants: Chlorophyll

- absorbs light to transform CO<sub>2</sub> and water to glucose and oxygen



absorption spectrum of chlorophyll b

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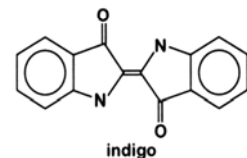
52



## Color in Other Organic Molecules



- certain regions of some complex organic molecules contain electrons which are suitable for absorption in the visible range
- **fluorescence** is common



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## 6 gemstones – 6 causes of color!



1 cm

- (1) lapis lazuli: S<sup>3-</sup>-anion-anion charge transfer.
- (2) maxixe-type beryl: radiation-induced color center
- (3) blue sapphire: Fe-Ti intervalence charge transfer
- (4) blue spinel: ligand-field color from a cobalt impurity
- (5) shattuckite: cobalt compound
- (6) colorless spinel: containing a layer of organic dye

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## Causes of Color: Moved Light #1



### Fluorescence

- re-radiation of incident energy at different wavelengths
- normally only re-radiation to lower energy<sup>\*)</sup>:
  - ◆ extends reflection spectra to matrices
  - ◆ hard to handle otherwise
- common effect, but hard to measure – bispectral photometers needed

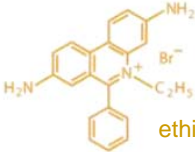
<sup>\*)</sup> in rare cases 2 photons of lower energy produce higher energy re-radiation

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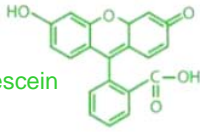
53



### Fluorescent Dyes

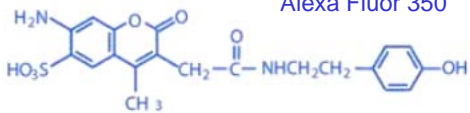


ethidium bromide



fluorescein

examples of some widely used fluorescent dyes



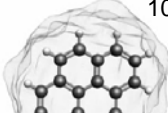
Alexa Fluor 350

Werner Purgathofer 54 images from www.invitrogen.com

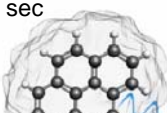
### Fluorescence

$10^{-15} - 10^{-9}$  sec

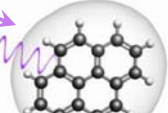
high energy



2. excitation

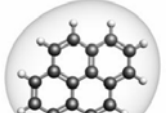


3. emission



1. absorption

low energy

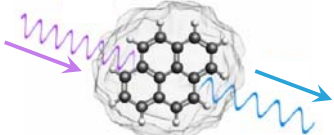


4. ground state

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### Fluorescence Wavelength Change

- when the fluorophore rearranges from the semi-stable excited state back to the ground state, the excess energy is emitted as light
- the emitted light is of lower energy, and thus longer wavelength, than the absorbed light
- ⇒ the color of the emitted light is different from the color of the absorbed light



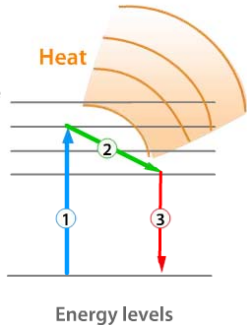
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### The Cyclical Fluorescence Process

- excitation through the absorption of light energy
- transient excited lifetime with some loss of energy
- return to ground state, with emission of light

emitted light energy is of longer wavelength than the absorbed light

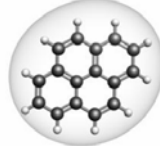
lost energy turns to heat



Energy levels


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### Photobleaching



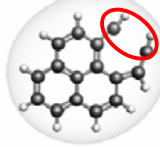
ground state

absorption




excitation

emission



absorption



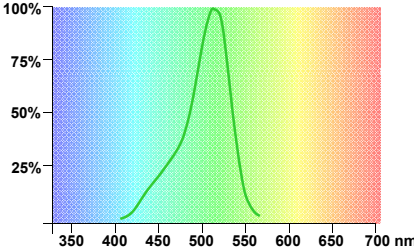
excitation

emission

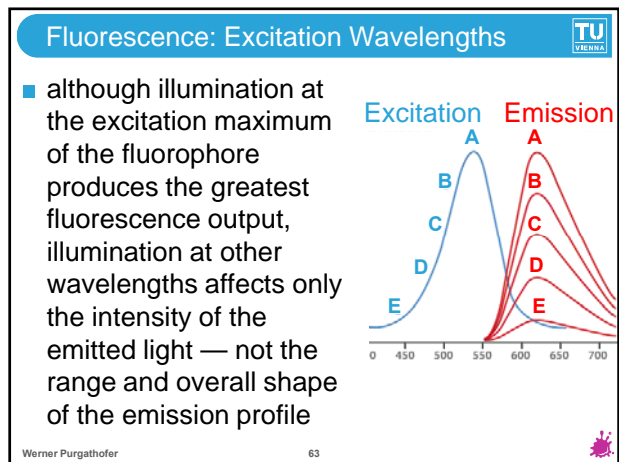
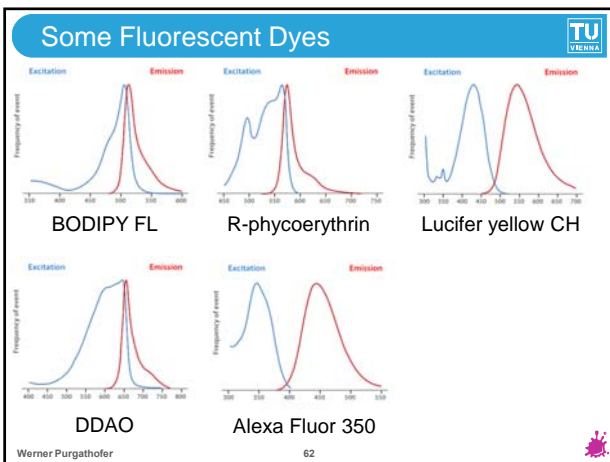
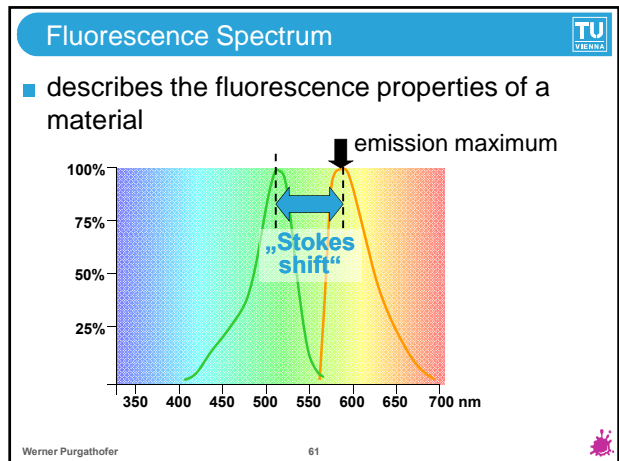
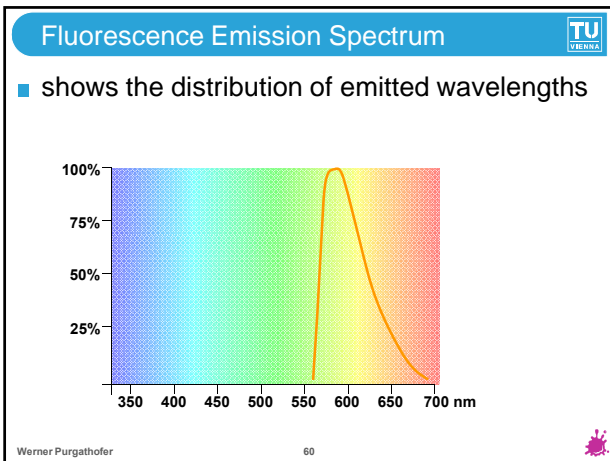
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### Fluorescence Excitation Spectrum

describes which wavelengths can excite the molecules (are absorbed)



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### Electric Discharge Lamps [Leuchtstoffröhren]

- 2 electrodes accelerate electrons to collide with gas molecules
- excited molecules return to normal state during a discharge process, emitting the excitation energy as radiant energy
- also called **fluorescent lamps**

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### Fluorescent Lamps

- most energy produces UV light  $\Rightarrow$  *fluorescent coating* transforms UV light into visible range
- different coatings define color temperature
  - warm white < 3300°K, cool white 3300° – 5300°K, daylight >5300°K

mercury vapor

mercury vapor lamp

400 450 500 550 600 650 700 nm

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### Example of Fluorescence

- tonic water is clear under normal light, but vividly fluorescent under ultraviolet light, due to the presence of the quinine used as a flavoring

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### Fluorescence: Re-radiation Example

- most common fluorescent pigments re-radiate at lower levels (here: pink 3M Post-it)

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### Fluorescence: Energy Transfer

In some areas, the reflection intensity appears to be larger than 1!

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### Fluorescence Reflection Experiment


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### Causes of Color: Moved Light #2

#### Phosphorescence

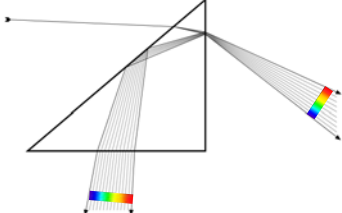
- re-radiation of incident energy with some time delay
- electrons are trapped at an excitation level
- room temperature provides enough energy to release them within seconds or minutes
- this produces a photon


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**Causes of Color: Moved Light #3** 

**Dispersion**

- different wavelengths behave differently
- this disperses light into color components
- examples: rainbow, optical glass, diamonds

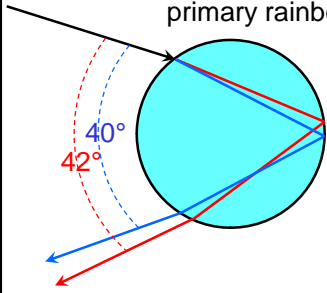




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**Dispersion: Rainbow** 

- raindrops are almost spheres

primary rainbow

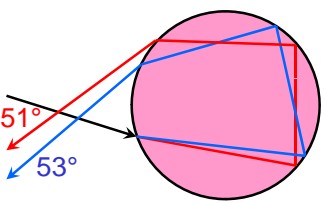





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**Dispersion: Rainbow** 

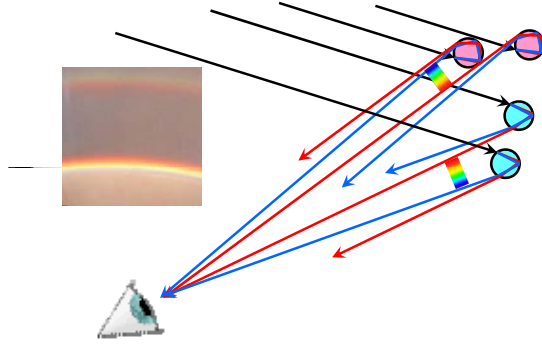

- secondary rainbow is lighter & “upside-down”


secondary rainbow





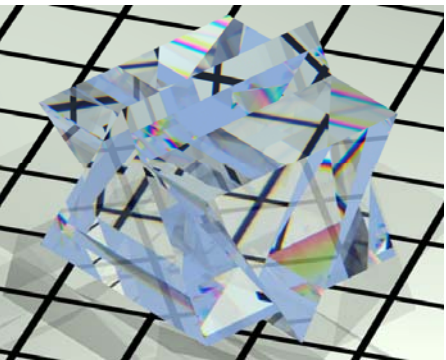
Werner Purgathofer 74 


**Dispersion: Rainbow** 






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**Dispersion Example** 



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**Dispersion Examples: Diamonds** 



### Causes of Color: Moved Light #4

#### Scattering

- deflection of light from its direction of propagation in transparent media
- caused by molecules and tiny particles

- size  $< 1/10$  wavelength  $\rightarrow$  **Rayleigh Scattering**
- size  $\sim$  wavelength  $\rightarrow$  **Mie Scattering**

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### Rayleigh Scattering

- independent of scattering aerosols (pure air scatters light on its own!)
- particle size  $< 1/10$  wavelength
- scatters in all directions
- scattering intensity is wavelength dependent  $\Rightarrow$  **blue sky** **red sunsets**

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### Rayleigh Scattering

- scattering intensity is wavelength dependent  $\Rightarrow$  **blue sky**

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### Rayleigh Scattering

- scattering intensity is wavelength dependent  $\Rightarrow$  **red sunsets**

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### Mie Scattering

- mostly by scattering aerosols
- particle size  $\sim$  wavelength
- scatters more in light direction
- produces the almost white glare around the sun when a lot of particulate material is present in the air
- responsible for the white light from mist & fog

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### Causes of Color: Moved Light #5

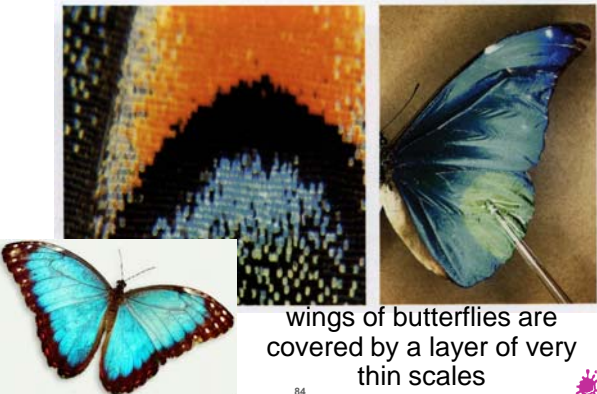
#### Interference

- very small structures can evoke effects that depend on wavelength of the incident light
- subtly different propagation times lead to selective


**A. reinforcement** or **B. cancellation**


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**Interference: Butterfly Wings** 




wings of butterflies are covered by a layer of very thin scales

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**Interference: Peacock Feathers** 



View at different angles: changing colors of a peacock feather are due to the change in angle of incident light, combined with a complex structure of indentations and plate-like layers called micro-lamellae


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**Interference in Daily Life** 

- soap bubbles
- oil on the street








**Metallic & Pearlescent Paint** 


- goniochromism – viewing angle changes hue
- differences in micro and macro appearance
- coherence glitter
- binocular glitter, luster & mottle  
*[zweiäugiges Funkeln, Glanz, Körnigkeit]*
- interference pigments


pearlescent pigments



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**Pearlescent Pigments** 




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**Interference Pigments** 

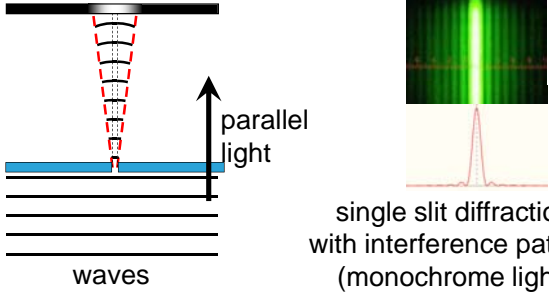




**Causes of Color: Moved Light #6** 

**Diffraction** [Beugung]


- spreading of light at edges of an obstacle




parallel light


waves

single slit diffraction with interference pattern (monochrome light)

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**Color from Diffraction** 


- different wave-lengths in white light have different diffraction patterns
- ⇒ color stripes




diffraction effects in a spiderweb


slit diffraction of white light play of color in an opal

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**Some Diffraction Phenomena** 

diffraction corona




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glory [Glorie] as seen from a plane





color effects on CD



halo [Lichthof] around the moon



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**(15) Causes of Color** 

**Summary**

- **made light**
  - ◆ incandescence, gas excitation, doped semiconductors
- **lost light**
  - ◆ absorption for various molecular reasons
- **moved light**
  - ◆ fluorescence, phosphorescence, dispersion, scattering, interference, diffraction

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