Colour Imaging

Jean-Baptiste Thomas
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Digital
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Colour imaging
is our monkey-attempt to simulate our visual system and to fool it so that we can develop a technology that permits to acquire and reproduce/display colour images…

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is our monkey-attempt to simulate our visual system and to fool it so that we can develop a technology that permits to acquire and reproduce/display colour images…
-In a controlled and reproducible manner
-To obtain a pleasant/artistic/best/good result
-Independently from or adapted to different conditions
-To extract most visual information from the scene.
…

About the academic field

- Fundamental **knowledge, technologies, methods, models, quality evaluations, tools**, to achieve acquisition and reproduction of colour images.
- Often an **inverse problem**: Inversing an imaging model (image reconstruction)
- What information? What is colour? How to encode it?
- Stable representation of information, independent from or adapted to viewing conditions
- Several pre-processing for applications (Computer Vision), very important for visualization (e.g. in remote sensing)
- Hot topic, fashion 70's – 00's, drop down around 2010, rising again (spectral, computational appearance, wearable devices)
- Very much intricated with the industry

Agenda

- From colour science to colour imaging
  - Major aspects of colour science used for colour imaging
    - Additive mixture of stimuli / Trichromaticity
    - Temporal and spatial contrast sensitivity
    - Metamerism
    - Chromatic adaptation
- Imaging model
- Technologies
  - Acquisition, displays, printers
  - Color management
- Imaging model***S***
- Future challenges in colour imaging
  - Note on reflectance
  - HDR
  - Wearable devices

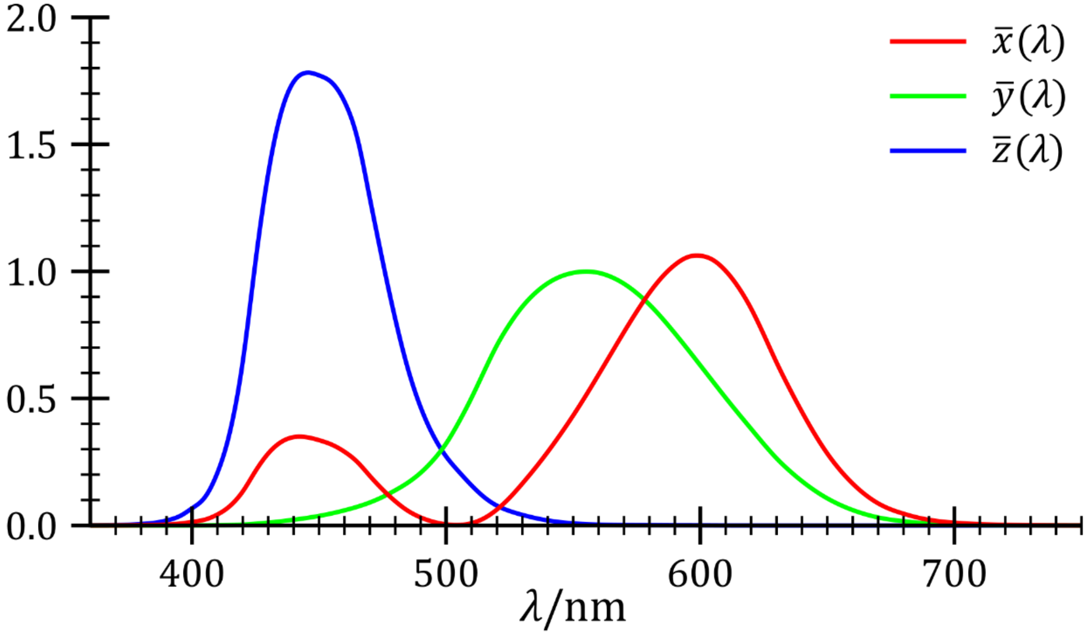
17-236 colour-matching functions (of a trichromatic system)

tristimulus values of monochromatic stimuli of equal radiant power

NOTE 1 The 3 values of a set of colour-matching functions at a given wavelength are called "colour-matching coefficients" (formerly: "spectral tristimulus values").

NOTE 2 The colour-matching functions may be used to calculate the tristimulus values of a colour stimulus from its colour stimulus functions $\varphi_\lambda(\lambda)$.

http://eilv.cie.co.at/indexpage/



https://commons.wikimedia.org/wiki/File:CIE_1931_XYZ_Color_Matching_Functions.svg

17-506 Grassmann's laws

3 empirical laws that describe colour-matching properties of additive colour mixtures of colour stimuli:

- to specify a colour match, 3 independent variables are necessary and sufficient,
- for an additive mixture of colour stimuli, only their tristimulus values are relevant, not their spectral compositions,
- in an additive mixture of colour stimuli, if one or more components of the mixture are gradually changed, the resulting tristimulus values also change gradually

http://eilv.cie.co.at/indexpage/

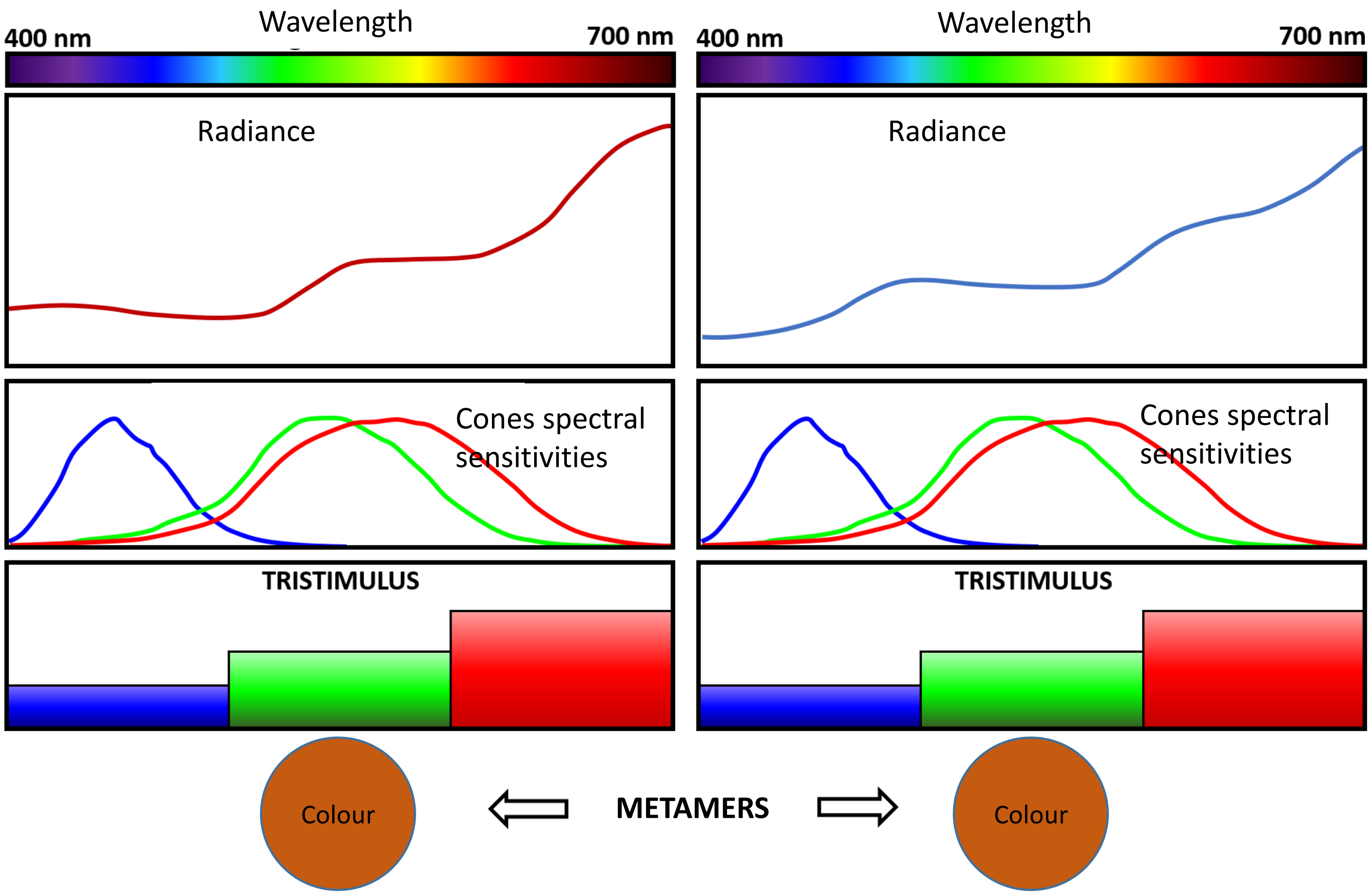
$$X = \int_\lambda L_{e,\Omega,\lambda}(\lambda)\,\overline{x}(\lambda)\,d\lambda,$$

$$Y = \int_\lambda L_{e,\Omega,\lambda}(\lambda)\,\overline{y}(\lambda)\,d\lambda,$$

$$Z = \int_\lambda L_{e,\Omega,\lambda}(\lambda)\,\overline{z}(\lambda)\,d\lambda.$$

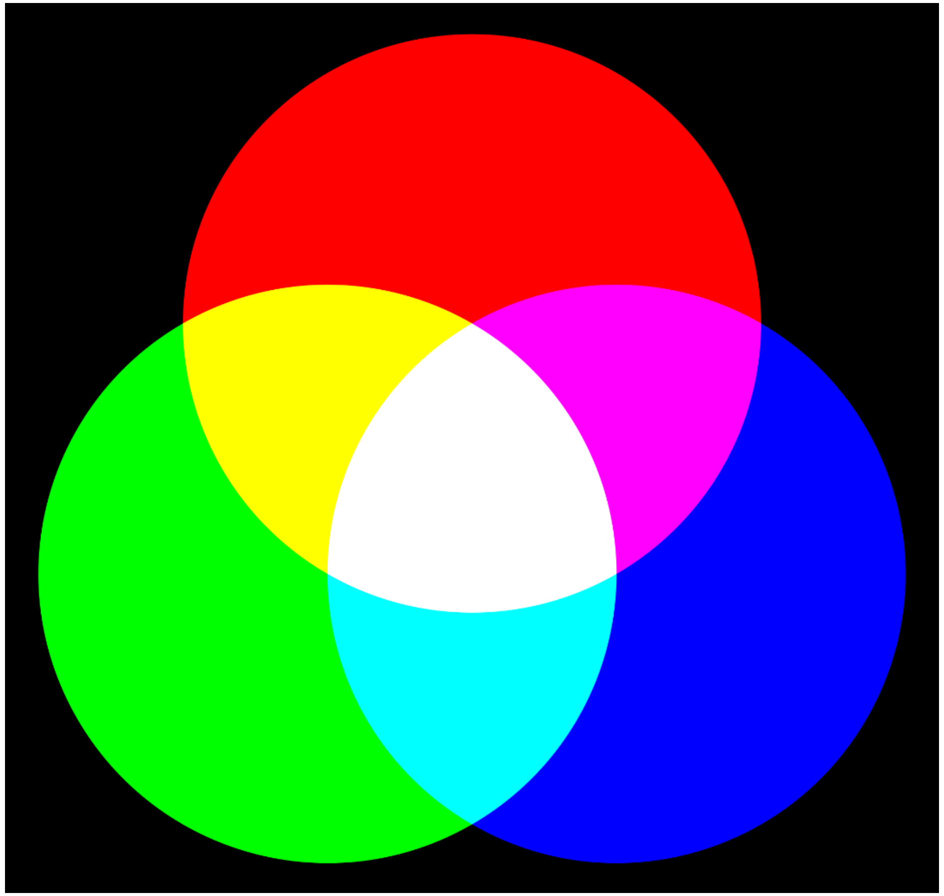
17-768 metameric colour stimuli
spectrally different colour stimuli that have the same tristimulus values in a specified colorimetric system
http://eilv.cie.co.at/indexpage/

17-140 chromatic adaptation
visual process whereby approximate compensation is made for changes in the colours of stimuli, especially in the case of changes in illuminants
http://eilv.cie.co.at/indexpage/

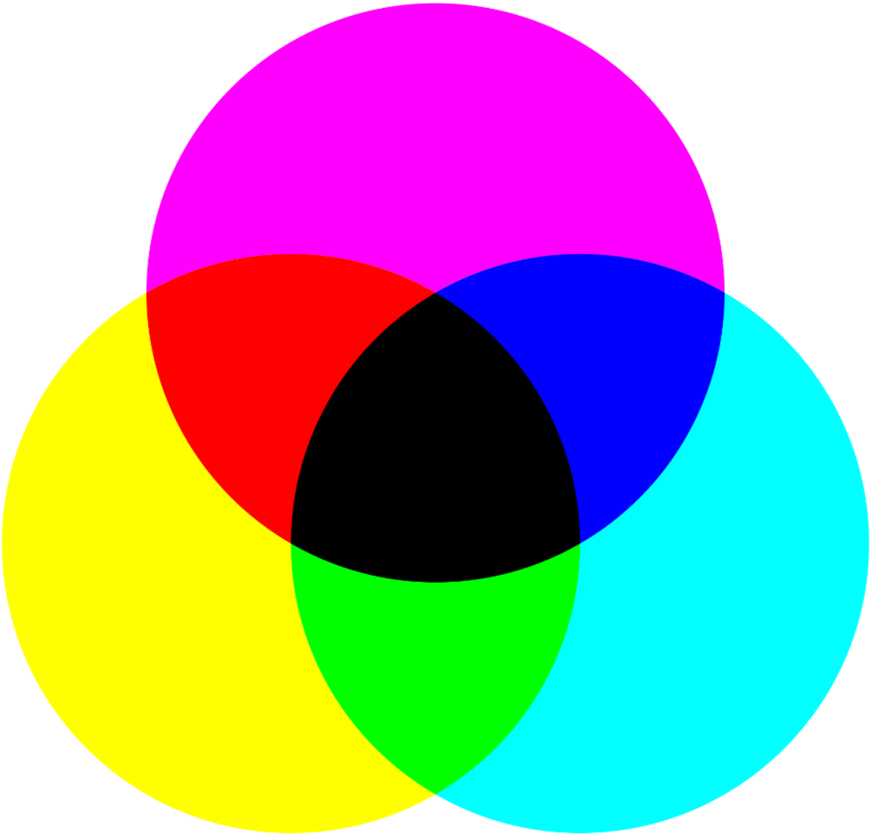


https://fr.wikipedia.org/wiki/Couleur_m%C3%A9tam%C3%A8re

17-24 additive mixture of colour stimuli
stimulation that combines on the retina the actions of various colour stimuli in such a manner that they cannot be perceived individually
http://eilv.cie.co.at/indexpage/



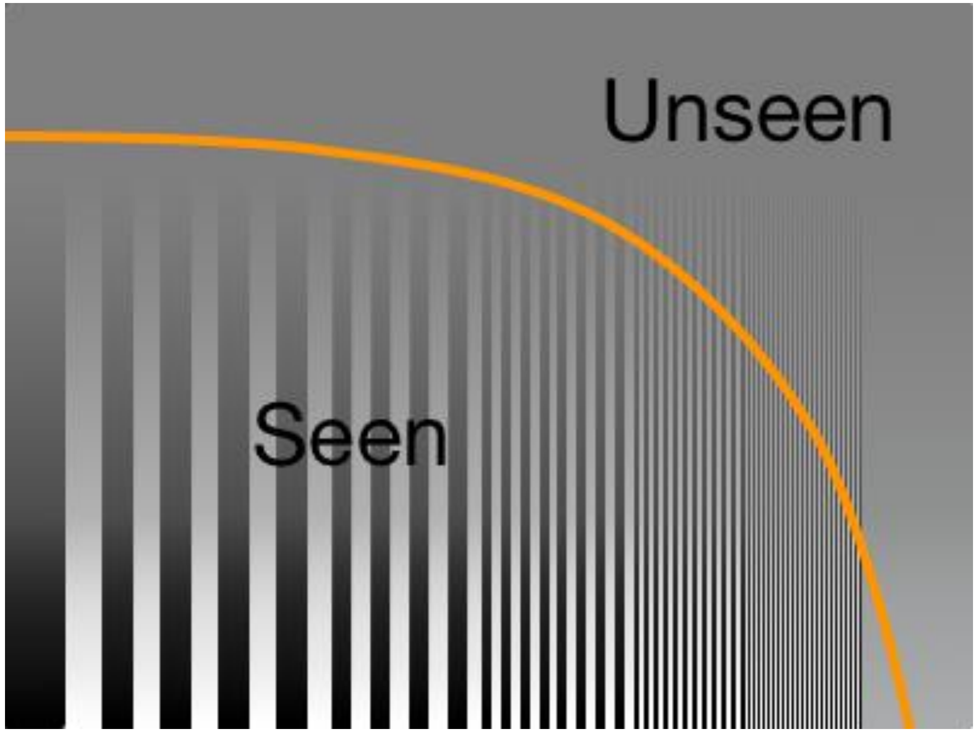
https://fr.wikipedia.org/wiki/Synth%C3%A8se_additive#/media/Fichier:Synthese+.svg

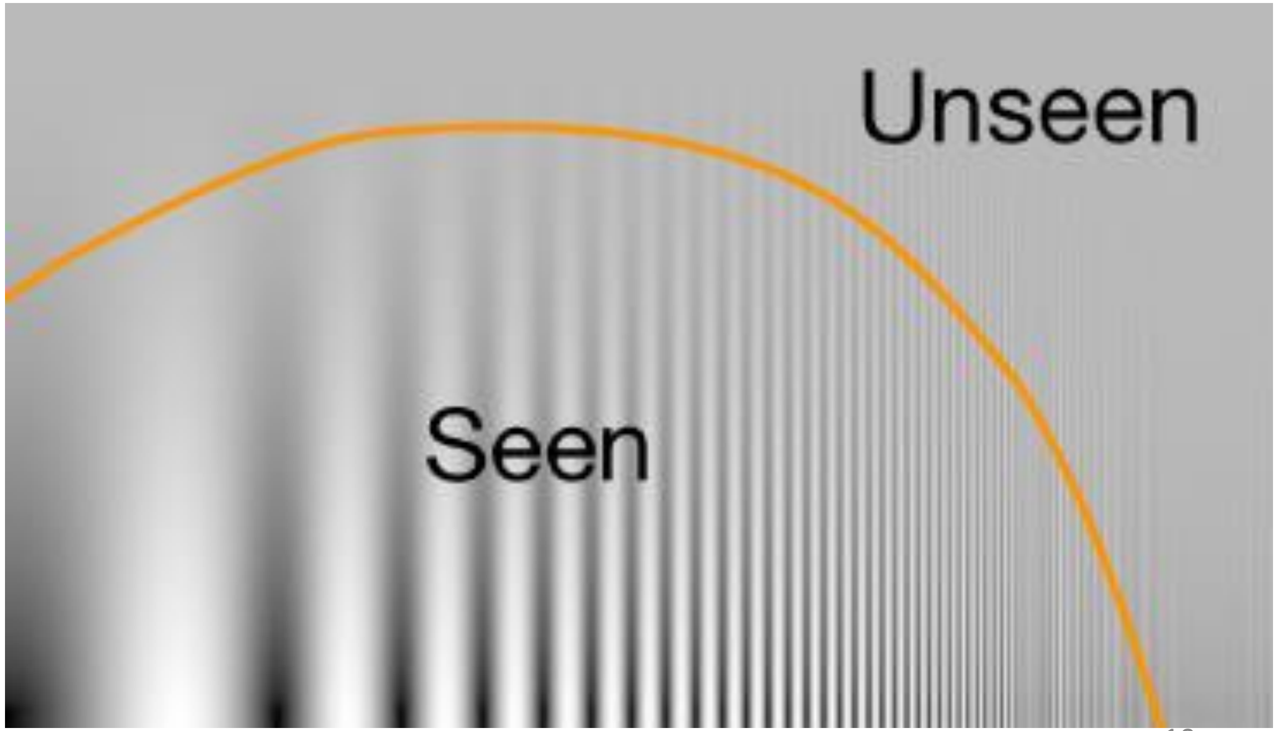


https://fr.wikipedia.org/wiki/Synth%C3%A8se_soustractive#/media/Fichier:Synthese-.svg

17-255 contrast sensitivity [S_c]
reciprocal of the least perceptible (physical) contrast, usually expressed as $L/\Delta L$, where L is the average luminance and ΔL is the luminance difference threshold
http://eilv.cie.co.at/indexpage/

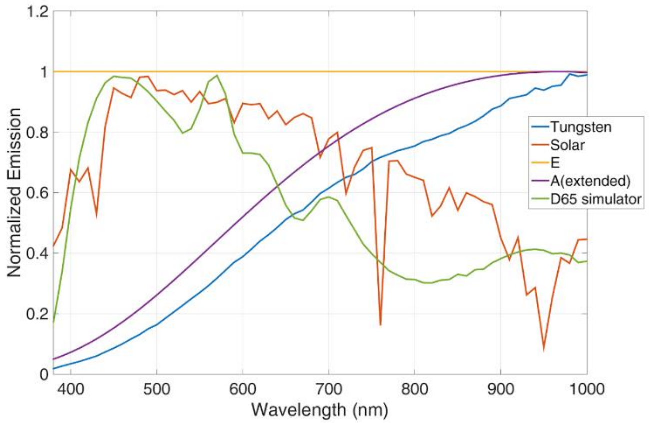
17-1403 visual acuity
1. qualitatively: capacity for seeing distinctly fine details that have very small angular separation
2. quantitatively: any of a number of measures of spatial discrimination such as the reciprocal of the value of the angular separation in minutes of arc of 2 neighbouring objects (points or lines or other specified stimuli) which the observer can just perceive to be separate
http://eilv.cie.co.at/indexpage/



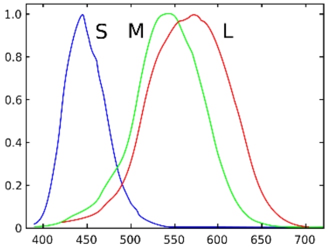


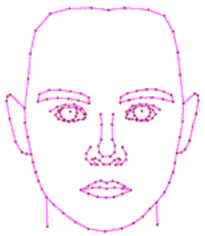
https://understandinglowvision.com/2-0-contrast-sensitivity-function/

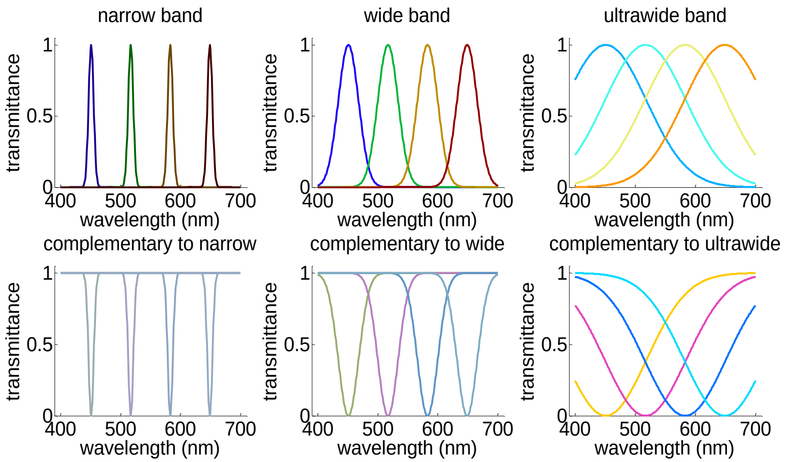
Imaging Model: Flat, Matte, Diffuse

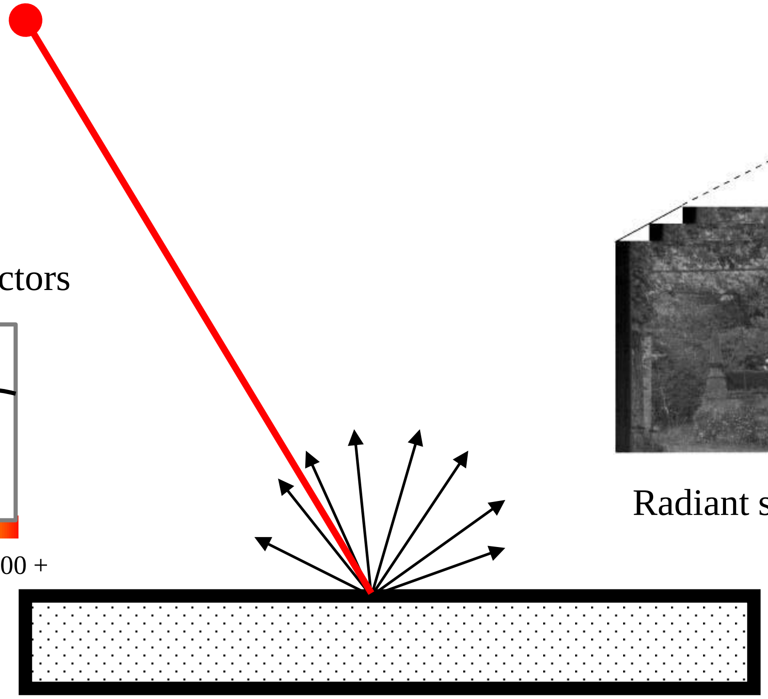


https://fr.m.wikiversity.org/wiki/Fichier:Cones_SMJ2_E.svg

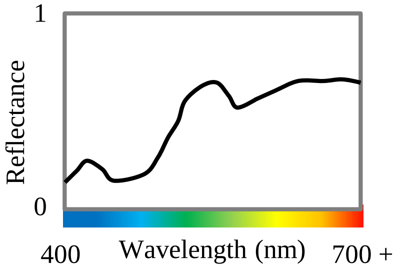


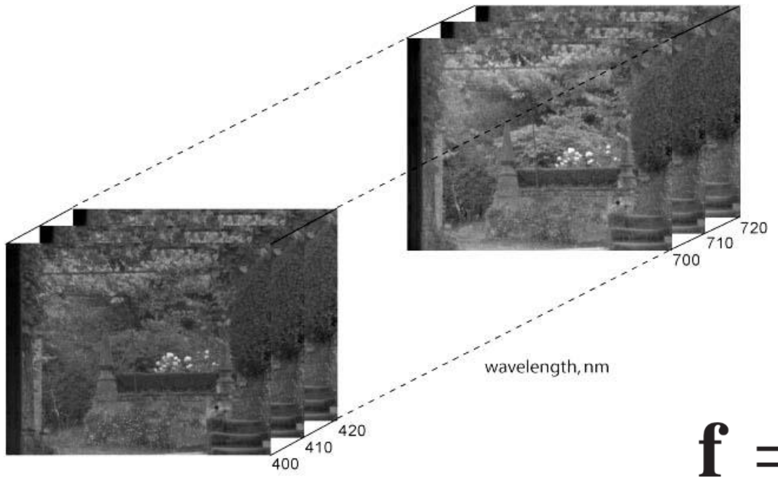






Spectral reflectance factors





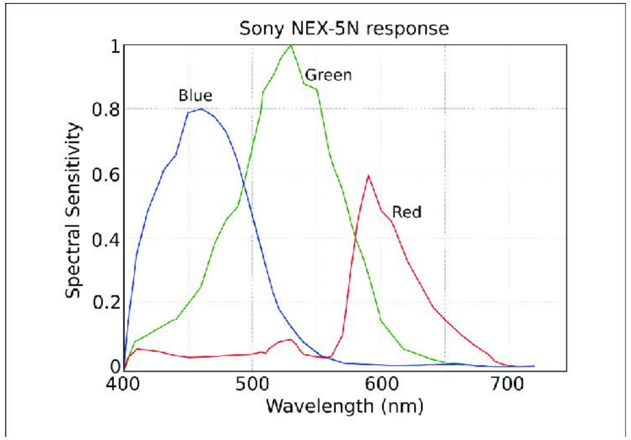
Radiant spectral power distribution

$$\mathbf{f} = \int_{\omega} e(\lambda) r(\lambda) \mathbf{c}(\lambda) d\lambda$$

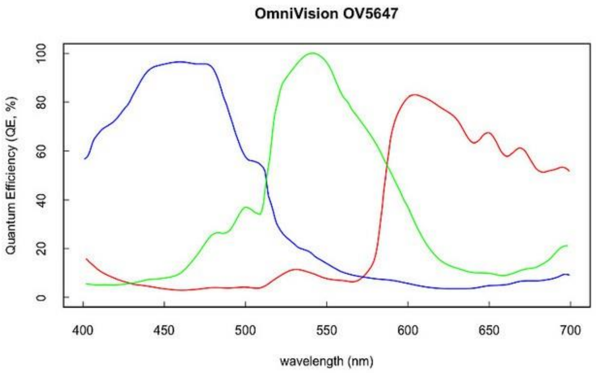
$$\mathbf{F} = \mathbf{REC}$$

Technologies

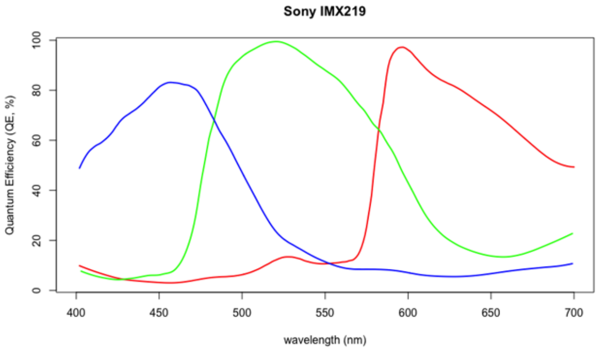
- Printers
- Displays
- Cameras
- Head mounted displays (Virtual headsets)
- Augmented reality glasses
- …?

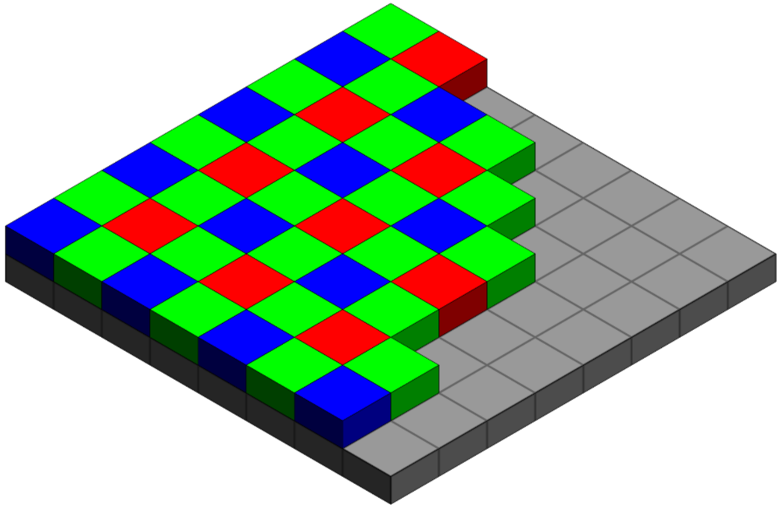


https://3.img-dpreview.com



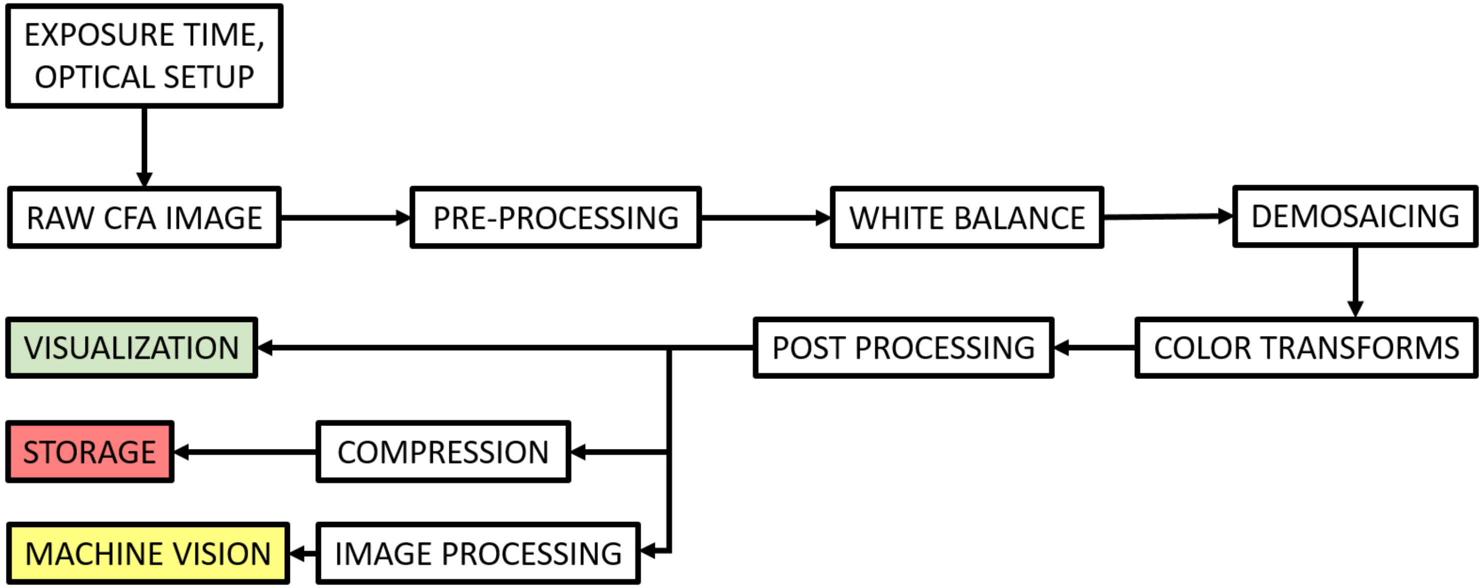
https://raw.githubusercontent.com/khufkens/





https://commons.wikimedia.org/wiki/File:Bayer_pattern_on_sensor.svg

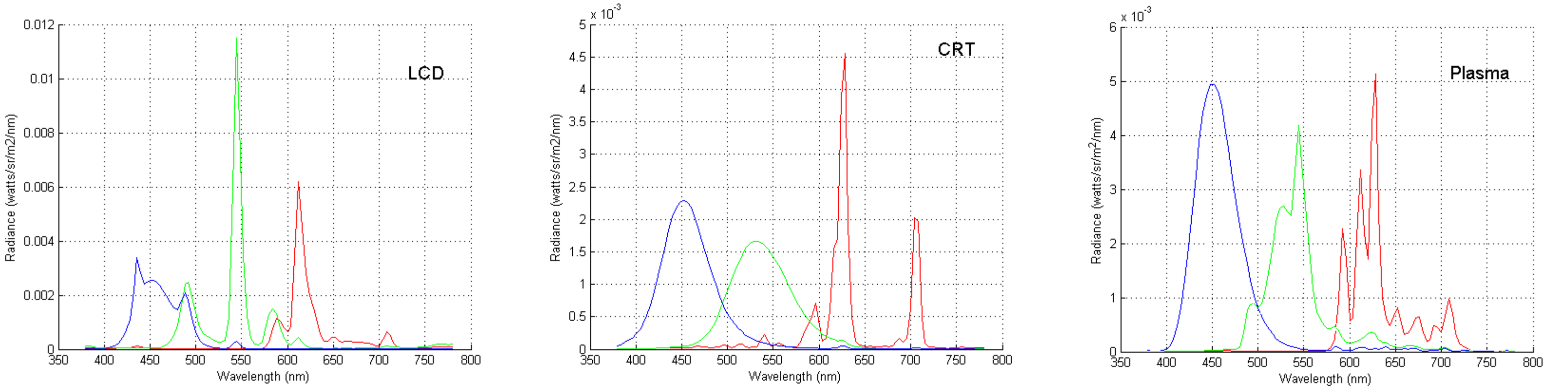
Sony A7 alpha7, II



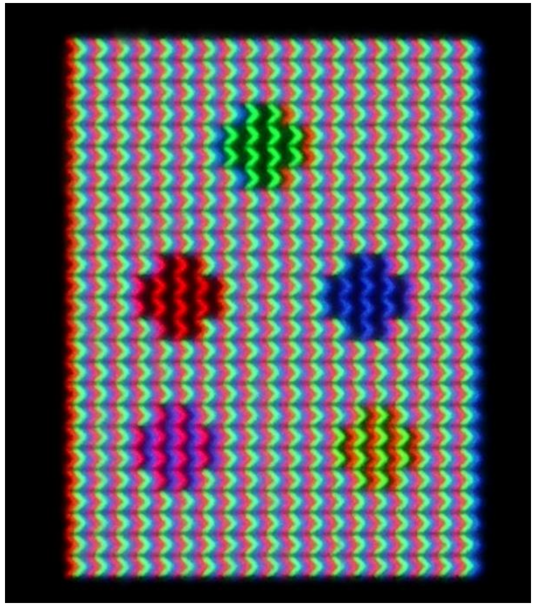
Lapray, P.-J.; Thomas, J.-B.; Gouton, P. High *Dynamic Range Spectral Imaging Pipeline For Multispectral Filter Array Cameras*. *Sensors* **2017**, *17*, 1281

https://fr.m.wikipedia.org/wiki/Fichier:LG_L194WT-SF_LCD_monitor.jpg

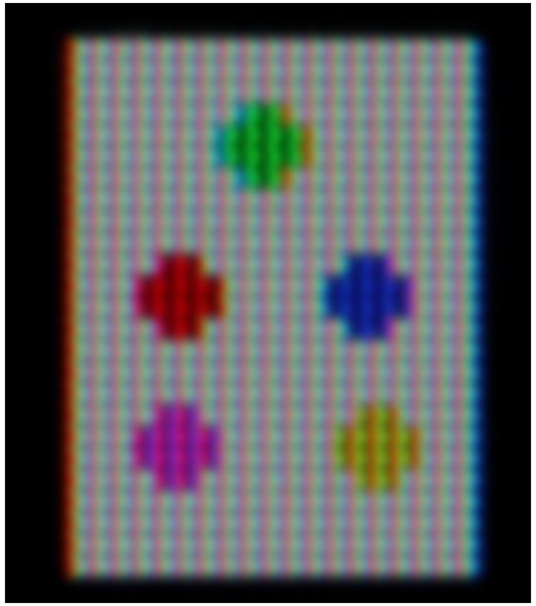
https://commons.wikimedia.org/wiki/File:IFA_2012_IMG_5767.JPG

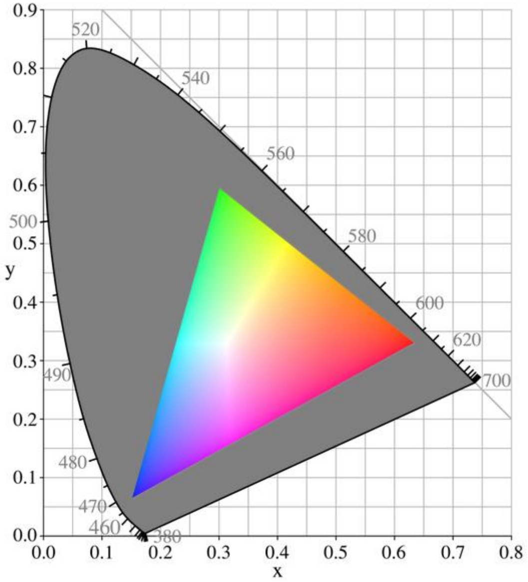


Joyce E. Farrell, Peter B. Catrysse, and Brian A. Wandell, "Digital camera simulation," Appl. Opt. 51, A80-A90 (2012)

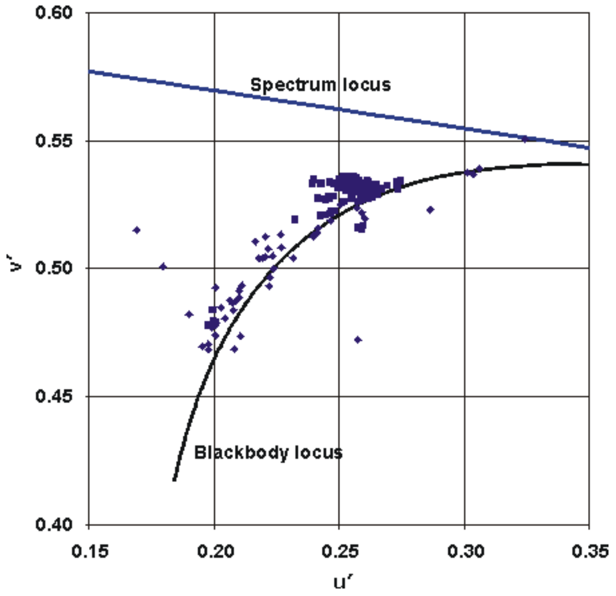


https://commons.wikimedia.org/wiki/File:Wiki_dell_lcd.jpg



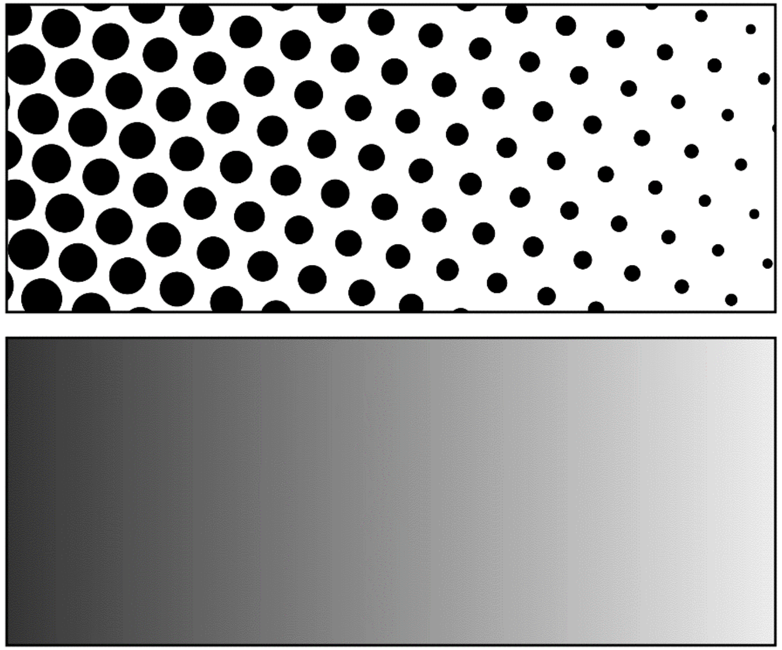


https://commons.wikimedia.org/wiki/File:CIExy1931_srgb_gamut.png



Chromaticities of 67 commercial light sources
plotted in the CIE 1976 color space
https://www.lrc.rpi.edu/programs/nlpip/lightinganswers/lightsources/measure.asp

http://printsmith.co.in



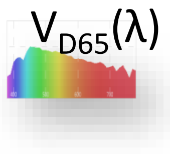
https://commons.wikimedia.org/wiki/File:Halftoning_introduction.svg

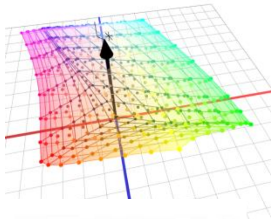
https://github.com/glslify/glsl-halftone

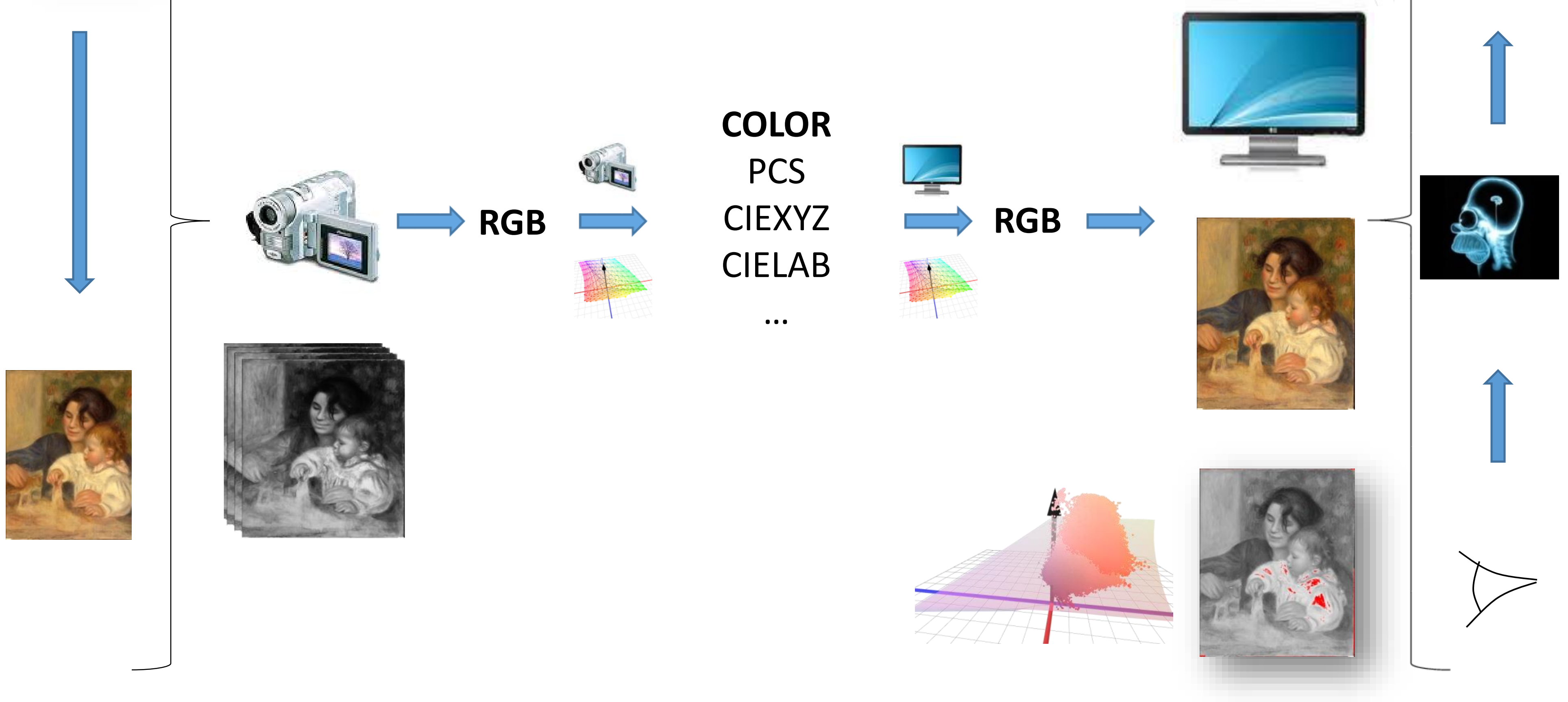
Color management

communication of the associated data required for unambiguous interpretation of colour content data, and application of colour data conversions, as required, to produce the intended reproductions.

Glossary, WP5 of the ICC



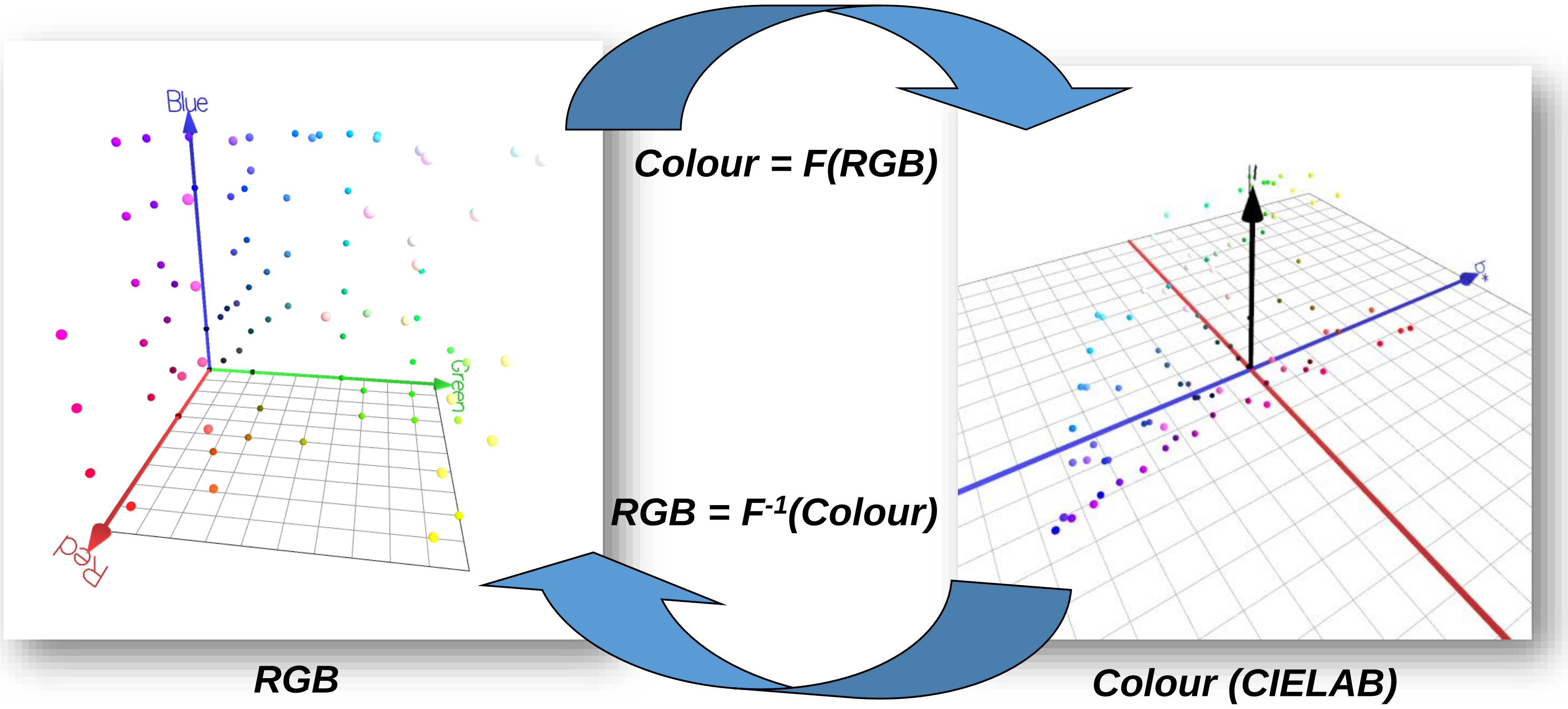




Device (colorimetric) characterization

defining the relationship between device values and tristimulus values, or their derivatives.

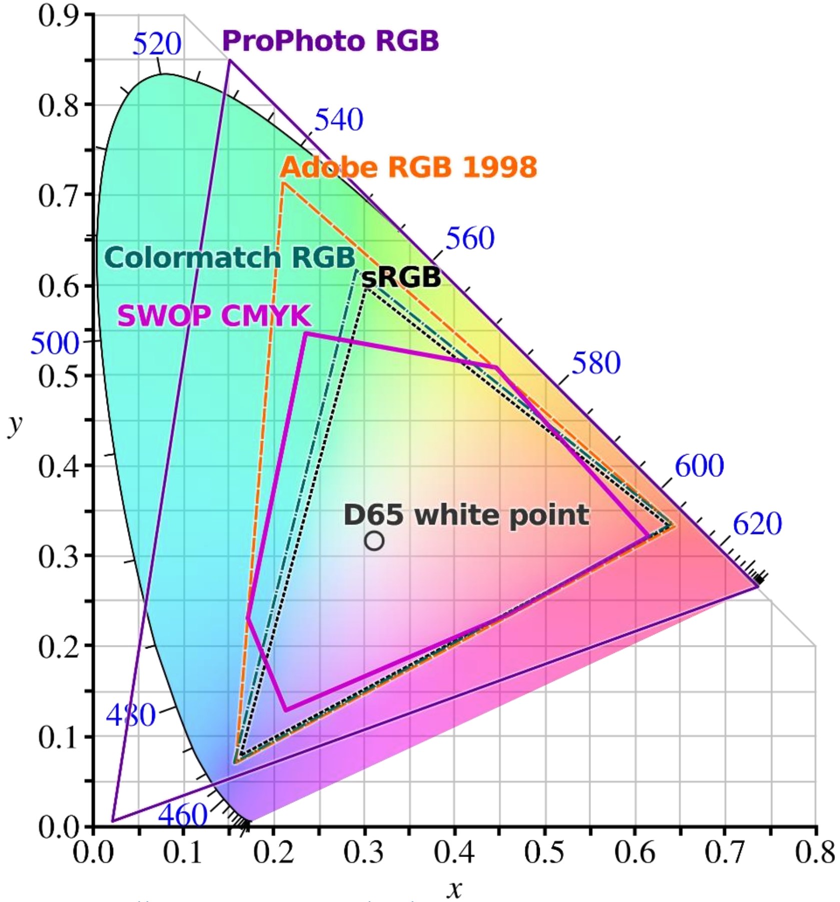
Glossary, WP5 of the ICC



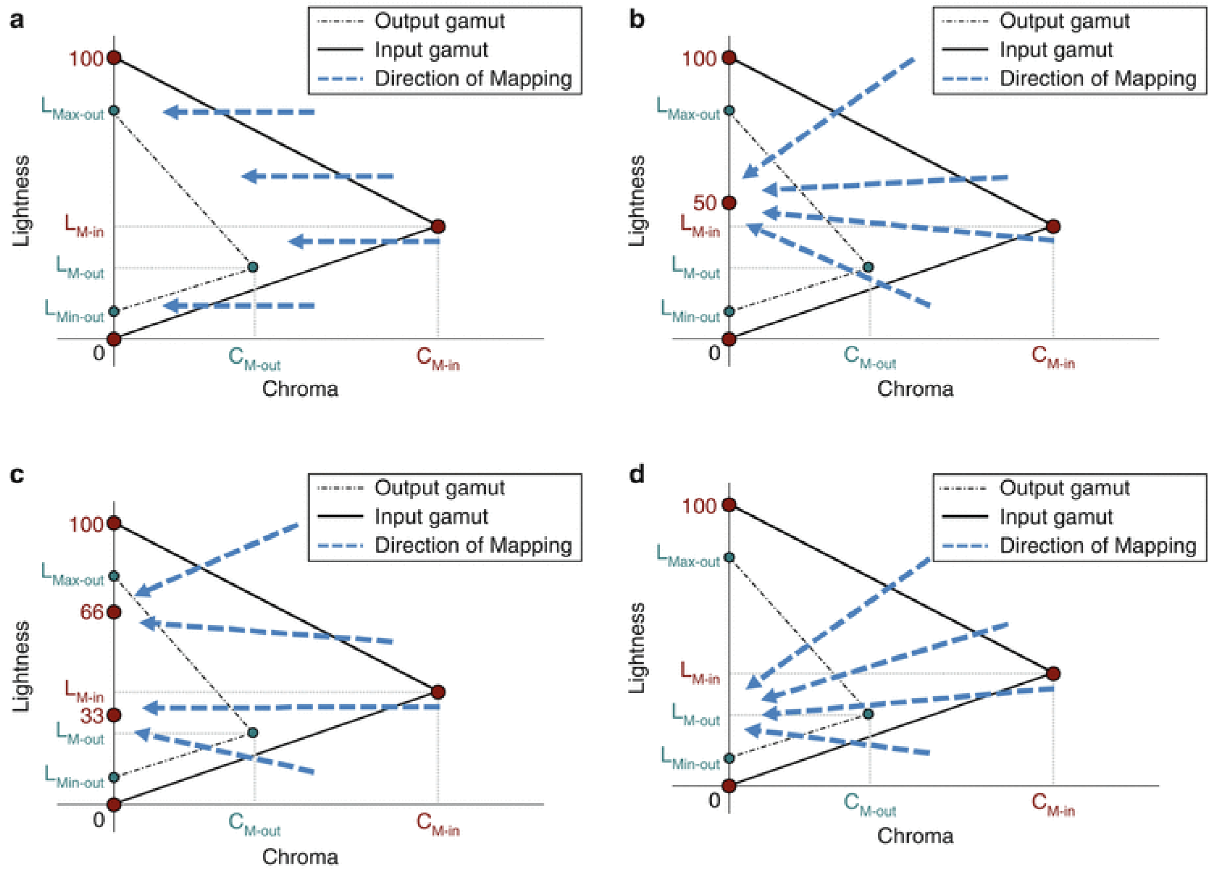
Gamut mapping

mapping of the colour-space coordinates of the elements of a source image to the colour-space coordinates of the elements of a reproduction to compensate for differences in the source and output medium colour gamut capability.

Glossary, WP5 of the ICC

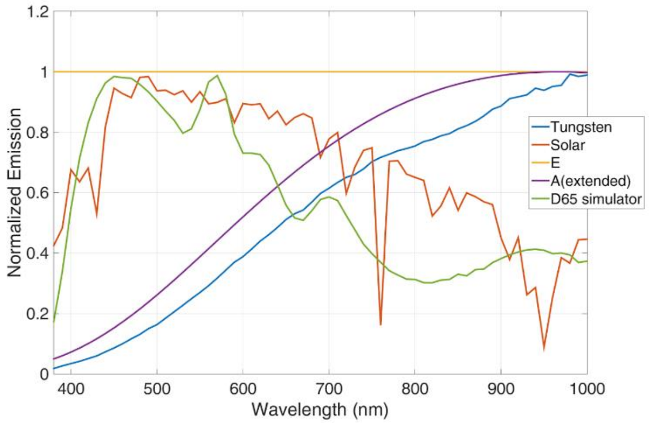


https://commons.wikimedia.org/wiki/File:CIE1931xy_gamut_comparison.svg

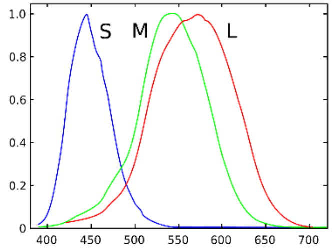


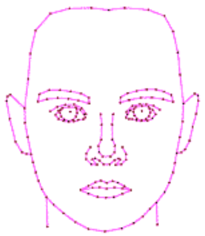
Ramanath R., Drew M.S. (2014) Gamut Mapping. In: Ikeuchi K. (eds) Computer Vision. Springer, Boston, MA

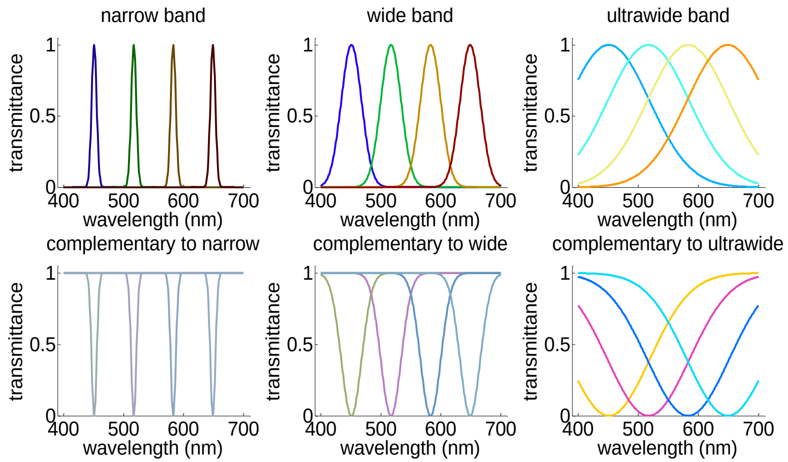
Flat, Matte, Diffuse

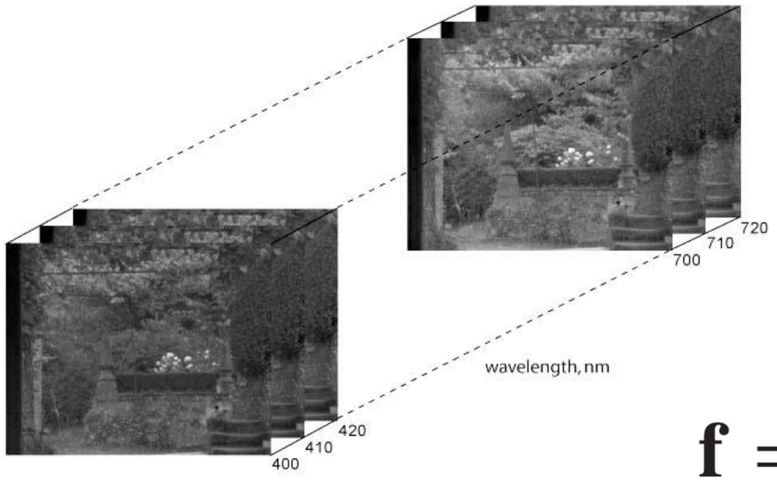


https://fr.m.wikiversity.org/wiki/Fichier:Cones_SMJ2_E.svg



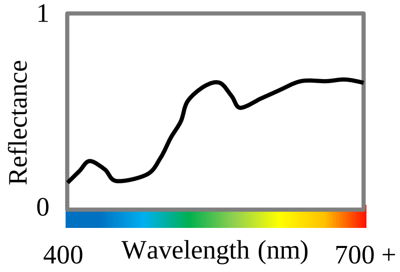


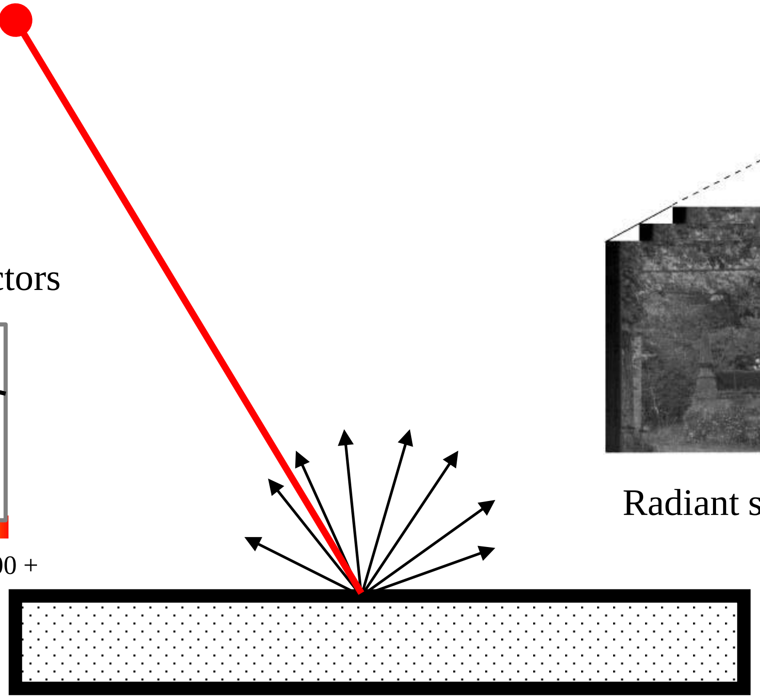




Radiant spectral power distribution

Spectral reflectance factors





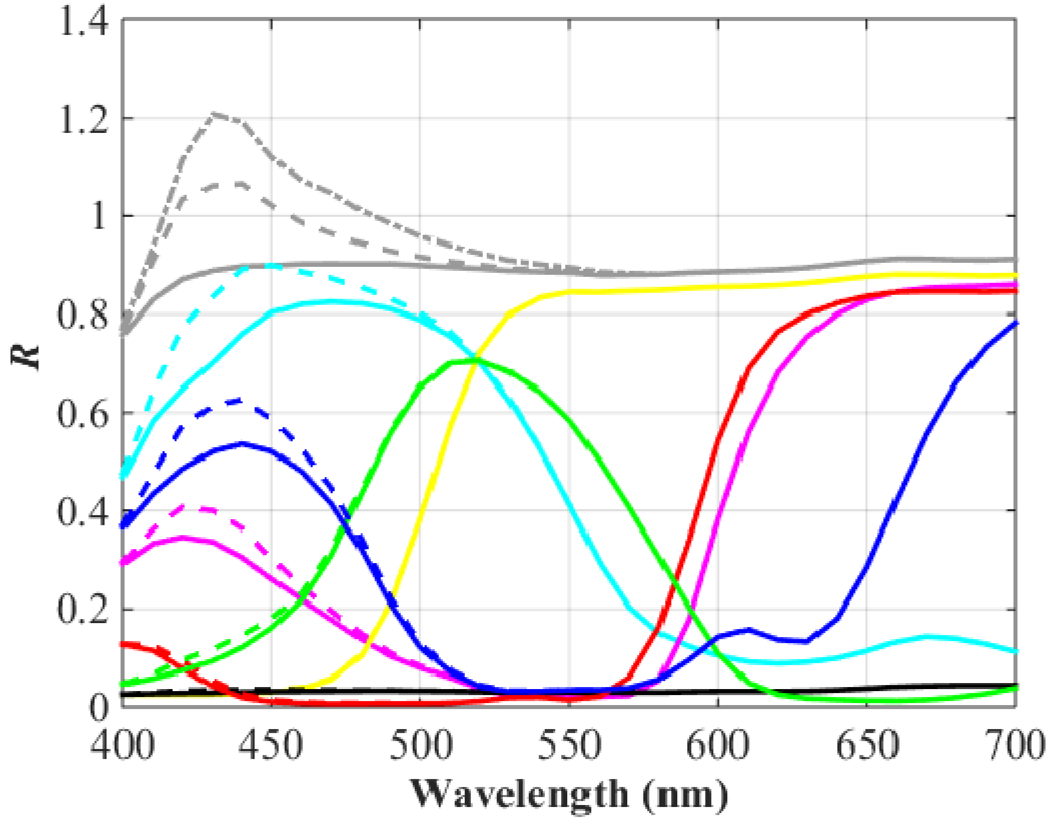
$$\mathbf{f} = \int_{\omega} e(\lambda) r(\lambda) \mathbf{c}(\lambda) \mathrm{d}\lambda$$

$$\mathbf{F} = \mathbf{REC}$$

BUT…

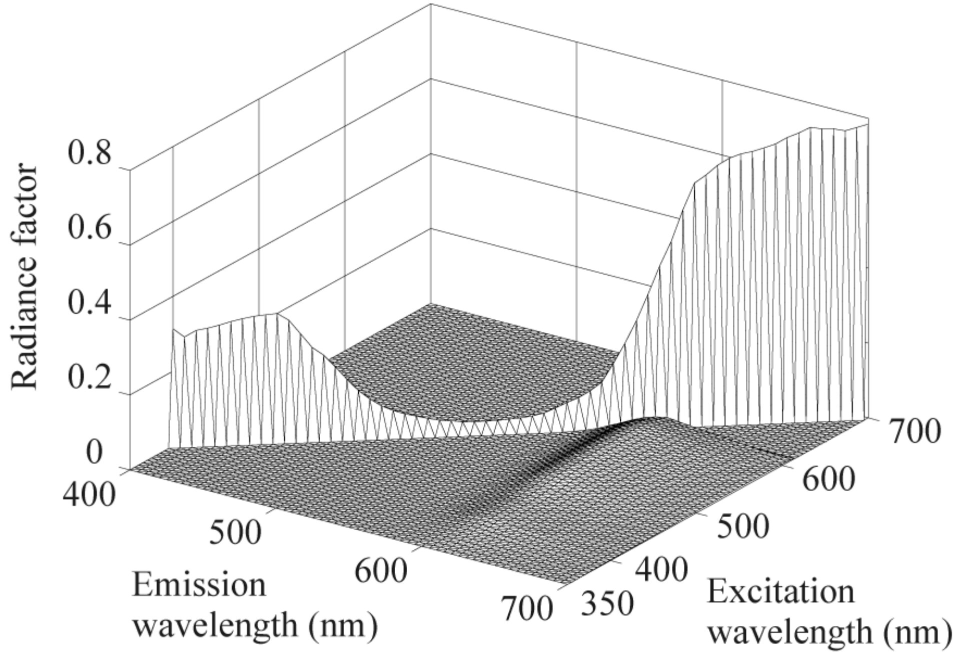
Fluorescence

Measured reflectance factors R of the process inks and paper without fluorescence (solid) and simulated R with fluorescence in illuminant CIE A (dash) and CIE D65 (dash-dot, only bare paper).



Le Moan, S. and Coppel, L. G. (2015) Perceived Quality of Printed Images on Fluorescing Substrates under Various Illuminations, in proceedings of the 16th International Symposium on Multispectral Color Science, AIC 2015 Mid-term meeting, Tokyo, May 2015, Color Science Association of Japan

Donaldson matrix obtained from a pink sample containing an orange fluorescent color.

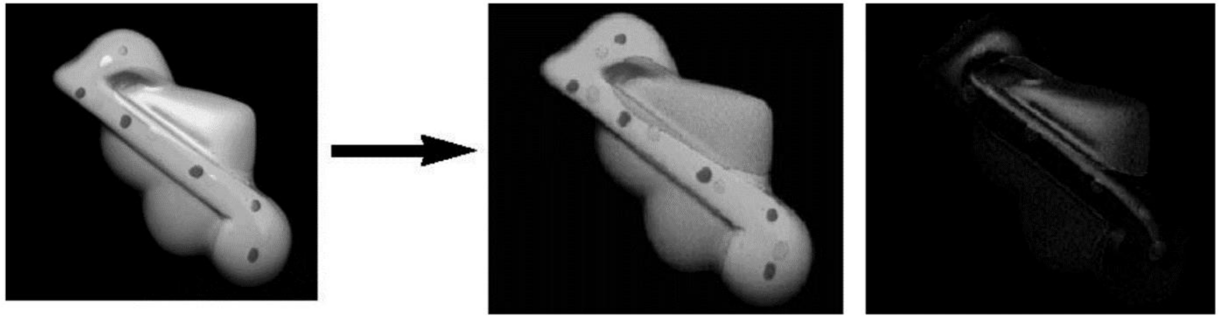


Shoji Tominaga, Keita Hirai, and Takahiko Horiuchi, "Estimation of fluorescent Donaldson matrices using a spectral imaging system," Opt. Express 26, 2132-2148 (2018)

Dichromatic model

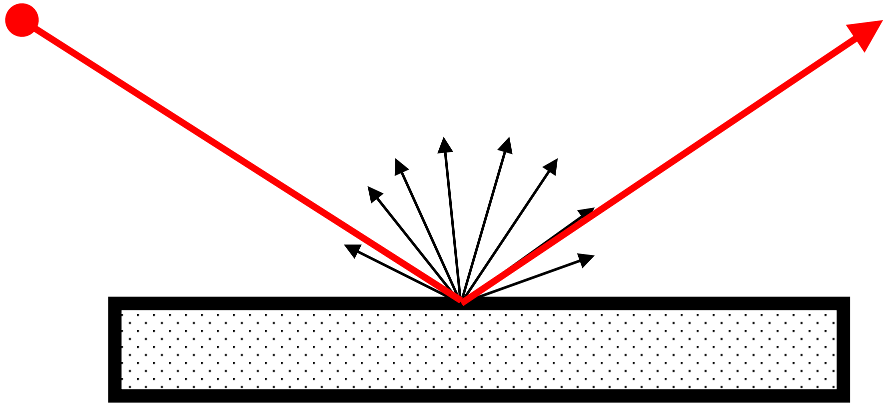
- Widely used in computer vision

Steven A. Shafer. Using color to separate reflection components. *Color Research & Application*, vol. 10, no. 4, pages 210218, 1985.
Shoji Tominaga and Brian A. Wandell. Standard surface-reflectance model and illuminant estimation. *J. Opt. Soc. Am. A*, vol. 6, no. 4, pages 576-584, Apr 1989.



$$\mathbf{f}(\mathbf{x}) = m^b(\mathbf{x}) \int_\omega e(\lambda)s(\mathbf{x},\lambda)\mathbf{c}(\lambda)d\lambda + m^s(\mathbf{x}) \int_\omega e(\lambda)\mathbf{c}(\lambda)d\lambda$$

$$F = w_b REC + w_s EC$$



H A Khan, J-B Thomas and J Y Hardeberg. Towards highlight based illuminant estimation in multispectral images. MCS, 2018.
H A Khan, J-B Thomas and J Y Hardeberg. Analytical Survey of Highlight Detection in Color and Spectral Images. CCIW 2017.

Koschmieder model for dehazing

Hazy Image — *Transmission map*

$$I(x) = J(x)\,t(x) + \alpha\,(1 - t(x))$$

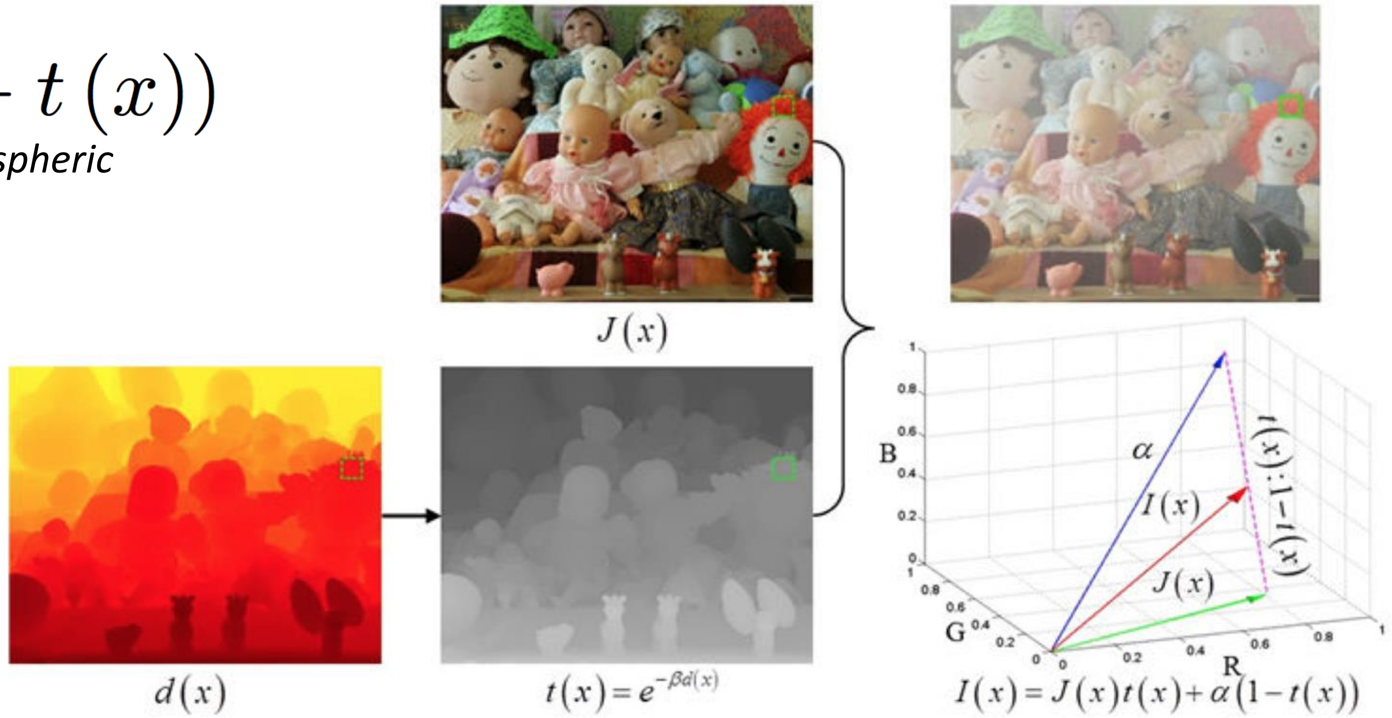
Haze-free image — *Global atmospheric light*

Where:

Attenuation coefficient

$$t(x) = e^{-\beta d(x)}$$

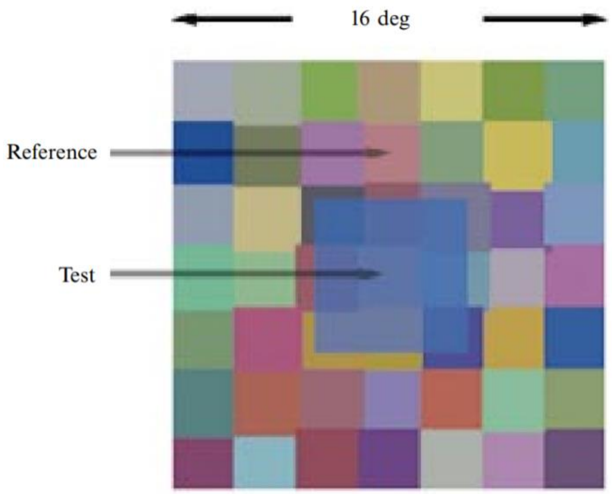
Distance from the object to the camera



H. Koschmieder, Theorie der horizontalen Sichtweite: Kontrast und Sichtweite (Keim & Nemnich, Munich, 1925).
Jessica El Khoury. *Model and quality assessment of single image dehazing*. PhD thesis, Université de Bourgogne, 2016.
El Khoury J, Thomas J-B and Mansouri A, *"A Database with Reference for Image Dehazing Evaluation"*, Journal of Imaging Science and Technology. Vol. 62(1), 2018
LC Valeriano, JB Thomas, A Benoit, Deep learning for dehazing: Comparison and analysis, CVCS 2018

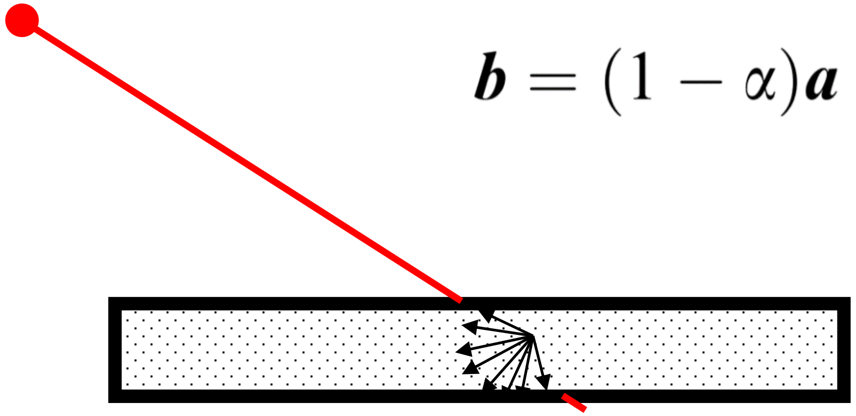
A model of transparency perception(Convergence model)

Metelli, F. (1970). An Algebraic Development of the Theory of Perceptual Transparency. Contemporary Problems in Perception. London, Taylor and Francis.
Metelli, F. (1974). "The perception of transparency." Scientific American 230: 91-98.
M D'Zmura, P Colantoni, K Knoblauch, B Laget, Color Transparency, Perception, 1997
Hagedorn, J. & D'Zmura, M. (2000). Color appearance of surfaces viewed through fog. *Perception* 29, 1169-1184.



Object as light source

$$\boldsymbol{b} = (1 - \alpha)\boldsymbol{a} + \alpha \boldsymbol{s}$$



Attenuation by the transparent layer:
absorption AND scattering

Models assume no scattering

Jessica El Khoury. *Model and quality assessment of single image dehazing*. PhD thesis, Université de Bourgogne, 2016.

A model of superposition (See through reflection)

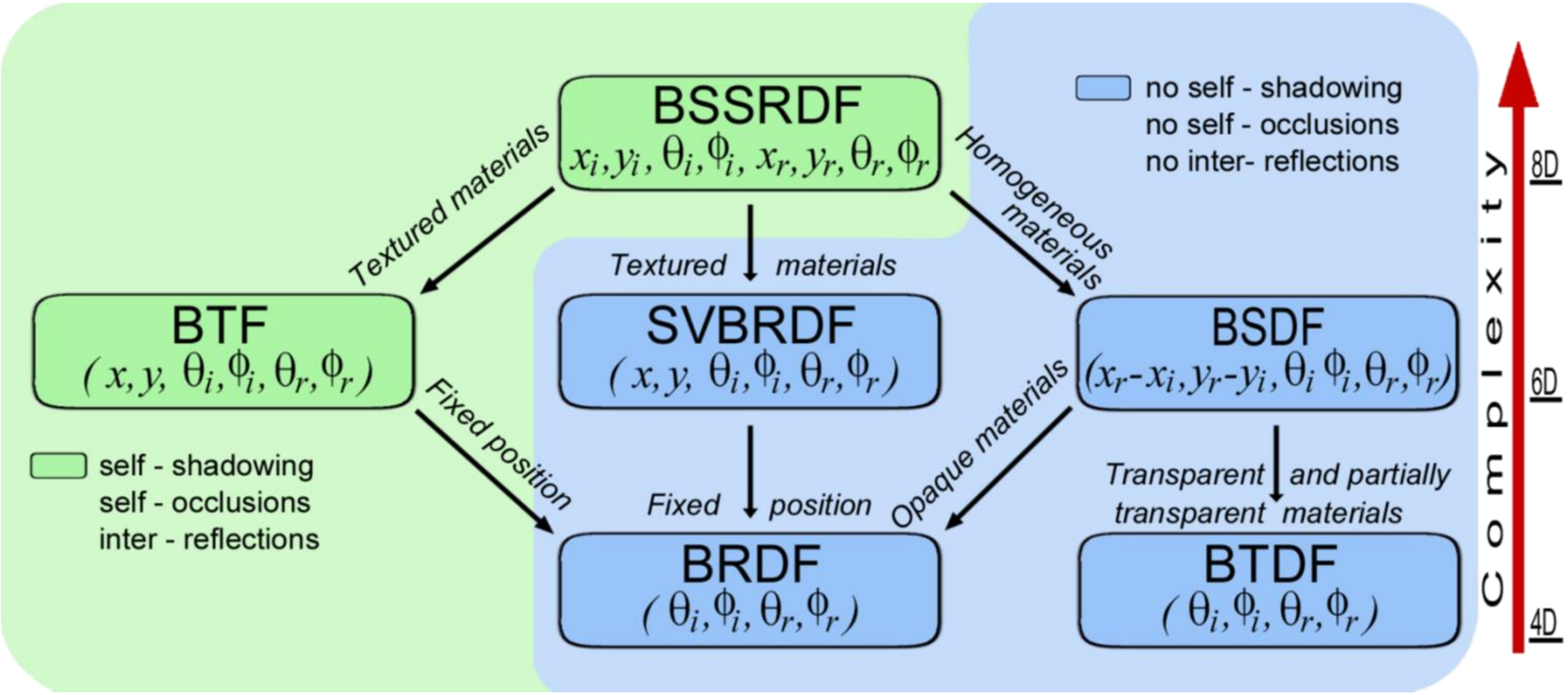
Y = T + R

M. Jin, S. Süsstrunk and P. Favaro, "*Learning to see through reflections*," 2018 IEEE International Conference on Computational Photography (ICCP), Pittsburgh, PA, 2018, pp. 1-12.
D Heydecker, G Maierhofer, A I. Aviles-Rivero, Q Fan, C-B Schönlieb, S Süsstrunk, *Mirror, Mirror, on the Wall, Who's Got the Clearest Image of Them All? - A Tailored Approach to Single Image Reflection Removal*, ArXiv, 2018

Inverse problem solving

- Linear and non-linear methods
- Interpolation, fitting, approximation
- Statistical approaches
- Optimization
- Models
- Machine learning
- Priors
- …

Deeper…



Guarnera, D., Guarnera, G.C., Ghosh, A., Denk, C. and Glencross, M. (2016), BRDF Representation and Acquisition. *Computer Graphics Forum*, 35: 625–650. doi:10.1111/cgf.12867

17-1058 reflectance (for incident radiation of given spectral composition, polarization and geometrical distribution) [ρ]
ratio of the reflected radiant flux or luminous flux to the incident flux in the given conditions
Unit: 1
NOTE Reflectance, ρ, is the sum of regular reflectance, ρ_r, and diffuse reflectance, ρ_d: $\rho = \rho_r + \rho_d$.
http://eilv.cie.co.at/indexpage/

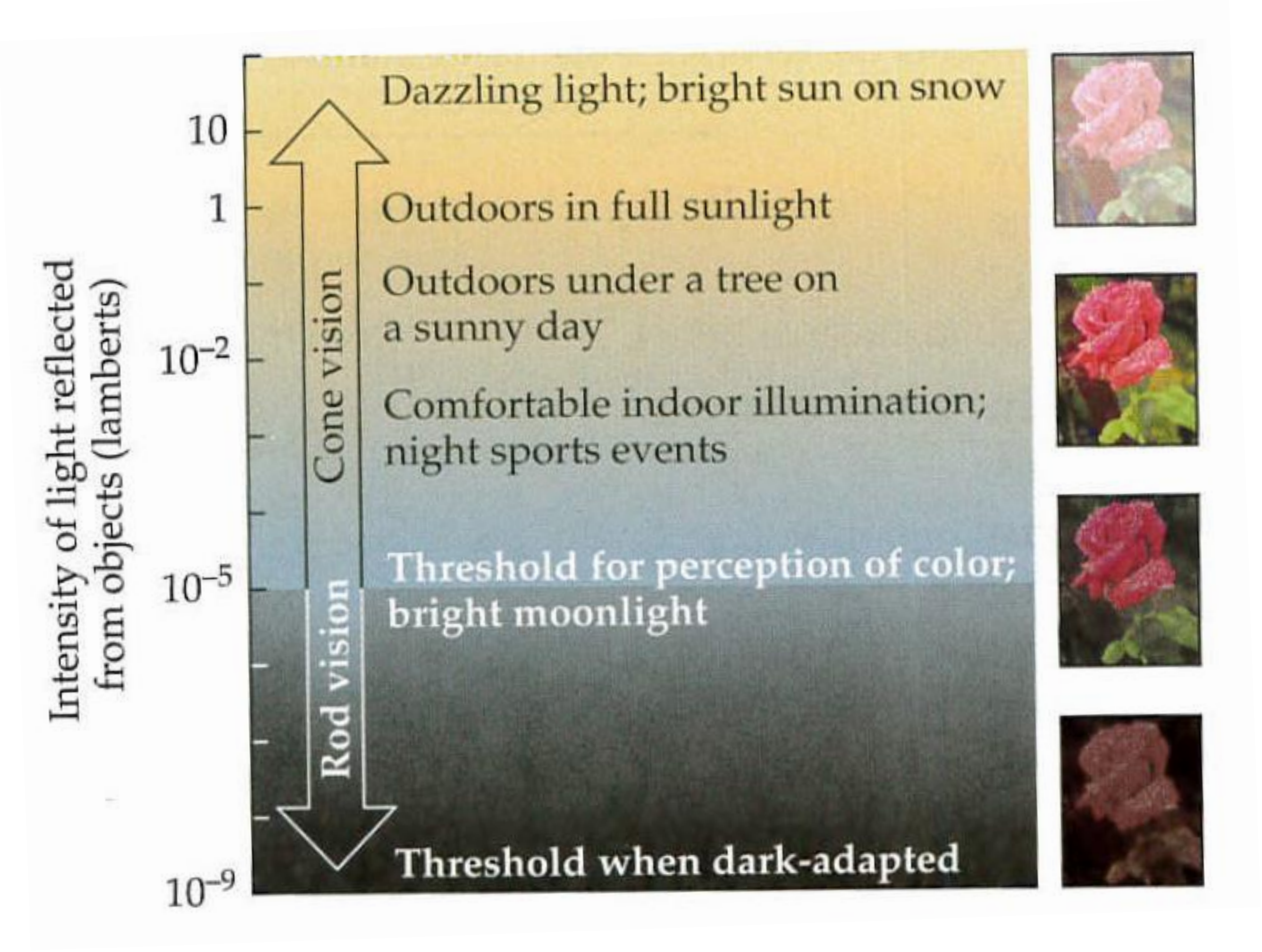
$$\mathbf{f} = \int_{\omega} e(\lambda) r(\lambda) \mathbf{c}(\lambda) \mathrm{d}\lambda$$

'Reflectance factors' should be preferred

Often sub-scattering, inter-reflections, shadows, etc.

17-1059 reflectance factor (at a surface element, for the part of the reflected radiation contained in a given cone with apex at the surface element, and for incident radiation of given spectral composition, polarisation and geometric distribution) [R]
ratio of the radiant flux or luminous flux reflected in the directions delimited by the given cone to that reflected in the same directions by a perfect reflecting diffuser identically irradiated or illuminated
Unit: 1
NOTE 1 For regularly reflecting surfaces that are irradiated or illuminated by a beam of small solid angle, the reflectance factor may be much larger than 1 if the cone includes the mirror image of the source.
NOTE 2 If the solid angle of the cone approaches 2π sr, the reflectance factor approaches the reflectance for the same conditions of irradiation.
NOTE 3 If the solid angle of the cone approaches 0, the reflectance factor approaches the radiance factor or luminance factor for the same conditions of irradiation.
http://eilv.cie.co.at/indexpage/

Current challenges in colour imaging

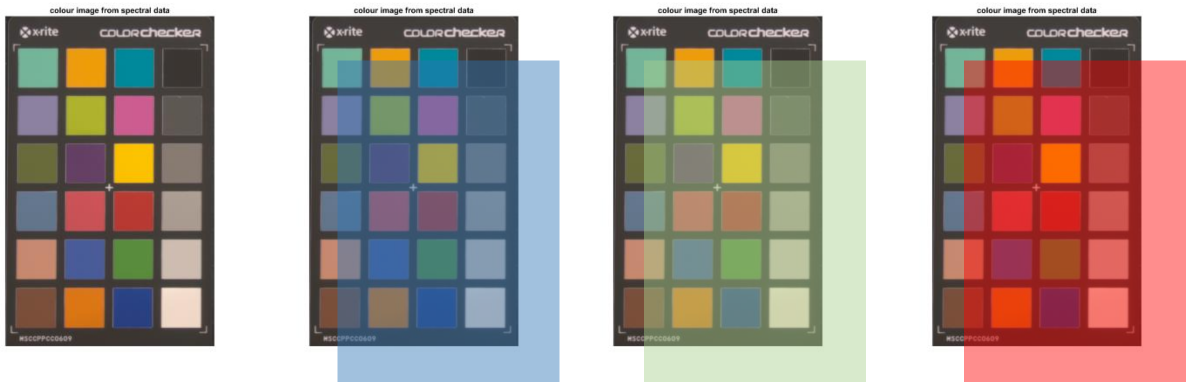


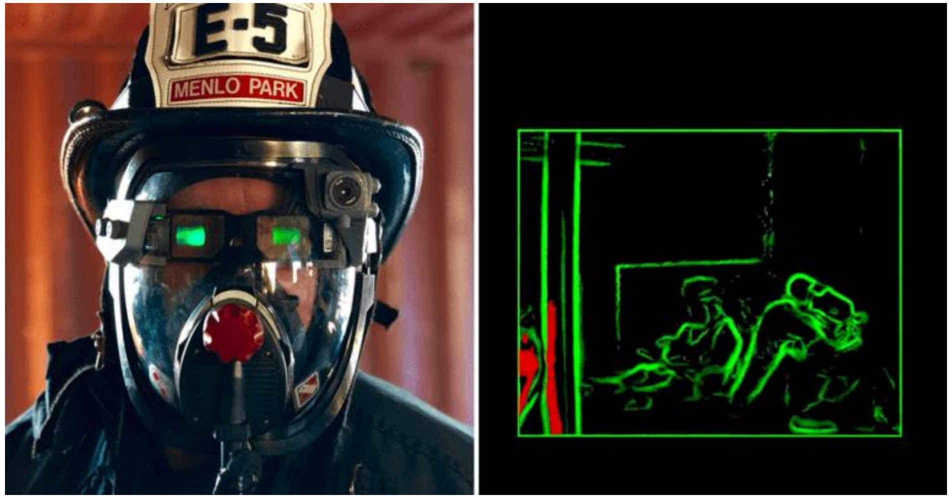
High and small intensities in the scene: High dynamic range
Dynamic: Ratio between the largest and smallest simultaneously observable signals

Current challenges in colour imaging

Wearable devices
Uncontrolled conditions
Individual users
Complex imaging models
Little fundamental understandings
Early-stage technology

Google glass 2.0





Quake Technologies, C-thru

Some literature

- Colour Imaging: Vision and Technology
- Digital Colour Imaging Handbook
- Introduction to Color Imaging Science
- Encyclopedia of Color Science and Technology
- Color Technology for Electronic Imaging Devices
- …