Display color measurement

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Colorimetry

- Color – the *response to,* or *sensation* caused by the *stimulation* of the retina by radiation of varying spectral power distribution, P(λ)
- Colorimetry – the measurement of color
- How do we *measure* a *sensation*?

Colorimetry background

- The retina of a normal human eye contains ρ, γ, β pigmented cones that absorb long, medium and short wavelengths respectively
- Absorption of radiation causes bleaching of the pigments and *stimulates* the nervous system

Thomas Young, "On the Theory of Light and Colors," *Philosophical Transactions of the Royal Society of London*, **92**, (1802)
James Clerk Maxwell, "The Diagram of Colors," *Transactions of the Royal Society of Edinburgh*, **21** (1857)

Colorimetry basics

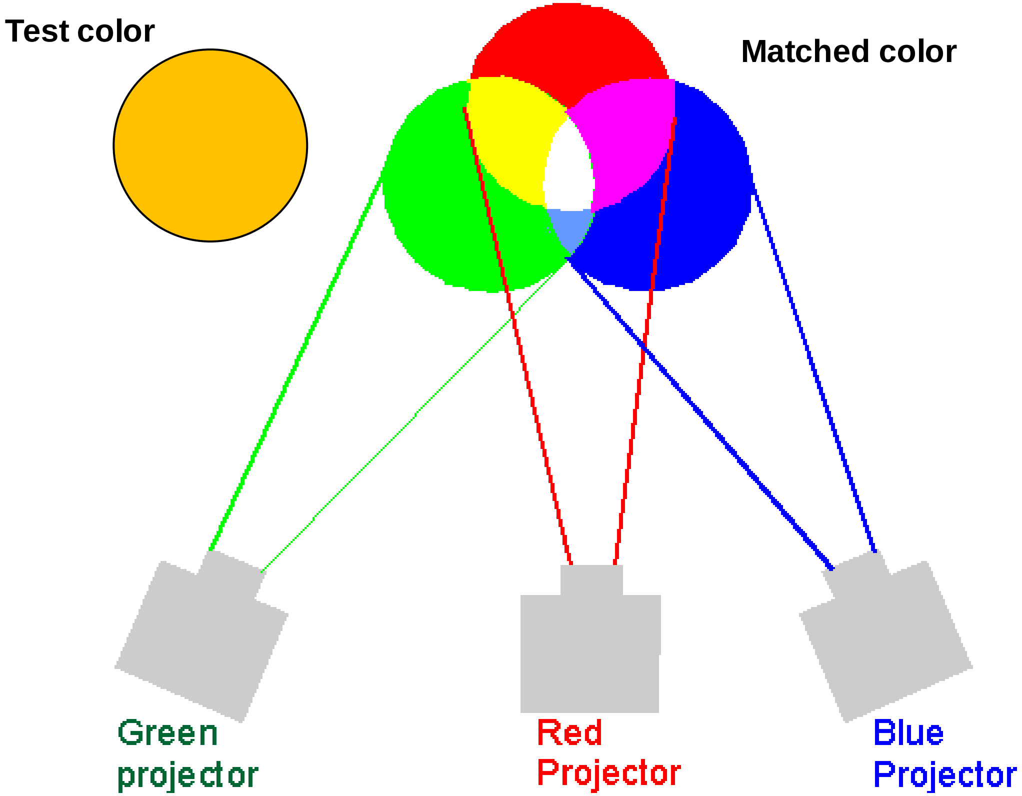
- Colors are *equal* if and only if they match
- Equal *stimulation* of the ρ, γ, β cones causes a color match, or response
- Equal sensation ≠ equal perception
- All colorimetry is derived from basic *matching* experiments

Tristimulus colorimetry

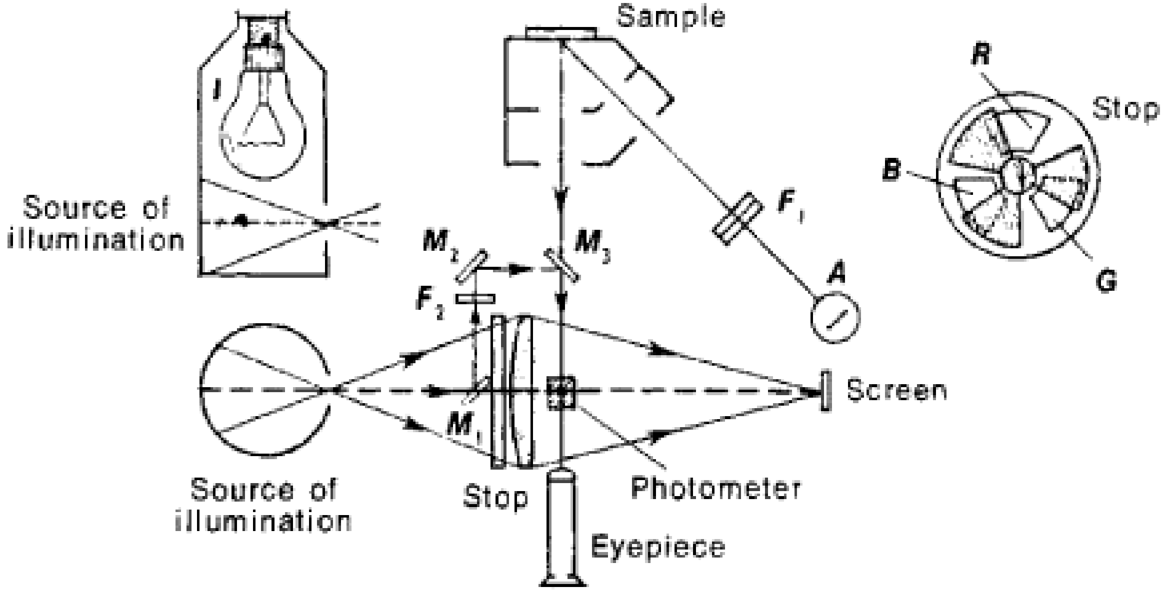
- Any test color can be matched with a mixture of three independent primaries
- Test colors that match with the same mixture of primaries match each other
- The *amounts* of the three primaries required to match the test color are the Tri-Stimulus Values (TSVs) of that test color *relative* to those primaries
- The resulting vector is the measure of the test color

James Clerk Maxwell, Theory of Compound Colors and the Relations of the Colors of the Spectrum, *Proceedings of the Royal Society of London*, **10** (1860)

Color mixing schematic



Visual colorimeter



Tristimulus colorimetry conditions

- The primaries must be independent
  - None can be matched by a combination of the others
- Negative amounts of primaries are permitted
  - One or more primaries are added to the test color to obtain the match

Color difference formulae

- If two colors are *not* equal their differences can be measured with any number of derived units of the color difference formulae are based on color difference thresholds called *Just Noticeable Differences* (JNDs)
- A JND is the degree of difference of *stimulation* that cause a normal observer to *sense* a difference in 50% of observations using visual matching methods

Types of TS colorimetry

- Visual methods
  - Awkward, time consuming, not used in practice
- Instrumental methods
  - Tristimulus filter
  - Spectral

Basis of instrumental colorimetry

- *Any* color can be matched with a linear combination of three primaries (the TSVs)
  - This includes the *spectral* colors
  - This includes the primaries themselves
    - Matched with a *different* set of primaries
- Any *spectrum* is the superposition of all of the individual monochromatic components

Color Matching Functions (cmfs)

- The TSVs of unit power of the monochromatic spectral colors form a set of cmfs relative to those primaries
- Established through visual TS colorimetry
- Can be mathematically transformed to represent cmfs relative to any other set of primaries

Wright and Guild cmf data

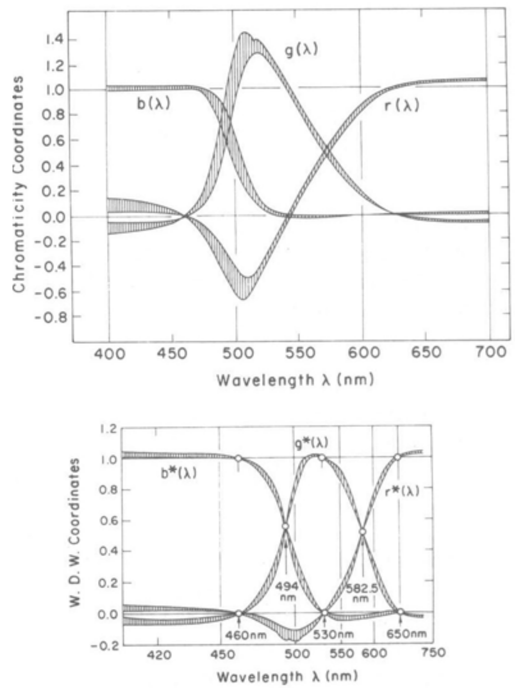
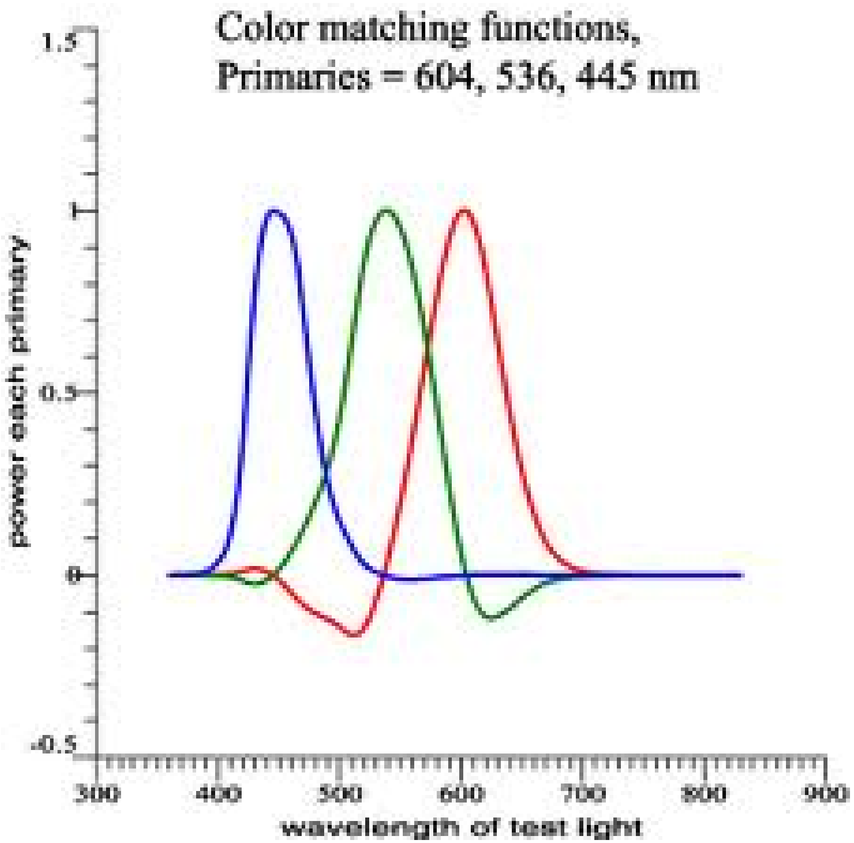
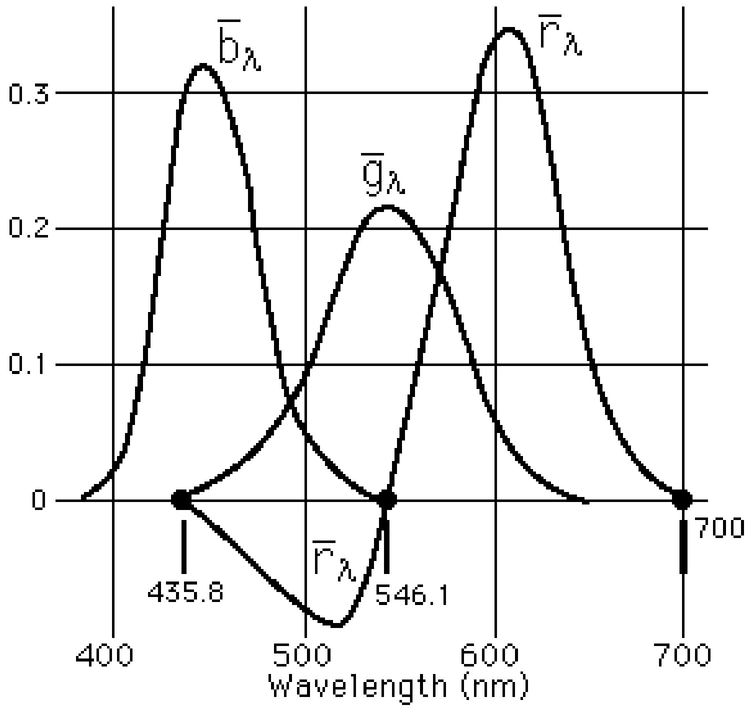


Fig. 1(5.5.6). Two-degree spectral chromaticity coordinates determined by Guild (1931) and W.D.W. coordinates determined by Wright (1928–1929) with ranges of variation for the different groups of observers involved. Guild's data (upper graph) are based on measurements made by seven observers, those of Wright (lower graph) are based on measurements made by 10 observers.

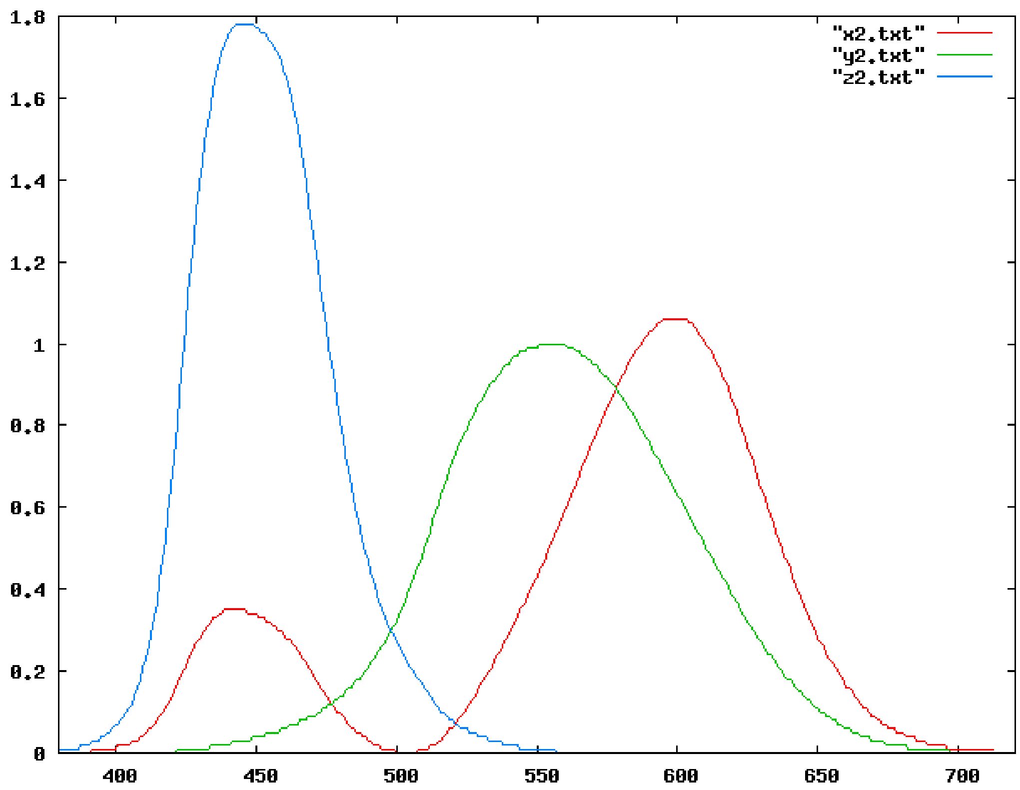
Günter Wyszecki and W. S. Stiles, Color Science, 2nd Edition (New York: John Wiley & Sons, 1982)

Other examples of cmfs





CIE *Standard* Observer cmfs



Properties

- $\bar{y} = V_{\lambda}$
- All positive lobes
- Non-physically realizable primaries

TSVs from CMFs

- For test color with Spectral Power Distribution, P(λ)
- At each λ:

  $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ match unit power

- So

  P(λ) $\bar{x}(\lambda)$, P(λ) $\bar{y}(\lambda)$, P(λ) $\bar{z}(\lambda)$ match P(λ)

- Integrated over all λ to get the TSVs of the full spectrum

Integrate over contributions at all λ

$$X = \int P(\lambda)\bar{x}(\lambda)\, d\lambda$$

$$Y = \int P(\lambda)\bar{y}(\lambda)\, d\lambda$$

$$Z = \int P(\lambda)\bar{z}(\lambda)\, d\lambda$$

Reference:

Arthur Hardy, *Handbook of Colorimetry* (Cambridge: The Technology Press, 1936)

Filter and spectral colorimeters

- Filter colorimeters
  - Three or four color sensing channels
  - cmfs for sensitivities

  Directly measures the TSVs of the test color
- Spectral colorimeters
  - Monochrometer and sensor or sensor array
  - Measure the SPD of the test color
  - Compute the TSVs by approximating the integrals with summations

Colorimeter basics summary

- Filter colorimeter spectral sensitivity functions must form a set of color matching functions (cmfs) to measure color (TSVs)
- These can be transformed via linear transformation to the *Standard* observer TSVs (CIE XYZ)
- Spectral colorimeter must have sufficient bandwidth, sensitivity and computational ability

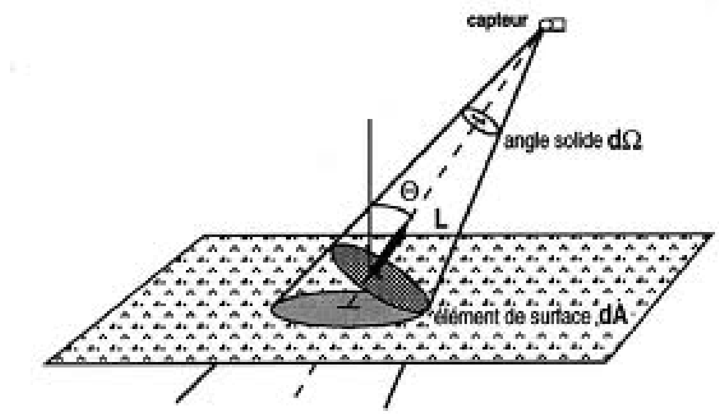
Radiometry and photometry

- Physical quantity *radiance* (L_e) and corresponding visual quantity *luminance* (L_v) roughly correlate with what we would call *brightness* or *lightness* and is related to the *quantity* of light
- L is the radiant flux emitted per unit area and solid angle of a source

$$L_e = d^2\Phi_e / d\omega \, dA \cos\theta$$

$$L_v = d^2\Phi_v / d\omega \, dA \cos\theta$$

$$\Phi_v(\lambda) = \Phi_e(\lambda) \, V(\lambda)$$



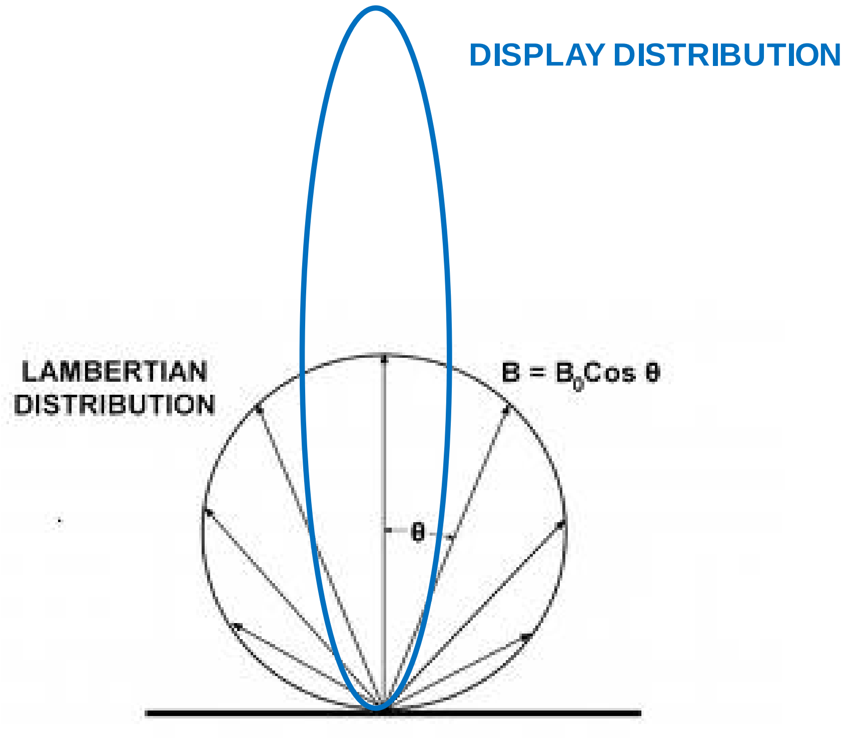
Geometric considerations

- Luminance (radiance) measurement requires an optically defined solid angle and source area
- Ideal Lambertian source
  - L_v is direction independent
- Modern display
  - L_v varies with viewing angle

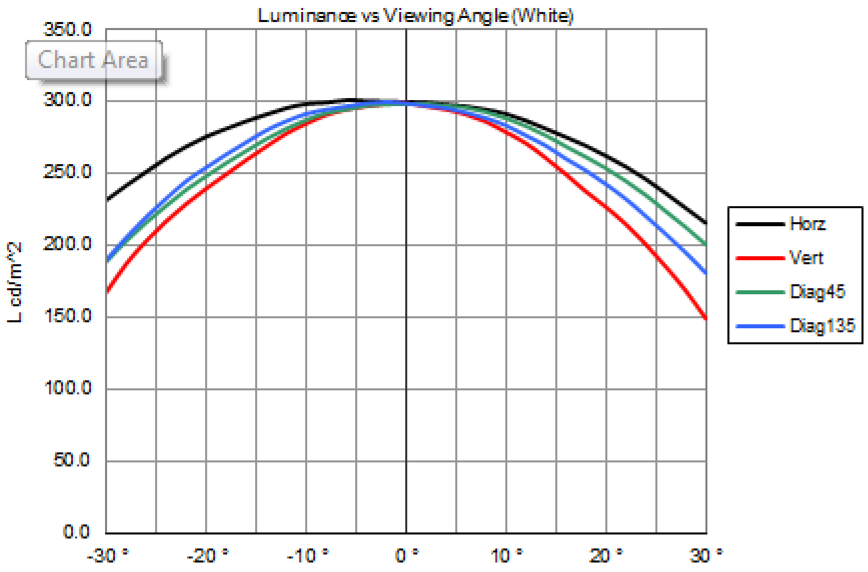
Colorimeter components

- Optical front end
  - Limits field of view (collection angle)
  - Limits measurement field (spot size)
- Optical spectrum analyzer and detectors
  - 3 or 4 channel
  - Spectral
- Signal processing & calibration
- Interface and/or display

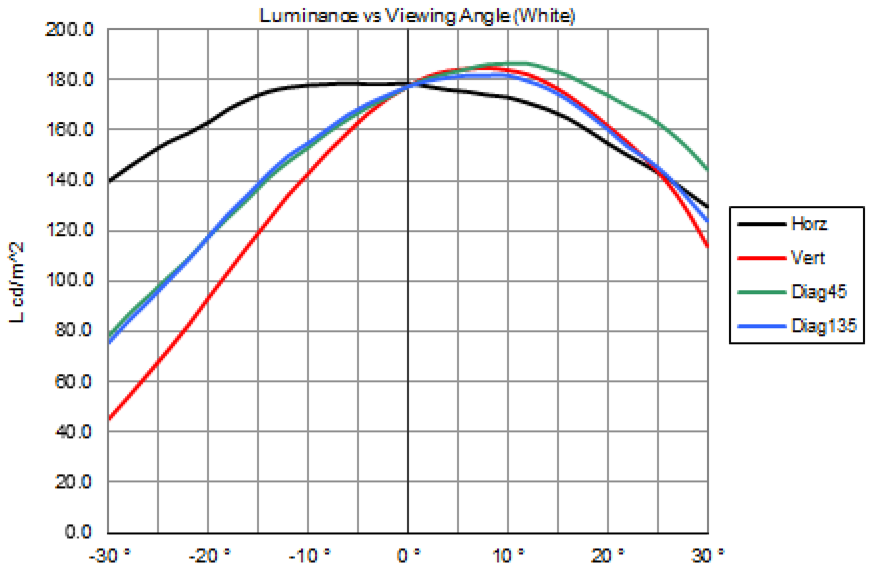
Displays are not Lambertian radiators



Viewing angle dependence

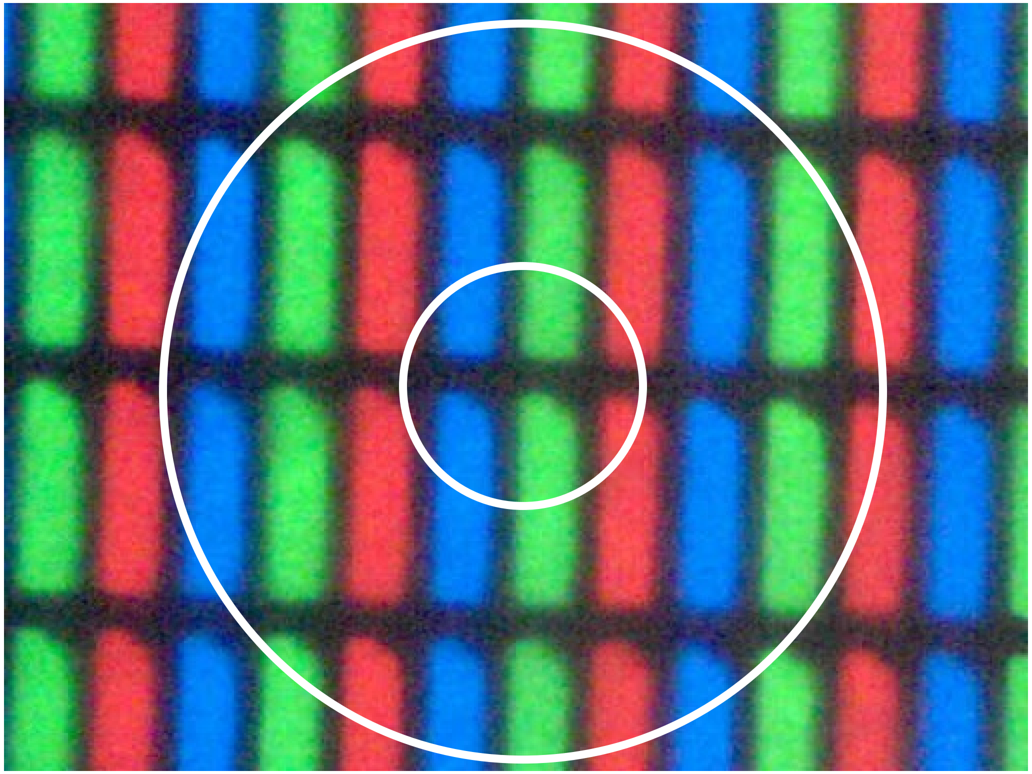


IPS desktop display

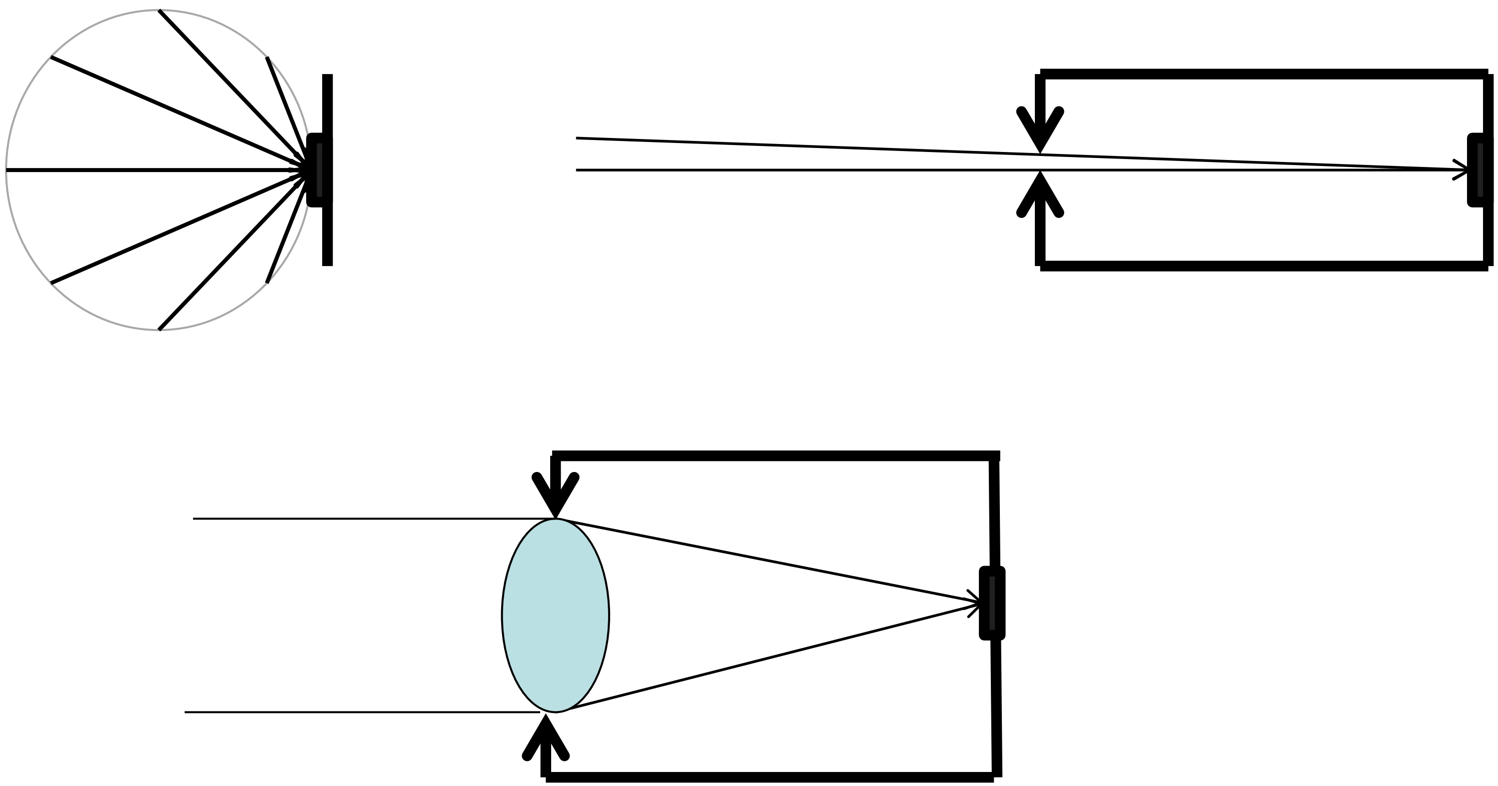


TFT laptop display

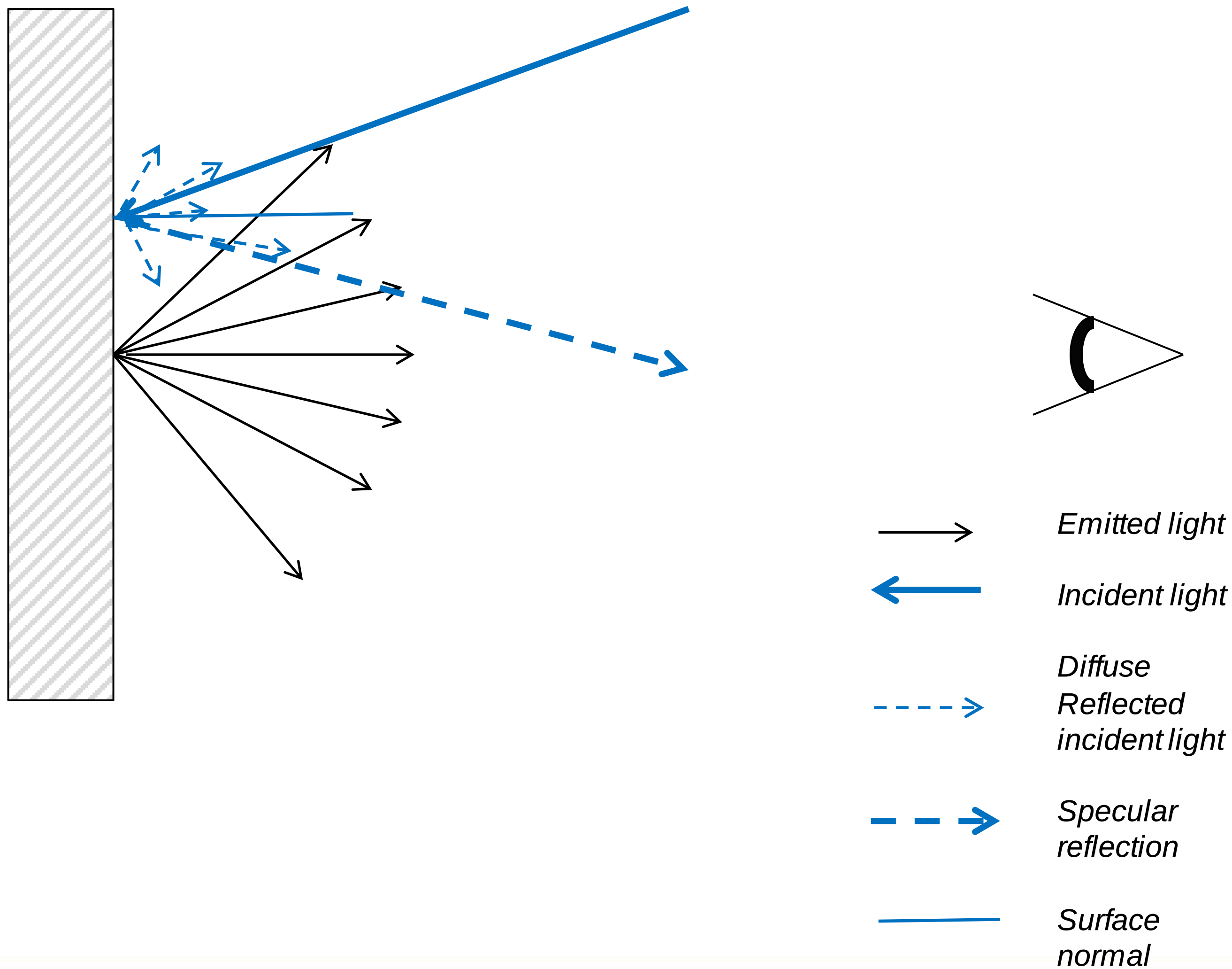
Spatial dependence



Optics to limit collection angle



Stray light

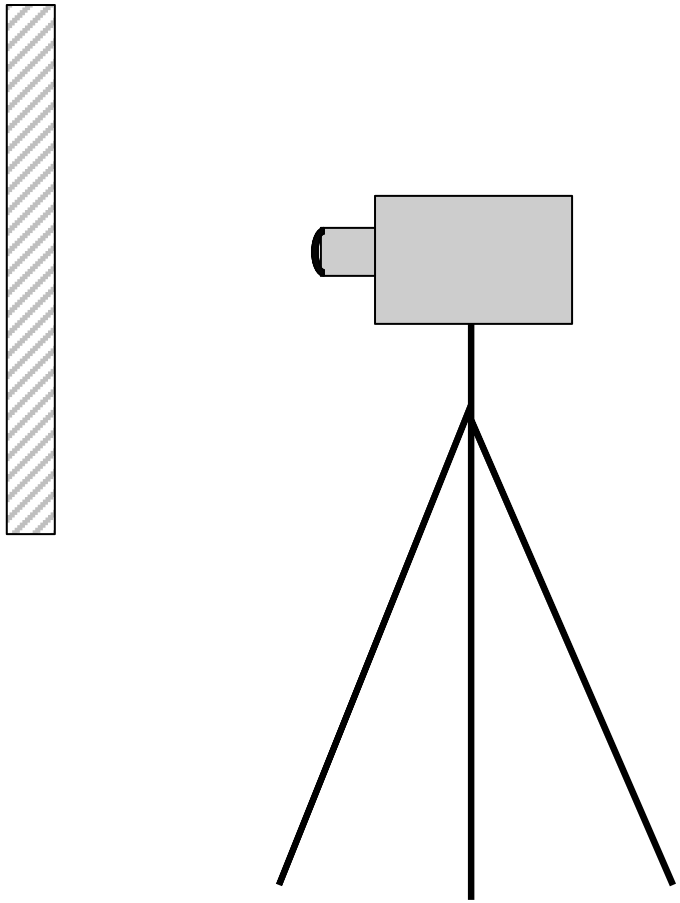


Emitted light
Incident light
Diffuse Reflected incident light
Specular reflection
Surface normal

Stray light

- Diffuse component
  - Limits the dark level and the display's contrast ratio
  - Acts as an offset so has a proportionally larger affect on dark colors
- Specular component
  - Very bright mirror image of the light source
  - Must be avoided when measuring

Stand-off and contact measurements



Stand-off measurement

- Includes affects of stray light
  - Must re-measure when ambient conditions change
- Instrument must be positioned
  - Normal to the screen surface
  - Excluding specular reflection components
  - Excluding back reflections of the instrument

Contact measurement

- Self orienting
- Eliminates stray light and specular components from measurement
  - Stray light can be measured separately and compensated

Display colorimeter requirements

- Build cmf sensitivity function by
  - Filter/sensor design
  - Monochrometer design and BW
  - Calibration and computation
- Limit collection angle
- Collect with large spot
- Limit ambient and stray light or measure and compensate

Other considerations

- Repeatability intra-unit
  - Short term
  - Long term
- Repeatability inter-unit
- Precision/least digital count
- Calibration to standard
- Ease of use
  - Set-up
  - Calibration and adjustment
  - Speed of measurement
- Cost
- Interface/workflow