Introduction to Colour Science NPGR025

Unit 1: Introduction, Physics

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Sources:
K. Nassau, Color for Science, Art and Technology

Overview

- Introduction / Lecture Info
- Lecture topics
- Some colour science history
- Physics background
- The 15 causes of colour

Course Information

- Course ID: NPGR025
- There are several books that contain parts of the material discussed in this course, but there is no single, „official" book
- You do not have to buy any of the books mentioned on the lecture pages
- A list of sample exam questions (plus outlined answers) is available
- Oral exams at the end of the semester

Course Schedule

- During the winter semester the course will be held here in S4 every Wednesday at 1040
- Exceptions:
  - March 4th

Lecture Topics 1

- History
- Physics background
  - The nature of electromagnetic radiation
  - Interactions of light and matter
- Human perception
  - Anatomy of the eye
  - Spatial sensitivity vs. illumination
  - Monochrome and colour vision
  - Visual defects – colour blindness etc.

Lecture Topics 2

- Optical illusions
- Colour spaces
  - Device – based vs. device independent
  - Perceptually uniform
  - Artistic & custom
- Reproduction of colour on output devices
  - Technology of colour displays, printers, films, beamers, (holograms)

Lecture Topics 3

- Properties of output devices
  - Limitations
  - Calibration routines – ICC profiles
  - Gamma & gamut correction
- Measurement of colour
  - Device types
  - Capabilities and limitations
  - Practical demonstration

Lecture Topics 4

- Tone mapping
  - Problem definition
  - Algorithms – simple, perceptually correct, time-dependent, real-time
- Choosing and using colour
  - Colour selection techniques
  - The symbolic values of colour
  - Design guidelines for colour use

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Lecture Topics 5

- Colour management systems
  - Problem definition and basic strategies
  - Examples – e.g. Apple ColorSync, Photoshop, Illustrator
  - ICC profile generation software
- Colour Constancy / White Balance
  - Problem definition
  - Common algorithms

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So What is Colour?

- Whatever it is, it is not easy to define
- Describes at least 3 subtly different things
  - Object properties (green grass)
  - Characteristic of light rays (grass reflects green light)
  - A sensation of the human perceptory system (we perceive grass to be green)
- We are dealing with a sensation that is at least partially defined within the human brain: exact descriptions are hard to achieve!

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Who wants to know?

- Colour science was (and of course still is) influenced by all of them:
  - Philosophers
  - Artists / painters / artisans
  - Physicists
  - Chemists
  - Psychologists
  - Neurologists / medical doctors
  - Publishers / graphical designers / printers
  - Computer scientists

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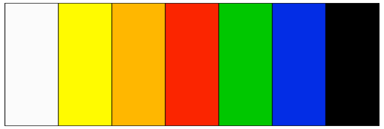
History of Colour Science

- Antiquity
  - Colour as part of natural philosophy
  - Linear colour models
- Middle ages
  - Variations of linear colour ordering systems
- Renaissance and beyond
  - Development of two- and three-dimensional colour models in lockstep with the development of natural science

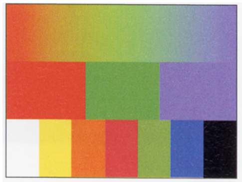
Antiquity: Aristotle

- Colours are assumed to be a mixture of white and black
- Colours are sorted according to their perceived brightness
- Partly motivated by philosophical beliefs
- Partly derived from observations of the sky
  - Approach typical for Greek natural philosophy
  - Mixture of white and black yields red



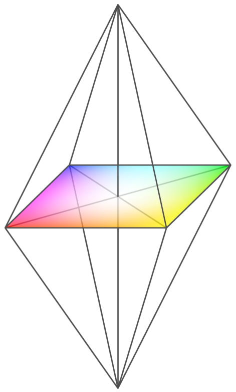
Linear Model: Issues

- Ordering of colours based on luminance
- Places black and white on a level equal to the colour hues
- Prediction of how colours mix is not always correct
  - Blue plus yellow should always yield green (shard experiment)
  - No concept of additive vs. subtractive colour mixing



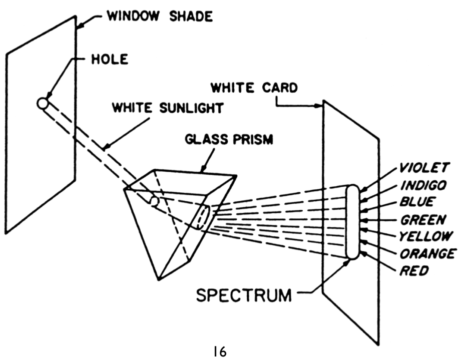
Middle Ages, Renaissance

- Iterative improvements of linear model
- Grosseteste (1230): first separation of chroma from hue
- Alberti (1435): 3D colour space
- Leonardo (1510): work on colour, dealt with questions such as:
  - whether green is a primary
  - whether white is a „proper colour“



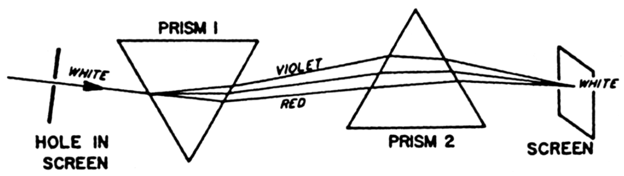
Newton (1672)

- Newton – first to draw the correct conclusions from the fact that white light can be broken up into the colours of the rainbow by a prism



Newton: Proof

- The second part of Newton's approach was to recombine a previously split beam to white light
- He correctly classified light as being a „heterogeneous mixture of different colours"



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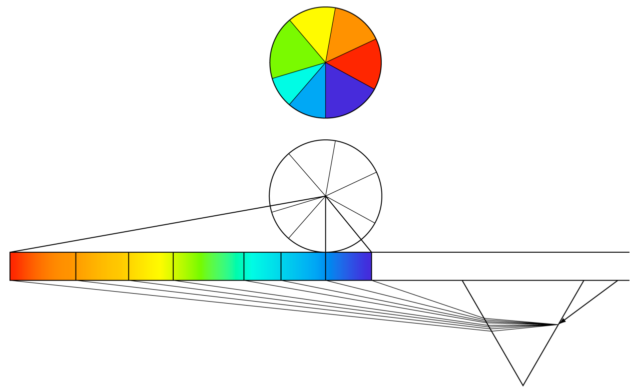
Newton: First Colour Circle

- Used the results of his prism experiment to motivate arrangement of colours in a circle



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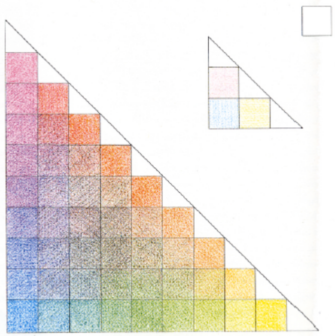
J.H. Lambert - 1760

- Attempted to describe all colours as a mixture of red, blue and yellow
- Effectively a precursor of the subtractive CMY models
- Not a universal colour model because not all real colours can be generated through subtractive mixture



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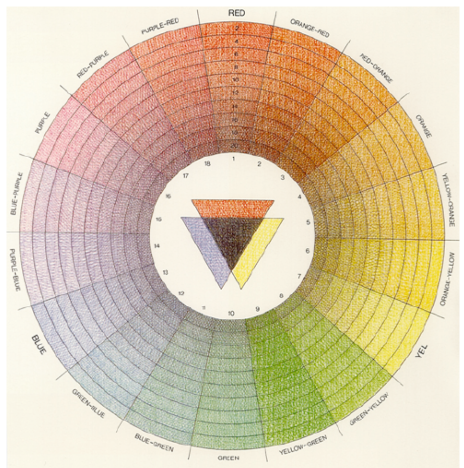
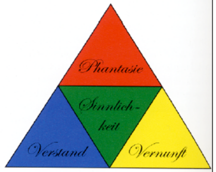
Colour Wheels: Harris (1776)

- 100 years after Newton, Harris and others made the wheel arrangement of colour systems popular
- Restricted to two dimensions

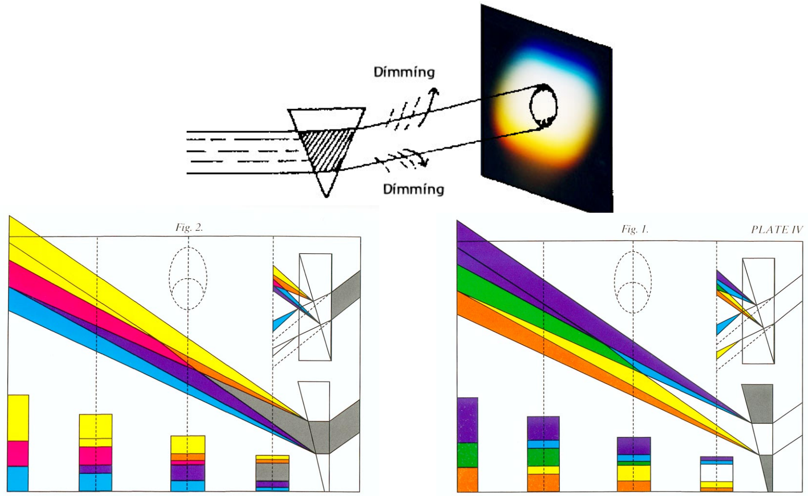


J.W. Goethe (1800)

- Wrote about 2000 pages on the topic of colour, and considered these to be one of the key accomplishments in his life
- Proposed an observer-centric and psychologically based approach which seemed to contradict Newton
- Nowadays the two theories are seen as two sides of the same coin

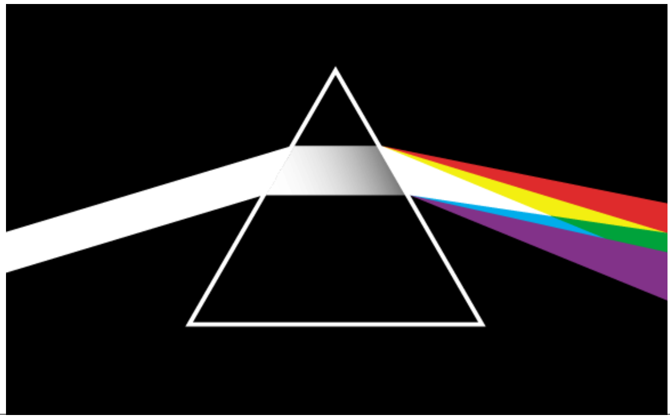


Goethe: Edge Colours, *Dark Light*

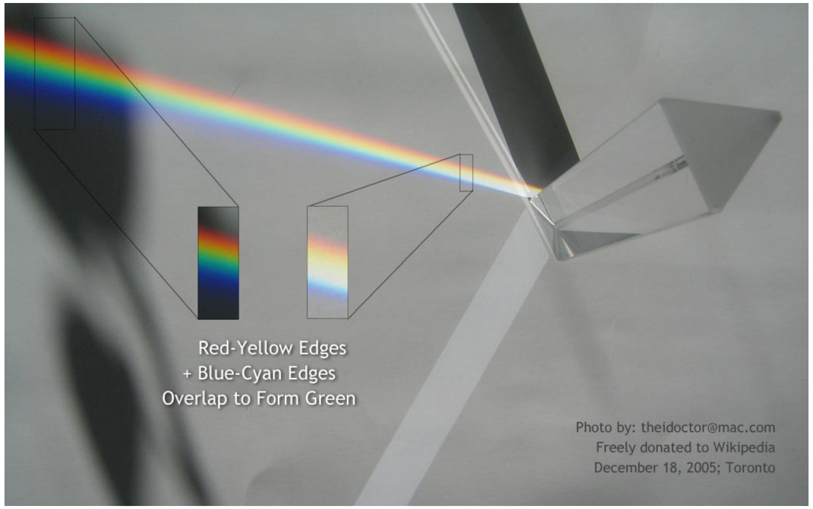


Edge Colours in Action #1

- With a prism, edge colours form on light-dark boundaries, and have a directional dependence

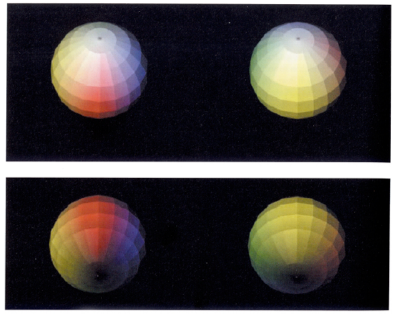


Edge Colours in Action #2



Otto Runge: Colour Sphere (1810)

- As a painter, he worked with a sub-tractive model and assumed red, blue and yellow to be the only primaries
- The spherical arrange-ment was intended to:
  - Provide a practical guide for mixtures
  - Serve as an ideal geometric model



Overview

- The Physics Behind Colour
  - „Where colours actually come from“
  - Implications for colour reproduction technology
- Colour Perception
  - „How we see colour“
  - Implications for display technologies, in particular tone mapping
- Colorimetry & Colour Spaces
  - „How we can arrange colour“
  - How colour spaces relate to each other
  - Making sense of the colour space zoo out there

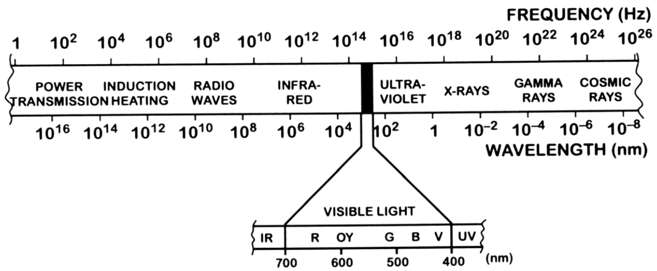
Physics – Motivation

Since all colour sensations are caused by perception of light, we have to consider both the properties of light itself, and those of our sensory organs, the eyes

Topic for today: physics

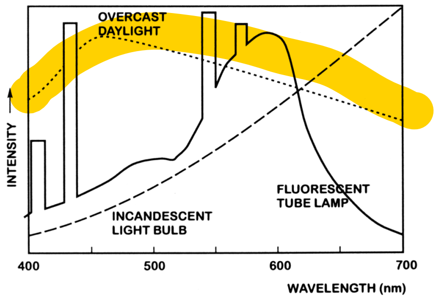
Light – Basic Properties

- Visible light is electromagnetic radiation in a particular region of the entire spectrum
- Distinguishing criterion: its frequency



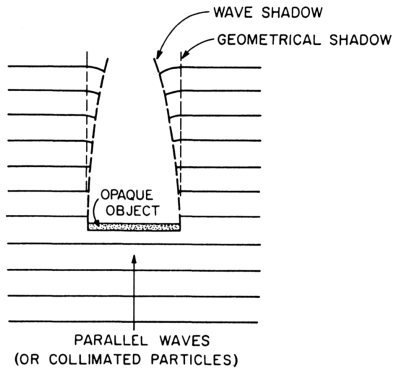
Light – Spectrum

- 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



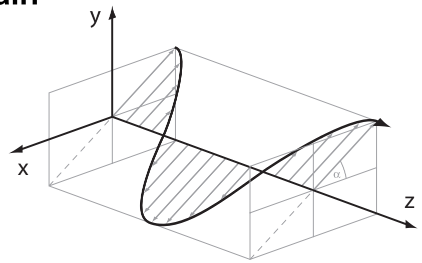
Light – Particle vs. Wave

- Light waves usually propagate according to the laws of geometric optics
- However, certain properties can only be described by taking their wave nature into account
  - Diffraction
  - (non-linear optics)

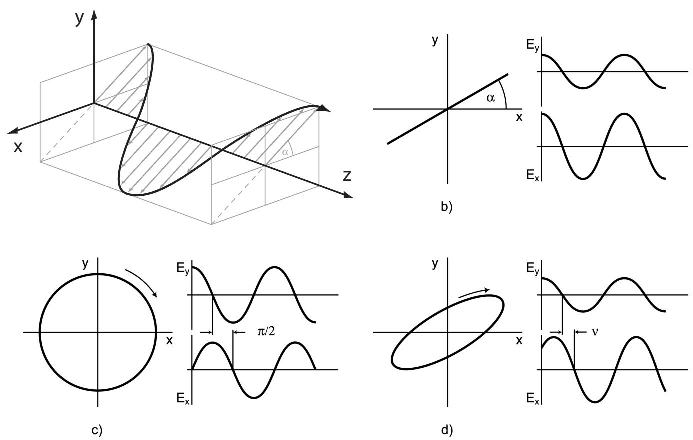


Light - Polarisation

- Light is a transversal wave
- Its frequency alone is sometimes not sufficient to describe a given wave train
- For coherent (meaning 1) beams of light, phase information has to be maintained
- This is referred to as the polarisation state of a light ray



Polarisation Examples



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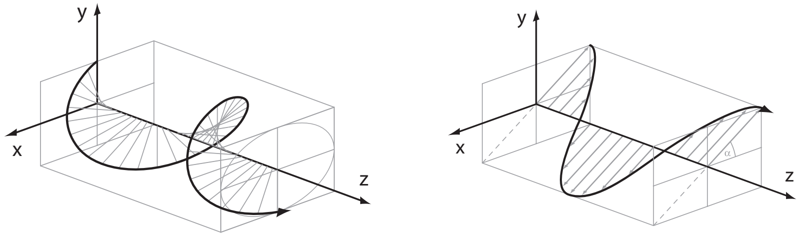
Polarisation Types



- Both wave-trains have the same frequency
  - To the human eye, they have the same colour!
- Interactions with matter (esp. reflection, refraction) can be different!

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Light – Laser

- Light Amplification by Stimulated Emission of Radiation
- Produces coherent (meaning 2) light
- Laser light is initially unpolarised, but all photons are in phase and usually of the same frequency
- Main difference to „ordinary" light: propagates in an almost perfectly straight line

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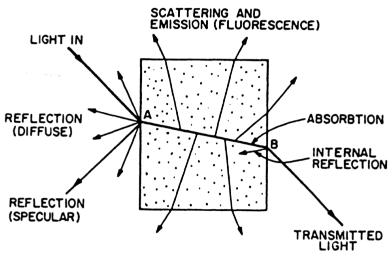
Causes for Light Colour

- 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 colour of an object



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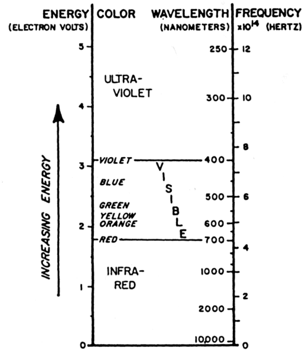
Energy Levels & Visible Range

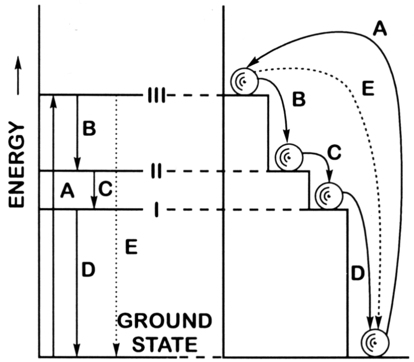
- A given light frequency corresponds to a fixed wavelength and energy level
- With organic sensors, „seeing" is best done in the visible range of humans:



  - Higher → energy destroys molecules (UV)
  - Lower → focus & transparency problems (IR)

Quantum Properties of Matter

- Quantum systems such as molecules can only exist in certain discrete states
- Only certain transitions between these states are allowed



- The states directly correspond to energy levels, and to frequencies!

The 15 Causes of Colour

- 1, 2, 3: Simple excitations and vibrations
- 4, 5: Transitions involving ligand field effects
- 6, 7: Transitions between molecular orbitals
- 8, 9, 10, 11: Transitions involving energy bands
- 12, 13, 14, 15: Geometric and physical optics

Effects numbered in red are self luminous, all others are not.

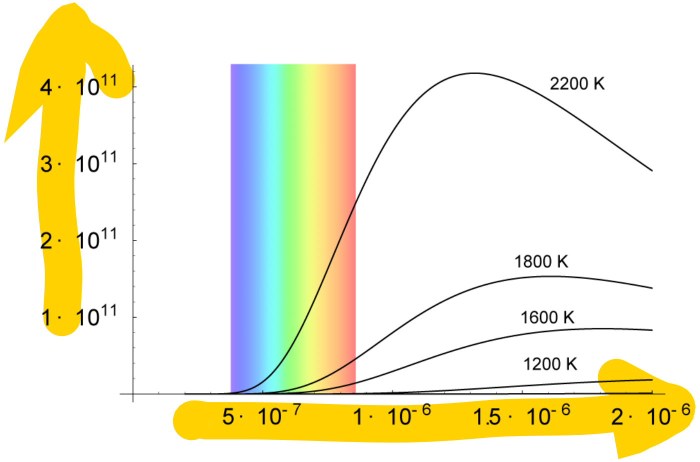
Excitations and Vibrations

1. Colour from incandescence
   - Blackbody radiation, glowing solids
2. Colour from gas excitation
   - Occurs in addition to (1), limited to certain substances and settings, such as sodium gas, or aurora borealis
3. Colour from vibrations and rotations
   - Effect usually only relevant for IR. Only molecules with small mass (H_2O) can affect the visible range. Reason for the light blue colour of pure water.

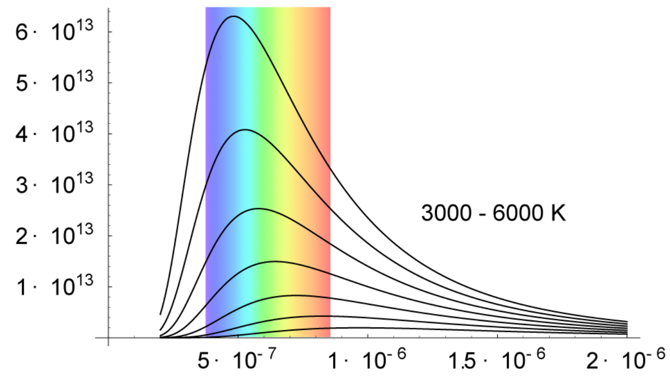
Blackbody Radiation

- BR is the 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 800 K most objects start to glow red (Draper point)
- Extremely hot iron furnaces can glow almost white
- Plasma can glow blue at about 20000 K (very bright and hot stars)

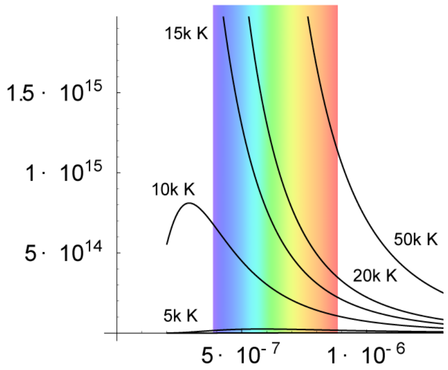
Blackbody Radiation #1

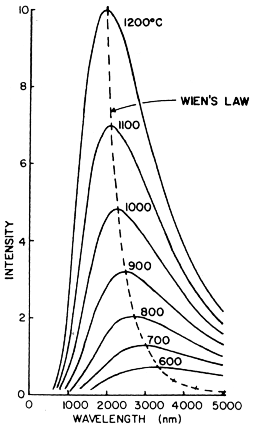


Blackbody Radiation #2

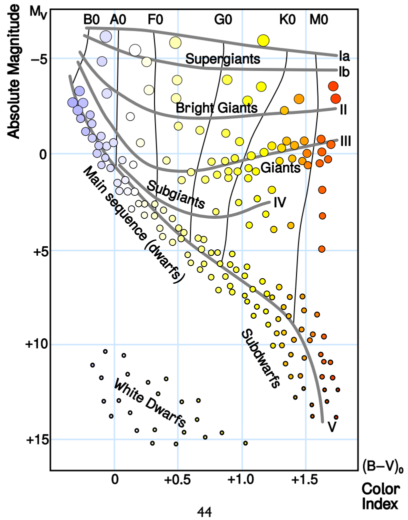


Blackbody Radiation #3



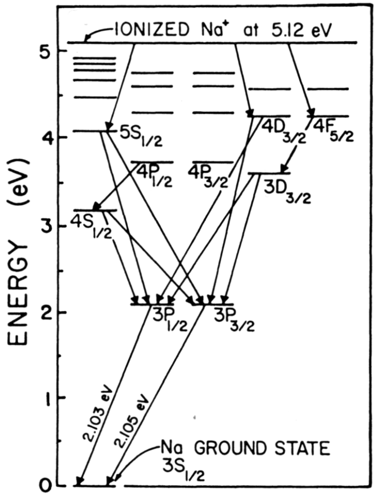


Blackbody Radiation: Star Colour

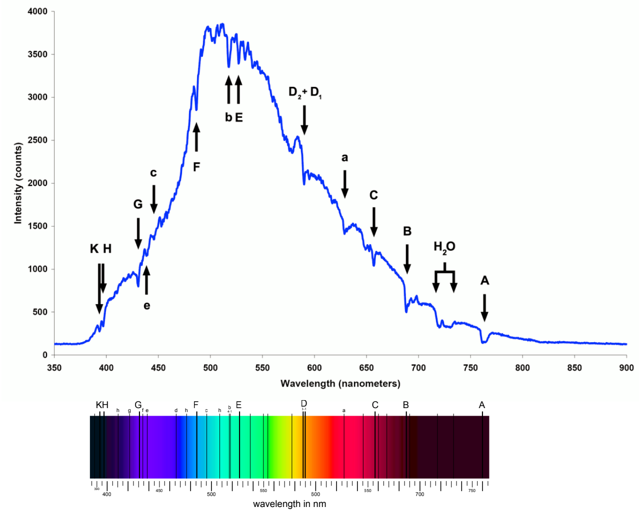


Gas Excitation – Sodium

- 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



Solar Spectrum: Fraunhofer Lines



Fluorescent Tube Spectrum

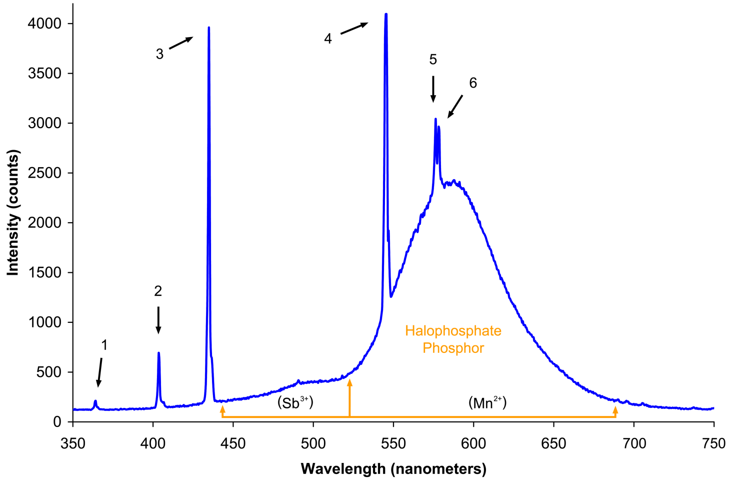


Image source: Wikipedia

Stark Shift

- Stark Shift: splitting of emission lines when the emitter is in a strong electrical field

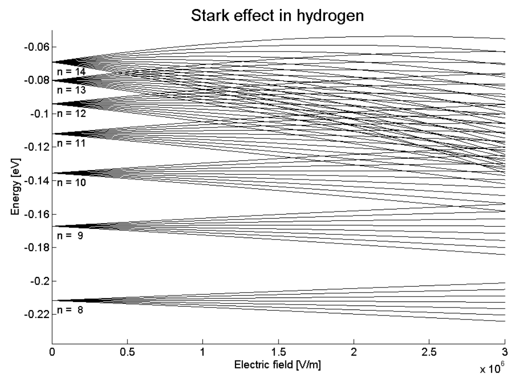


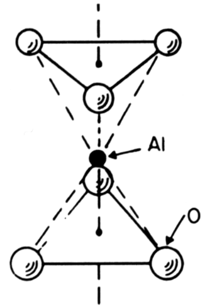
Image source: Wikipedia

Ligand Field Effects

- Colour in transition metal compounds
  - Responsible for the colour of many minerals and paint pigments, such as malachite and chrome green
- Colour from transition metal impurities
  - Occurs mostly in otherwise colourless minerals and gemstones, such as ruby or emerald

Ligand Field Colours

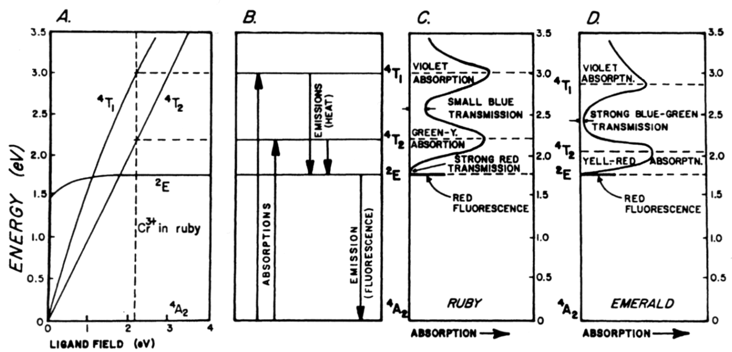
- Atoms with paired electrons require high energies to excite
- In complex molecules, the neighbourhood of an atom can influence this situation, especially if the atom is an impurity
- Pure Al2O3 is colourless
- 1% chrome turns it into ruby



Al surrounded by six O in Al_2O_3

Ruby vs. Emerald

- Ruby is corund-based, Emerald a beryllium derivative
- Both are coloured by 1% chrome

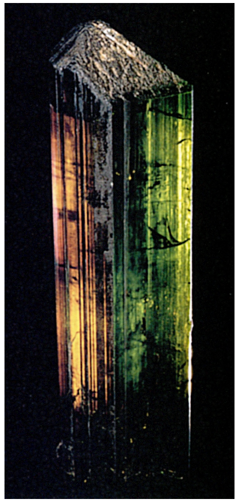


Chrome Colour: Intermediate

- Alexandrite: intermediate crystal lattice between ruby and emerald
- Green under daylight
- Red under incandescent illumination

Pleochroism

- Certain crystals exhibit differing colours according to the observer's position
- Specialised form of ligand field effects
- Dependent on orientation of crystal lattices
- Only occurs in multi-axial crystals



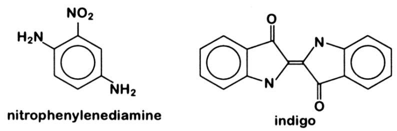
Chrome Ligand Colours: Family Photo

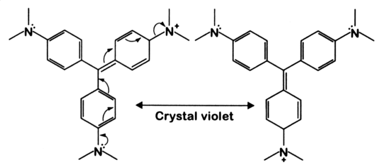
Colour from Molecular Orbitals

- Colour in organic compounds
  - Certain complex organic molecules contain electrons which are suitable for absorption in the visible range
- Colour from charge transfer
  - Occurs if two otherwise insignificant impurities in a crystal influence each other, such as in sapphire

Organic Dyes

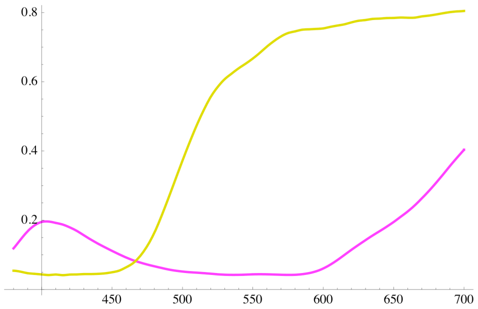
- Certain regions of complex molecules contain suitable electrons which are capable of absorbing light
- Fluorescence is comparatively common





Organic Molecule Reflectance

- Smooth reflectance spectra
- Easy measurement, easy representation in a rendering system



Fluorescence

- Re-radiation of incident energy at different wavelengths
- If only re-radiation to lower energy levels is taken into account:
  - Extends reflection spectra to matrices
  - Hard to handle otherwise
- Common effect, but hard to measure
  - Bi-spectral photometers are needed

Stokes Shift

- The phenomenon of light being re-emitted at a different frequency than the one at which it was absorbed is called Stokes Shift

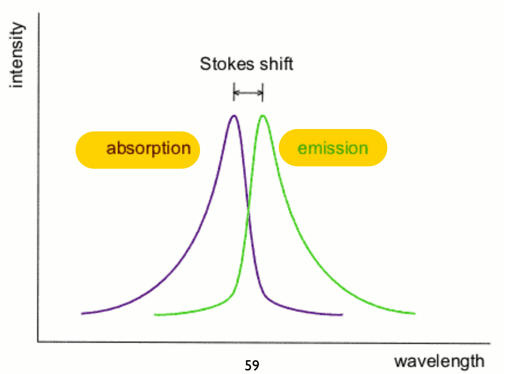
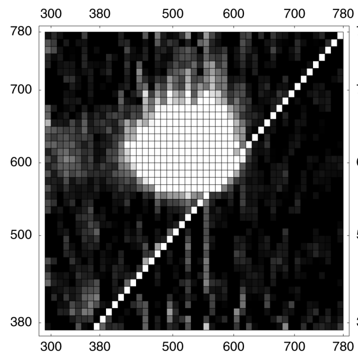
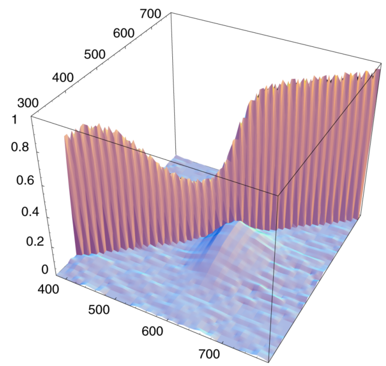


Image source: Wikipedia

Re-radiation Example





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

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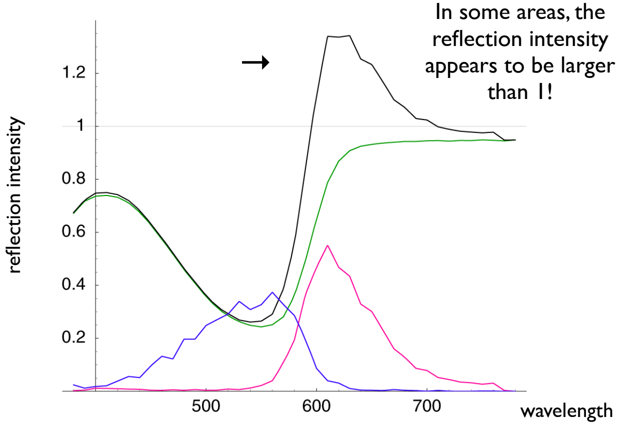
Fluorescence: Energy Transfer



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Fluorescence: Real-World Example

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Fluorescence: Real-World Example

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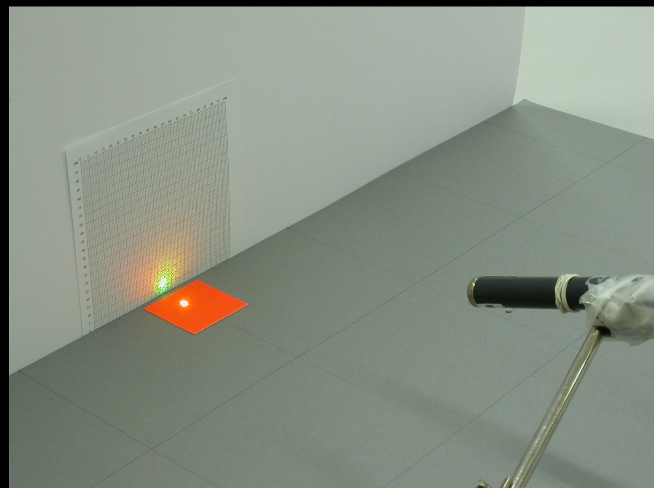
Fluorescent Reflection Experiment



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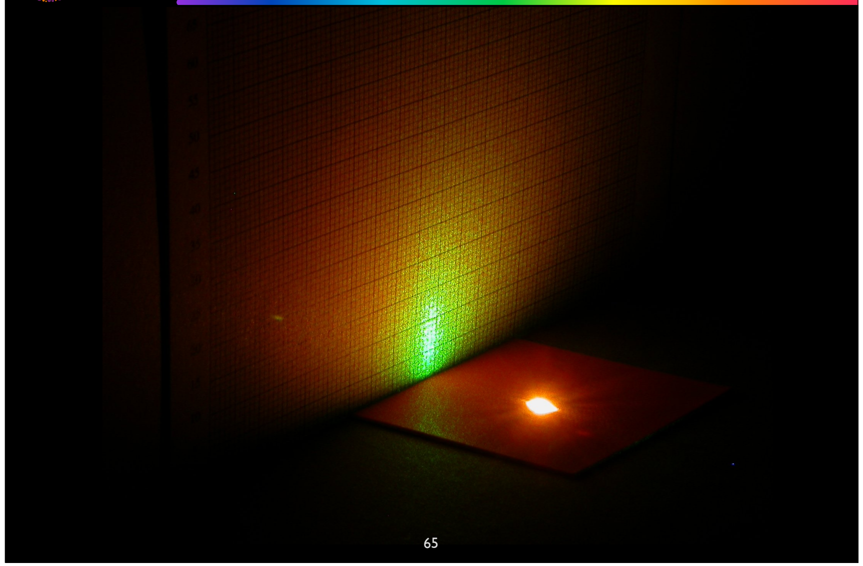
Plain vs. Fluorescent Sample



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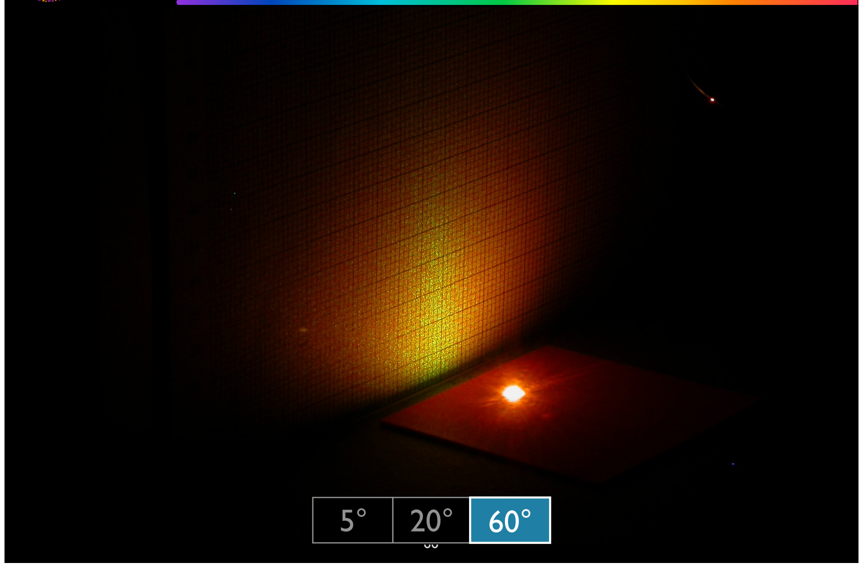
Fluorescent Sample @ 5°, 20°, 60°



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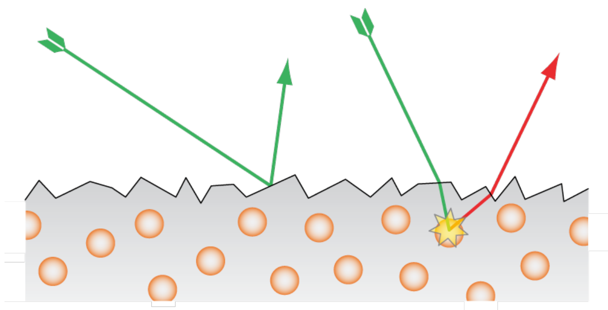
Bi-Coloured Reflection Pattern



- Rays which are reflected by the substrate retain their colour
- Rays which interact with the colorant molecules undergo wavelength shift

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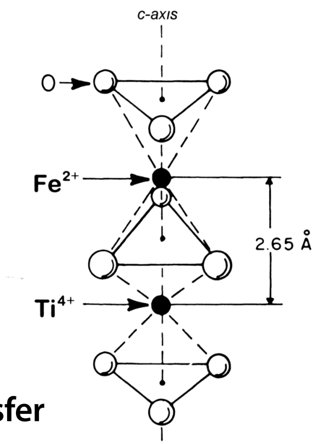
Charge Transfer: Sapphire

- Somewhat similar to ligand field
- Al2O3 + fractions of a percent Ti is colourless
- Same + similar % of iron: pale yellow
- Both: deep blue
- Fe and Ti influence each other by charge transfer



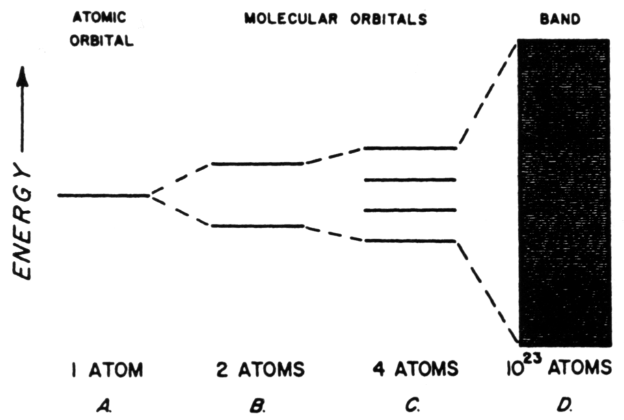
Colour from Band Theory

- Metals and alloys
  - Copper, silver, gold
- Pure semiconductors
  - Silicon, pure diamond, cadmium yellow
- Doped semiconductors
  - Coloured diamonds, LEDs
- Colour centres
  - Smoky quartz, amethyst

Energy Bands

- In non-metals, individual atoms and small molecules have individual electron orbitals
- A piece of metal can be seen as 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

Energy Band Illustration

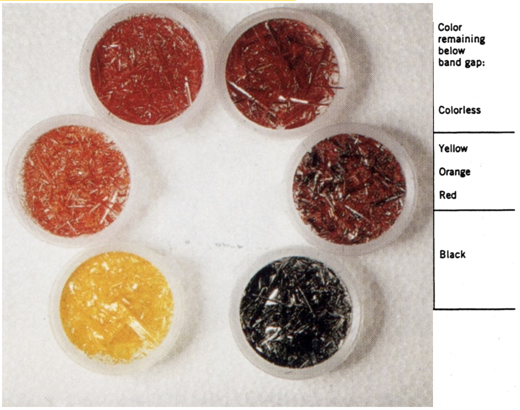


Colours of Metals

- Light cannot penetrate into a metal solid deeper than ~100 atoms
- Immediate reflection of incident photons
- Efficiency of this process can be wavelength – dependent: higher energies are less efficient for some materials (copper, gold)
- Direct absorption is hard to observe – gold plated sunglasses are an exception

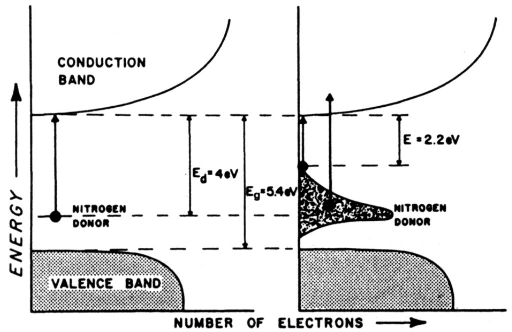
Energy Band Colours – Semiconductors

- Only photons of a certain minimum energy can be absorbed
- Low-pass filtering of incident light
- Band-gap differs between substances

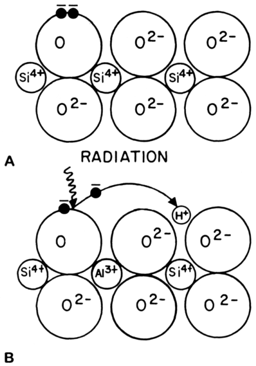


Energy Band with Dope

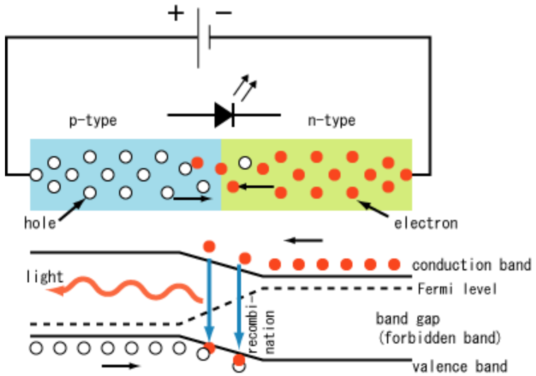
- Dope atoms offer intermediate levels in energy gap



Colour Centre Examples



Band Gap Emission - LED



- LEDs are semiconductor diodes with a band gap that causes a specific „tunnelling delta“ for electrons that cross it

Image source:

LED Properties

- „Spiky“, monochrome emission spectra
  - If „natural“ light colours are desired, several LEDs have to be combined (RGB), or fluorescent coatings have to be used
- Hard to design and build
  - The emission takes place in opaque materials!
- Much more efficient than blackbody radiators (i.e. incandescent bulbs)
  - Expect to see increased usage in the future!

White LED Spectrum

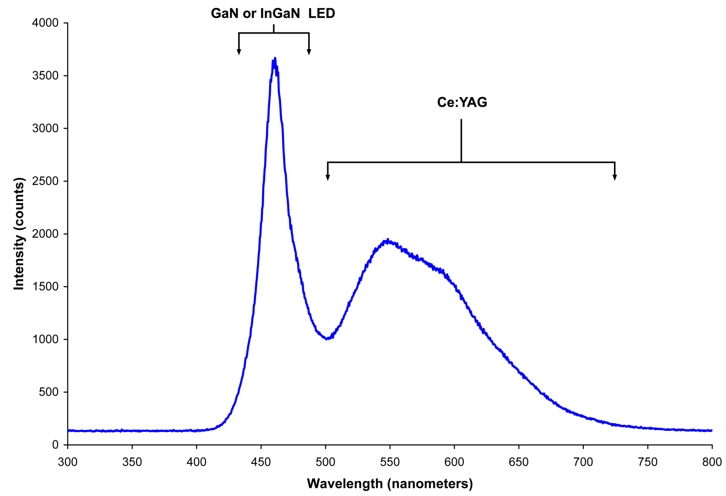


Image source: Wikipedia

Colour from Optics

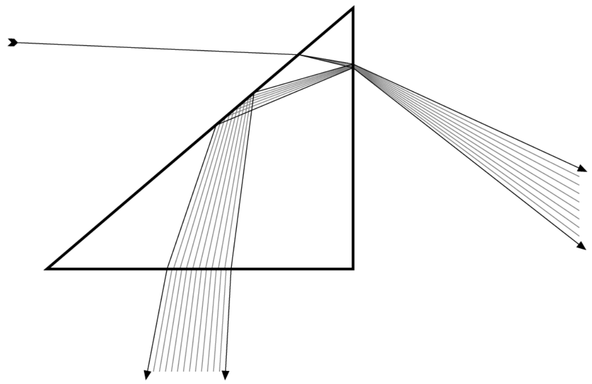
12. Dispersion
    - Rainbows
13. Scattering
    - Blue of the sky
14. Interference
    - Butterfly wings
15. Diffraction
    - Opal, diffraction gratings

(Anomalous) Dispersion

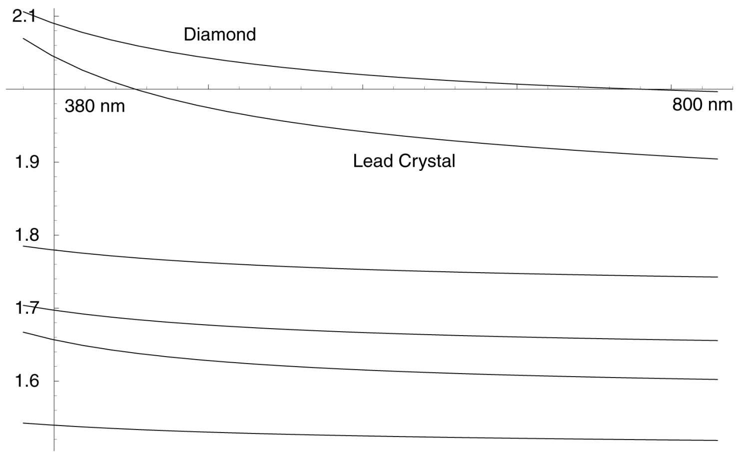
Dispersion

- Wavelength dependency of interference and refraction
  - Linear for interference
  - Nonlinear for refraction
- Sellmeier coefficients for glass and crystals characterise behaviour

Intersection Geometry



Sample Dispersions



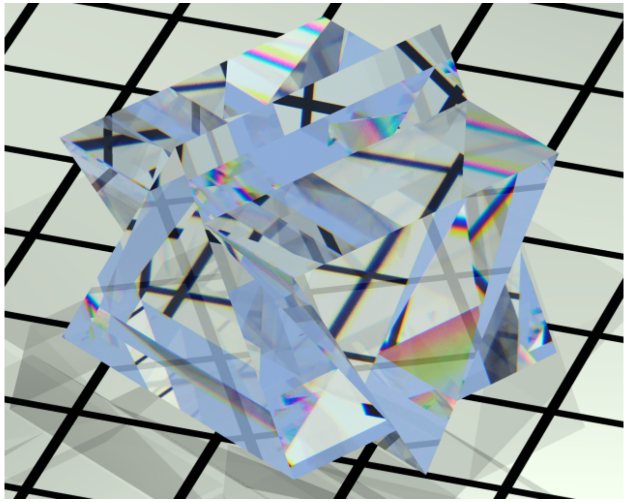
Sellmeier's Formula

- Approximation to dispersion curves of real materials

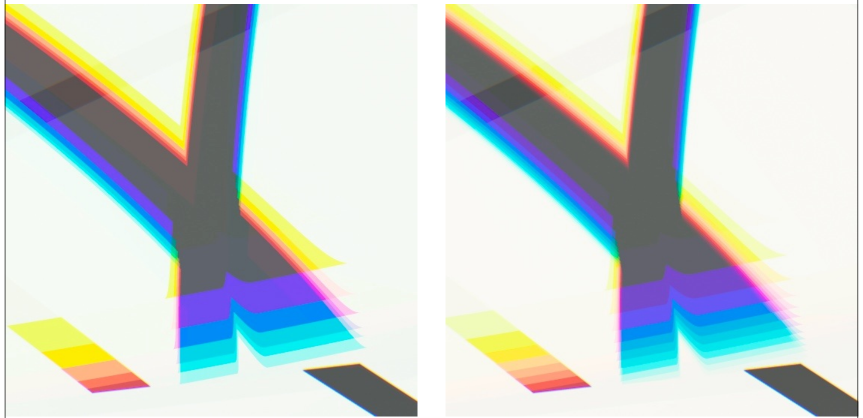
$$n_\lambda^2 = 1 + \sum_{i=0}^{n} \frac{A_i \lambda^2}{\lambda^2 - \lambda_i^2}$$

- Sum of quadratic terms with empirical coefficients
- Alternative: Cauchy's formula

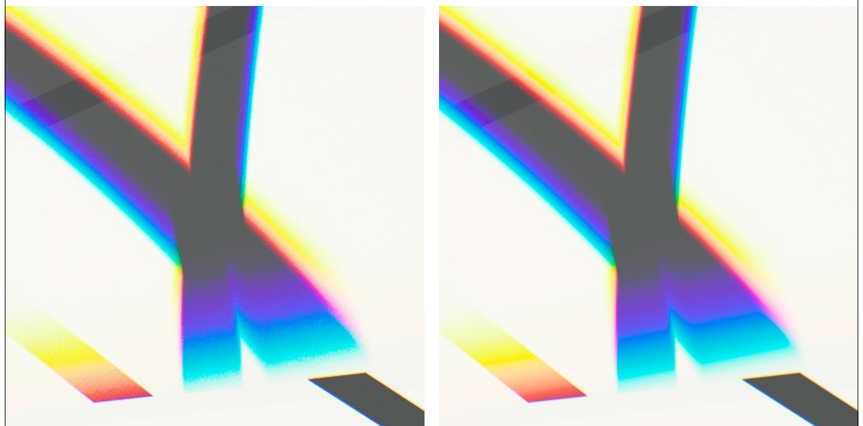
Full Dispersion Example



Dispersion Sampling 1



Dispersion Sampling 2



Dispersion Sampling

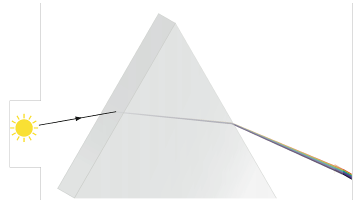
Either:

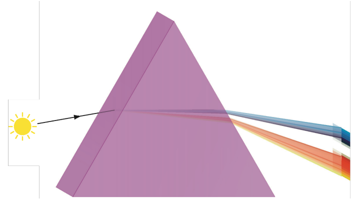
- Breadth-first in a normal ray tracer (turning it into a partial distribution ray tracer)
  - Regular sampling yields aliasing artefacts
  - Stochastic jitter by a single offset for all channels
- Single wavelength in a path tracer (but choose wavelength only once!)

Full Dispersion Example

Dispersion

- Index of refraction (IOR) depends on the wavelength
- Light is split into its spectral components
- Normal dispersion
  - IOR decreases with wavelength
  - Rainbow colours
- Anomalous dispersion
  - IOR non-monotonic!
  - Partially reversed prismatic colours



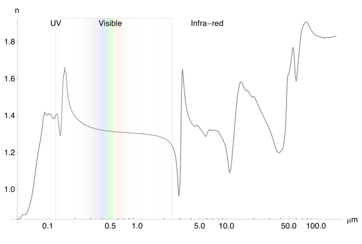


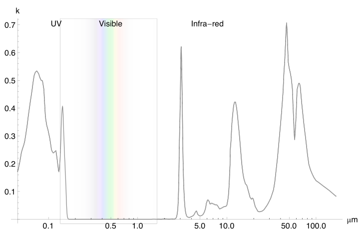
Dependency Absorption - IOR

- AD occurs around absorption frequencies
- IOR and absorption influence each other
- Use Kramers-Kronig relation to calculate one from the other

$$n(\omega) = 1 + \frac{2}{\pi}\mathcal{P}\int_0^\infty \frac{\omega' k(\omega')}{\omega'^2 - \omega^2}d\omega'$$

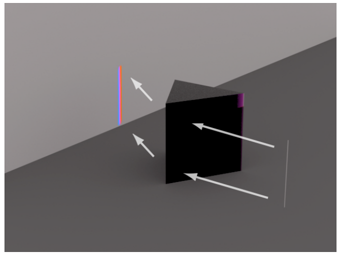
$$k(\omega) = -\frac{2\omega}{\pi}\mathcal{P}\int_0^\infty \frac{n(\omega') - 1}{\omega'^2 - \omega^2}d\omega'$$

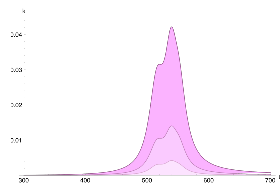


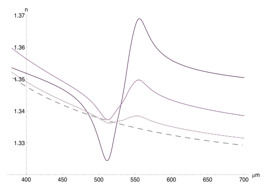


Experiment

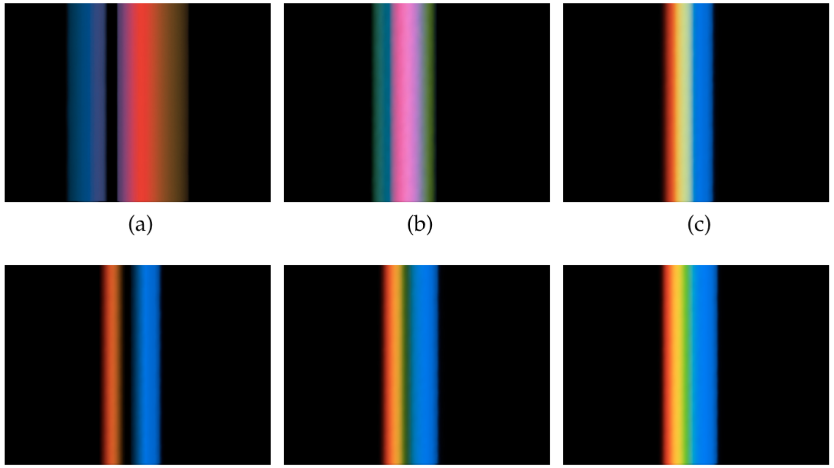
- Classical optical experiment
- Rose bengal diluted in water
- Three different concentrations
- Comparison with prisms that neglect the influence of the extinction coefficient on the index of refraction.







Results: Experiment



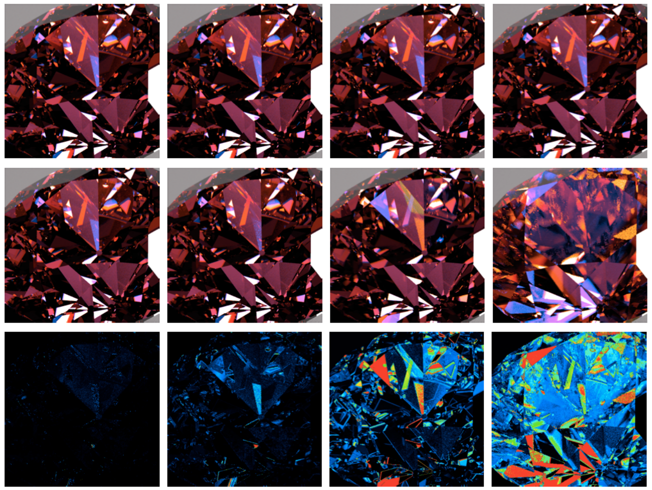
(a) (b) (c)

(d) (e) (f)

Results: Gemstone Appearance

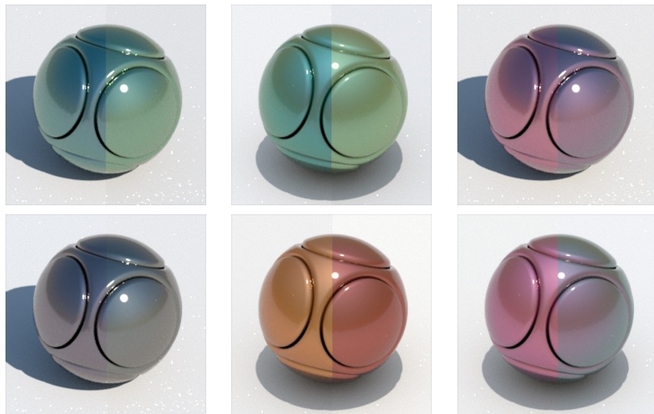
- For certain materials, AD cannot be neglected
- Importance for gemstone rendering?
- Spinel with and without AD
- Hardly any differences visible

Results: Small Structures



(a) (b) (c) (d)

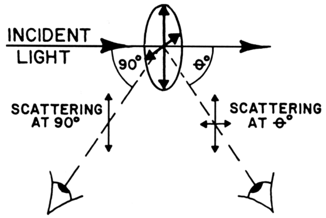
Pigment Particle AD



- Simulations of strongly coloured pigment particles used in complex BRDFs

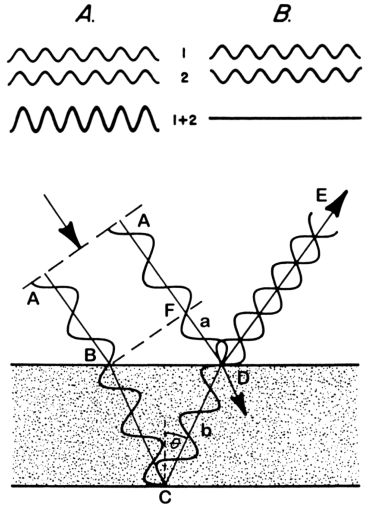
Rayleigh Scattering

- Deflection of light from its direction of propagation in transparent media
- Independent of scattering aerosols
  Pure air scatters light on its own!
- Wavelength dependency causes blue sky and red sunsets

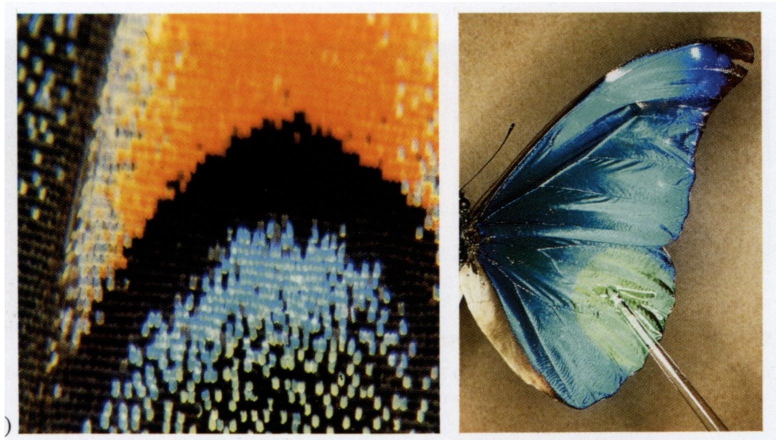


Interference

- Very small structures can evoke effects that depend on the wavelength of the incident light
- Subtly different propagation times lead to selective cancellation of reinforcement



Interference: Butterfly Wings



Structural Colour

Structural Colour

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Structural Colour

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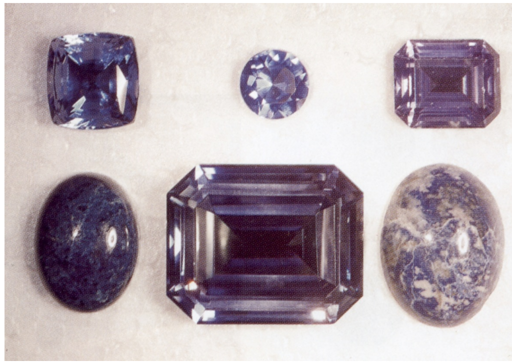
6 Gemstones – 6 Causes of Colour!



Metallic & Pearlescent Paint

- Goniochromism - hue changes with viewing angle
- Differences in micro and macro appearance
- Coherence glitter
- Binocular glitter, lustre & mottle
- Interference pigments

Structural vs. Pigment Colour

- Pigment Colour
  - Less intense
  - Does not change hue with viewing angle
  - Prone to fading (molecular degradation - UV!)
- Structural Colour
  - Very intense colours possible
  - Practically always change colour with viewing angle (at least a bit)
  - Extremely stable against UV degradation
  - Mechanically vulnerable!

Pearlescent Pigments

Interference Pigments

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Saturated Colours
Two Types of Rainbow

Credit for these slides goes to:

Professor Jan Koenderink

University of Utrecht

The slides are a re-creation of slides he showed at an EGSR keynote talk in 2004

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"Seeing By Spectrum"

- Newton introduced the myth that one "sees by spectrum"

- However, the spectrum does not include all the hues of daily experience
- Introduction of the colour circle solved this problem

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Band Pass vs. Band Gap Colour

- "Spectrum" or "Newtonian" colours can be seen in a spectroscope
- Band gap colours belong to the "inverted rainbow"

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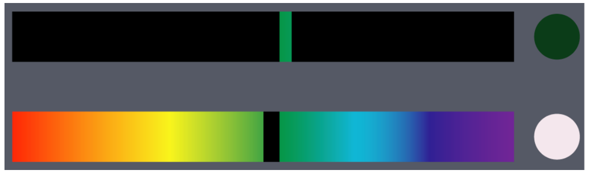
Band Pass vs. Band Gap Rainbow

- Top: spectral band pass colours ("Newtonian" colours, rainbow, dominant wavelength for all)
- Bottom: band gap colours ("non-Newtonion" colours, inverse rainbow, no dominant WL for the centre)
- Infinitely many of each, 1-1 mapping possible

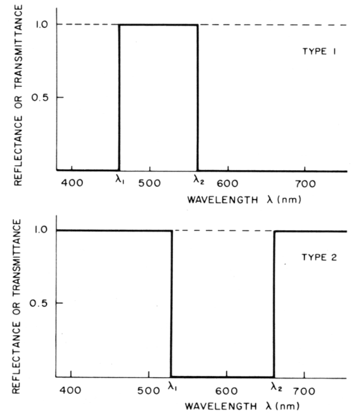
Object Colours: Reflection Spectra



- Monochromatic (or band pass) paints are necessarily almost black
- Narrow band gap paints are necessarily almost white
- Highly colourful paints must be “full” colours, or “semichromes”

Optimal Solid Colours

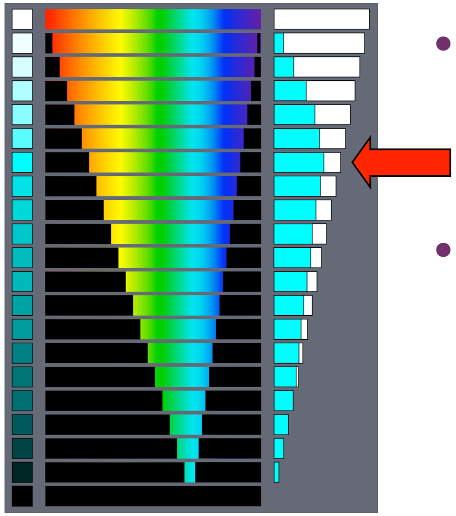
- Reflectances (as opposed to emissions)
- Not realisable in practice
- Interesting because they are the limiting case of all non-fluor-escent object reflectances



Goethe’s Edge Colours

- Special band pass spectra
- Cumulative spectra of daylight starting from the red or blue end of the spectrum
- Increase of filter width decreases saturation
- Seen in lenses at prisms at object edges - hence the name

Solid Colour Ramp



- Full colours have the maximum colour content for a given hue
- Band limits have to be at complementary wavelengths for maximum hue