Lecture 5:
Imaging by Visible Light III

Contents

◆ Colours

◆ Ultraviolet and Infrared Imaging

◆ Telescopes

◆ Mirror Optics

◆ Classical Microscopy

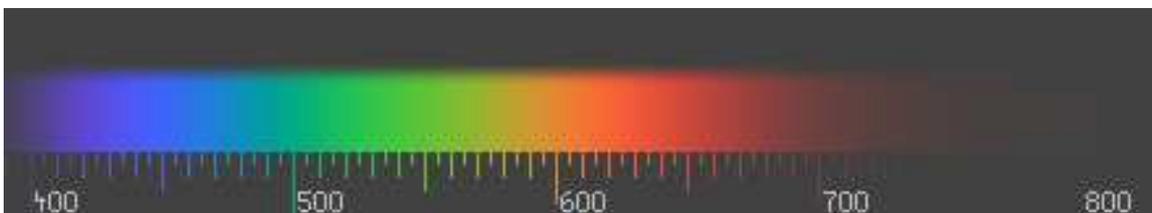◆ Confocal Microscopy

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Colours (1)

Colours

Spectra

Visible light of different wavelength is perceived as having different colour.

Continuous optical spectrum. *(Wikipedia)*

◆ The exact spectral composition of a visible light phenomenon is described by a function $f(\lambda)$ stating the energy density for each wavelength λ in the visible range $((380\ldots780)\,\mathrm{nm})$.
These functions form an infinite-dimensional space! (Let us assume that it is a Hilbert space.)

Isaac Newton (1642–1727)
(Wikipedia)

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Colours (2)
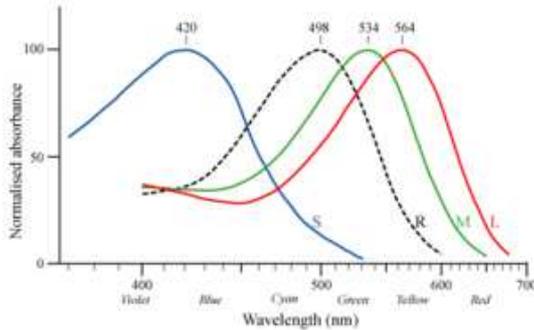
Retinal Colour Perception

Our retina contains four types of light-sensitive cells, namely *rods* and three types of *cones*.

These have different spectral sensitivities.

Light sensitivity of rods and the three types of cones. *(Wikipedia)*

◆ Rods are more sensitive than cones. They are responsible for vision in the dark (scotopic vision) but don't contribute to colour perception.

◆ Cones have absorption and sensitivity maximum either in the red, green or blue range of the spectrum.

Colours (3)

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◆ Each sort of cones (r/g/b) performs a *projection* from the infinite-dimensional space of spectra to a one-dimensional sub-space,

$$Q_{\nu,\mathrm{r/g/b}} = N_{\mathrm{r/g/b}} \int_{\lambda_1}^{\lambda_2} Q_\nu V_{\mathrm{r/g/b}}(\lambda)\, \mathrm{d}\lambda \ .$$

◆ Colours perceived by our retina therefore lie in a three-dimensional space.

Colours (4)

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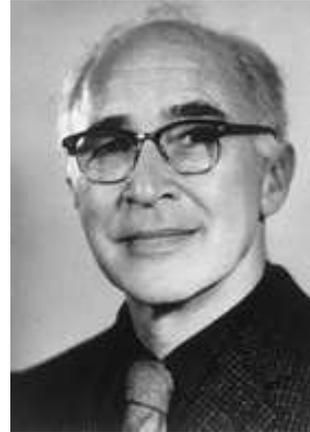15 16
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The three-colour theory goes back to Thomas Young and Hermann von Helmholtz. The existence of three different types of cones in human retina was finally verified by George Wald in 1967.

Thomas Young   Hermann von Helmholtz   George Wald
(1773–1829)   (1821–1894)   (1906–1997)

Image sources: Wikipedia (Young, Helmholtz),
http://nobelprize.org/medicine/laureates/1967/wald-bio.html (Wald)

Colours (5)

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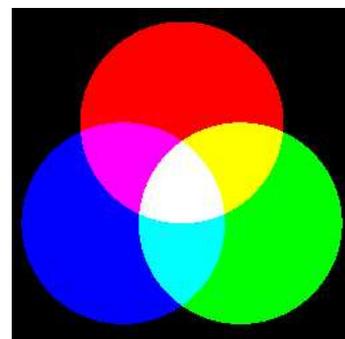19 20
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Additive Colour Mixing: RGB Colour Space

◆ Assume we measure the projections of visible light according to the three sensitivity functions for r/g/b cones: Then we have a representation of the given stimulus in the *RGB colour space*.

◆ Assume we have three light sources such that each of them emits light that stimulates one and only one type of cones. Then we can adjust the intensities of the light sources according to the RGB values measured. This compose a visual stimulus that is indistinguishable, for our retina, from the original one.
This is essentially what a computer or TV screen tries to do with the R, G, B fluorescents.
One calls this method of mixing colours *additive colour mixing*.

Colours (6)

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Subtractive Colour Mixing: CMY(K) Colour Spaces

◆ Non-radiant bodies, like printed paper, attain colour by modulating the wavelength profile of reflected light.

◆ Assume we have ideal white illumination that decomposes into three components each of which stimulates one and only one type of cones.

◆ Assume further that we have three pigments at hand each of which removes one component from the white light and lets the other two pass unreduced. Moreover, assume these can be thinned such as to transmit an adjustable portion of the respective colour component.

◆ Then we can prepare, by mixing these pigments in suitable concentration, a mixture that filters a desired stimulus out of the white light.

This is called *subtractive colour mixing*.

Colours (7)

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Subtractive Colour Mixing: CMY(K) Colour Spaces, continued

◆ Unfortunately, there are no such ideal pigments but some cyan, magenta, and yellow pigments can approximate this. Thinning does also not work with true pigments, instead one rasterises the image and covers only a part of the area with each pigment, depending on how much of each component is to be absorbed.
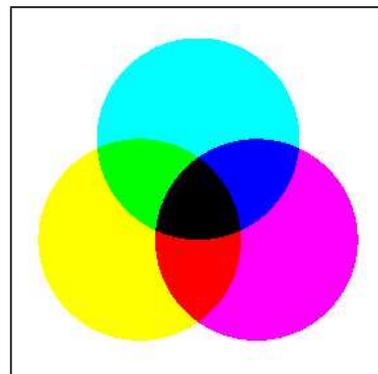
◆ Because of the use of cyan, magenta, and yellow, this colour space is called CMY colour space.

◆ To improve reproduction of dark colours, one adds a black pigment which leads to CMYK colour space. This is the most common colour space in printing.

HSV Colour Space

◆ Observation: Brightness information plays an outstanding role.

◆ Proper reconstruction of colours is difficult.

◆ For these reasons, one is interested in representing brightness and colours separately to allow separate processing.
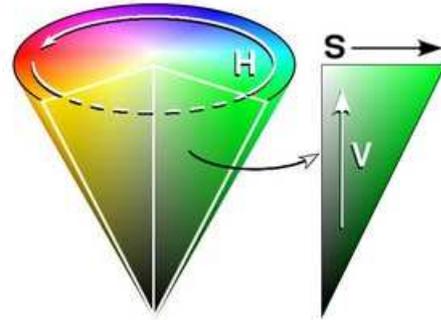
◆ In this way, the 3-D colour space is reparametrised.

(image: Wikipedia)

◆ One way to do this is the *HSV colour space* with three coordinates *hue*, *saturation* and *value* (or *brightness*).

Transformation $(R, G, B) \to (H, S, V)$: Let $M = \max(R, G, B)$, $m = \min(R, G, B)$,

$$V = M, \qquad S = \frac{M - m}{M},$$

$$H = \begin{cases} \frac{G-B}{M-m} \times 60°, & R \geq G, B, \\ (2 + \frac{B-R}{M-m}) \times 60°, & G \geq R, B, \\ (4 + \frac{R-G}{M-m}) \times 60°, & B \geq R, G \end{cases} \quad (\text{mod } 360°).$$

Opposite Colours: The Four-Colour Theory

◆ Observation: Yellow is subjectively perceived as an independent colour, rather than a mixture of green and red.

◆ There is no such colour as a *yellowish blue* or a *reddish green*.

These observations led E. Hering to postulate four primary colours which come in opposite colour pairs *blue–yellow* and *red–green*. Neurophysiological investigations have confirmed since 1966 that the retinal colour perception is in fact *recoded* in further neural processing to

◆ a black–white axis (brightness)

◆ a blue–yellow axis

◆ a red–green axis
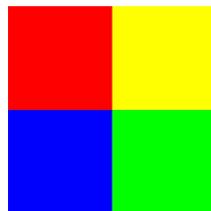
Ewald Hering
(1834–1918)

The *LAB colour space* is designed to reflect this coding.

image source: http://vlp.mpiwg-berlin.mpg.de/people/data?id=per90

Colour Image Sensorics

All colour image sensors which are in use today rely on the three-dimensional RGB colour space.

◆ **Photographic film:** Films contain three layers which are arranged, by adapted sensitivity and usually a yellow filter layer, such that each is sensitive for one primary colour (R, G, B). In development, silver is removed and pigments are created that realise a subtractive colour mixing.

◆ **CCD:** Light is filtered before approaching sensor pixels. So each pixel is sensitive for only one primary colour. A typical arrangement is based on 2×2-pixel cells with two green-sensitive, one red-sensitive and one blue-sensitive pixel.
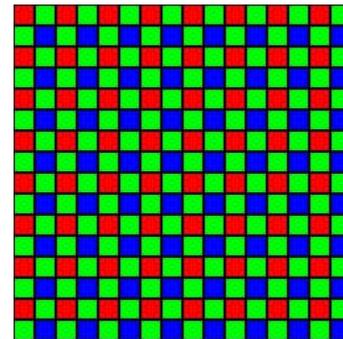
Often the nominal resolution of a camera refers to the full number of pixels but each colour component has indeed a lower resolution.

Interpolation of all components to full resolution leads to *mosaicking artifacts* (compare the list of image perturbations, end of previous lecture).

Colour Photography: Early Attempts

Spectrum, Edmond Becquerel, 1848

Alexandre Edmond Becquerel (1820–1891)
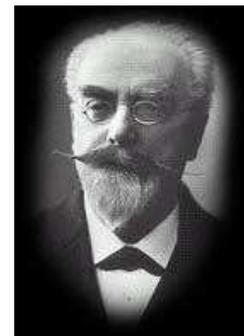
Gabriel Lippmann (1845–1921)

Versailles garden, Gabriel Lippmann, 1890.

Both Becquerel and Lippmann used methods based on interference of light waves within the emulsion. These techniques are not dependent on the RGB colour space but record light directly by its wavelength.

Image sources: Wikipedia (portraits), Spektrum der Wissenschaft, 2/1990)

Ultraviolet and Infrared Imaging

Photography in the ultraviolet, and near infrared ranges (to $\approx 1150\,\text{nm}$) follows mostly the same principles as in the visible light range. Special films and filters are needed to adapt to these wavelength ranges.

Appearance of objects differs from that in visible light. Infrared is particularly interesting because clouds and fog become transparent.
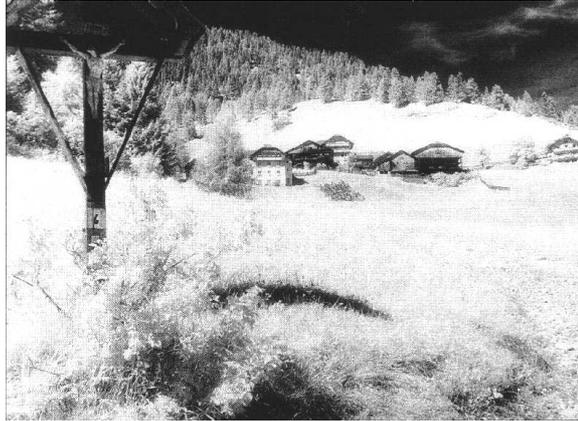
Infrared photograph. *(C. Seelbach, 1992)*

The use of a broad wavelength band reaching from UV to IR is also typical for remote sensing images obtained by satellites.

Here it is most common to use multispectral camera equipment (4 to 12 colour channels).

Telescopes

◆ invented in 1608 by Hans Lippershey

◆ *Objective lens* follows camera optics, generates a real image

◆ If used by human observer, an additional lens (*ocular lens*) is added which transforms the real image into a virtual one, like a magnifying glass
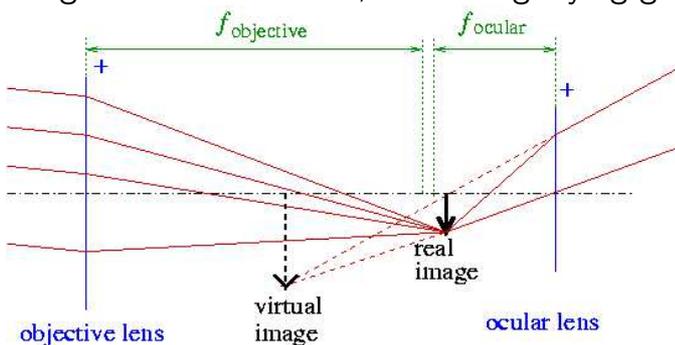

Hans Lippershey (1570–1619)
(Spektrum-Verlag, 2000)

◆ If used for capturing images, the real image is captured directly by a sensor.

◆ Modifications of this principle by additional lenses are possible.

◆ In *mirror telescopes*, the objective lens is replaced by a hollow mirror.
Mirror telescopes are dominant in modern astronomy.

Mirror Optics (1)

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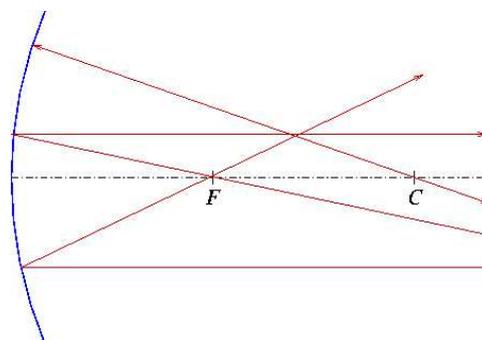| 1 | 2 |
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Mirror Optics

Planar Mirror

◆ Each object in front of a planar mirror gives rise to an upright virtual image behind the mirror in equal size and distance to the mirror.

Mirror Optics (2)

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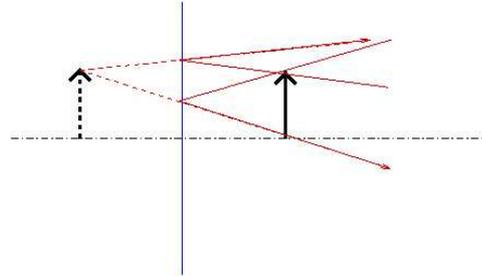
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Spherical Hollow Mirrors

◆ In the simplest case, the shape of a hollow (concave) mirror is a segment of a sphere (spherical mirror).

◆ Rays passing through the centre C of the sphere are reflected into themselves.

◆ Consider an optical axis. Then rays parallel and close to this axis are reflected approximatively into the point F on the optical axis half-way between C and the mirror. F is called *focal point*, the half (curvature) radius of the mirror is called *focal length* f.

◆ Analogously, rays from the focal point become almost parallel to the optical axis after reflection.

Mirror Optics (3)

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◆ Image formation is similar to ideal convex lenses.

◆ Difference:
Real images are *in front* of the mirror,
virtual images are located *behind* the mirror.

◆ Rules:

- Objects between the mirror and F cause enlarged, upright virtual images.
- Objects between F and C induce top-down enlarged real images beyond C.
- Objects beyond C generate top-down shrunken real images between F and C.

◆ These rules hold for rays in a sufficiently small angular range around the optical axis. With larger angles and distance from the optical axis, aberrations occur.


Mirror Optics (4)

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Paraboloid Mirrors

◆ Rotation surfaces of conics are an interesting alternative to spherical shapes for hollow mirrors.

◆ A *paraboloid mirror* reflects rays parallel to its rotation axis *exactly* into the focal point of the paraboloid, and vice versa.

◆ Paraboloid mirrors therefore reduce aberrations in the image formation for objects near the optical axis of the mirror, even at large mirror apertures – particularly interesting in astronomy.

Mirror Optics (5)
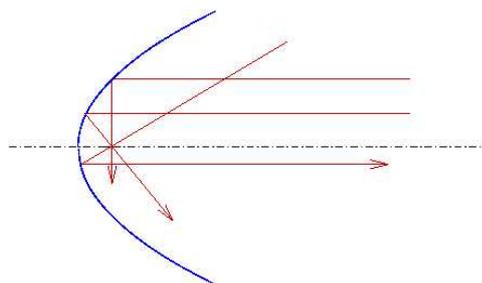
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Ellipsoid and Hyperboloid Mirrors

◆ A concave *ellipsoid mirror* has two focal points F_1, F_2 in front of the mirror. Rays from F_1 are reflected into F_2 and vice versa.

◆ A concave *hyperboloid mirror* – shaped like a component of a two-shell hyperboloid – has also two focal points F_1 and F_2 but only F_1 lies in front, while F_2 is behind the mirror. Rays from F_1 appear to come from F_2 after reflection, and rays directed to F_2 are reflected into F_1.

◆ These properties can be used for the manipulation of real images projected by objective mirrors, e.g. a hyperboloid mirror could serve as ocular in a telescope optic.

Classical Microscopy

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Classical Microscopy

◆ Primarily, lenses and optics analogous to telescopes.

◆ Adapted to short object distances ($f < s < 2f$ for objective – enlarged real image)

◆ Objects can be illuminated from above (reflected light is used for imaging) or from below (transmitted light is used).

◆ In case of microscopes, diffraction phenomena limit the spatial resolution. Ernst Abbe developed (ca. 1870) the corresponding theory: The main result is Abbe's formula

Ernst Abbe (1840–1905)
(Olms-Verlag, 1989)

$$d = \frac{\lambda}{n \sin \alpha}$$

that allows to calculate the minimum aperture $n \sin \alpha$ required to achieve some resolution d, given the wavelength λ.

Confocal Microscopy

◆ 3-D imaging technique that measures directly light intensity at points in space

◆ Marvin Minsky (b. 1927) invented the confocal microscopy principle in 1953. Mojmir Petran and Milan Hadravsky built a type of confocal microscopes in 1967 in Prague.

◆ The most important modality used today is *confocal laser scanning microscopy*. It is designed to image the distribution of fluorescent molecules within a transparent volume.

Fluorescence: property of certain chemical substances to emit light of a specific frequency when being hit by light of another, higher frequency. A molecule is *excited* by absorbing e.g. blue or ultraviolet light, and returns to its normal state while emitting a photon of e.g. green light.
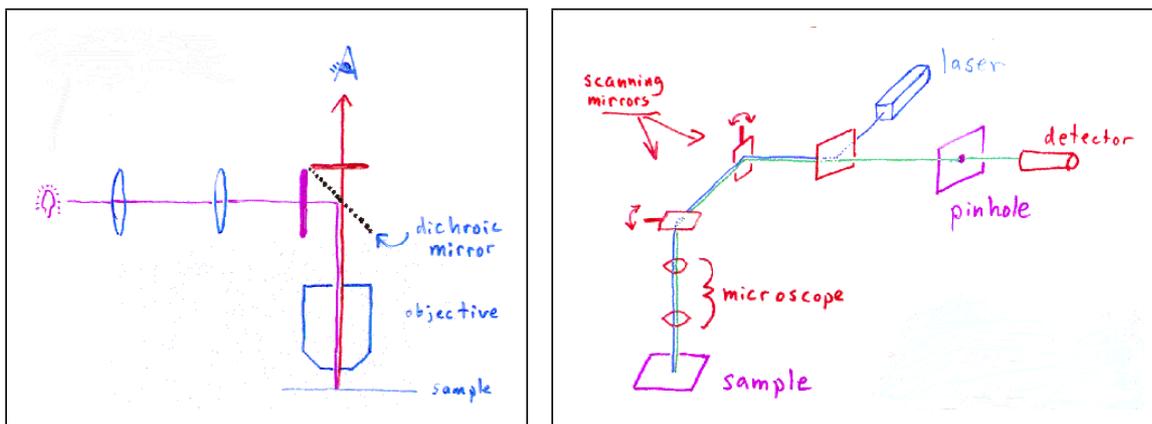
Top left: Fluorescence microscopy principle. The violet beam is the high-frequency illumination source, while the red beam stands for low-frequency fluorescent light from the object. **Top right:** Confocal microscopy principle. *(Images: E. Weeks, http://www.physics.emory.edu/~weeks/confocal/)* **Bottom right:** Marvin Minsky (∗1927) and some anonymous fish. Minsky invented the principle of confocal microscopy in 1953. *(Image: Wikipedia)*
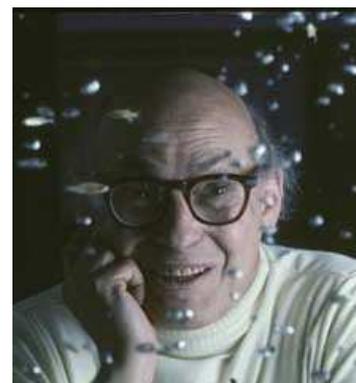
Confocal Microscopy (3)

◆ The object is illuminated by a laser as a point-shaped light source.

◆ Illuminating light is focussed by the objective lens to one point in the object volume.

◆ The focus point – and some other points in the object that are hit by the illuminating light – emit fluorescent light.

◆ Fluorescent light as well as reflected laser light is again imaged by the objective lens.

◆ Reflected laser light is separated by a dichromatic mirror (mirror with colour-dependent reflection/transmission).

◆ A pinhole diaphragm selects from the fluorescent light the part which really comes from the focussed object point. Only this part is transmitted to the detector.

◆ With a single detector, a full 3-D image is obtained by scanning in x, y and z directions (3-D scan). With a CCD array as detector, one has to scan only in depth direction (1-D scan).

Summary

Summary

◆ The human visual system uses three types of rods with sensitivity maxima in red, green and blue. This inspires the additive RGB system used in monitors.

◆ A related subtractive colour space is the CMY space used in printing.

◆ The HSV colour space separates brightness from colour information using cylindrical polar coordinates.

◆ The four-colour theory is implemented in the LAB space.

◆ CCD colour chips use a mosaic of cells that are sensitive either to red, green or blue.

◆ UV and IR imaging are based on similar priciples as visible light imaging.

◆ Classical telescopes follow the principles of camera optics.

◆ Mirrow telecopes replace the objective lense by a hollow mirror, e.g. a paraboloid mirror.

◆ Classical microscopy is based on similar principles as telescopes. Their reolution is limited by diffraction phenomena.

◆ Confocal miscroscopy is a 3D imaging technique that allows to measure directly the light intensity at points in space.

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◆ http://www.physics.emory.edu/~weeks/confocal/