Display Metrology of Electronic Displays

What you see
is what you
measure?

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Overview

- Introduction
  - Motivation
  - Specs
- Basic Parameters (Merits)
- Common Issues
- Display Technology Dependent Issues (Shortcomings)
- Summary
- Appendix: Additional information, methods etc. – not relevant for exam

Goal of Display Metrology Lecture

Basic knowledge about optical display parameters and shortcomings

Why ?

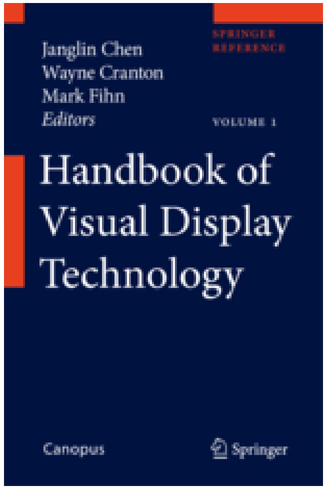
- Displays are at first hand selected by specifications from various Asian manufacturers through distributors or manufacturers office in Europe

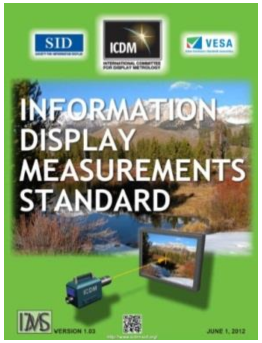
- Optical performance is noticed first by user, customer, …

- Optical parameters decide on technology for many applications

References

- Handbook of Visual Display Technology, Springer ("all-in-one") available via SPRINGERLINK
  Karlheinz Blankenbach: Section 11 – Display Metrology
  11.1 Introduction to Display Metrology p.2275
  11.2 Standard Measurement Procedures p.2289
  11.3 Advanced Measurement Procedures p.2331
  11.4 Display Technology-Dependent Issues p.2417
  11.5 Standards and Test Patterns p.2429
  11.6 Measurement Devices p.2447

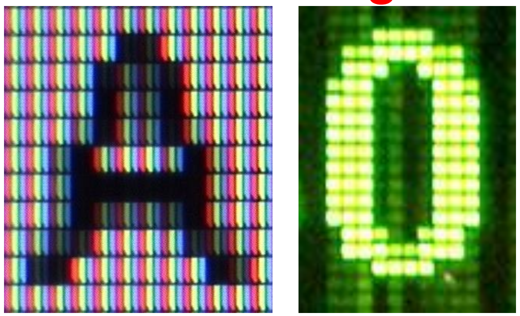


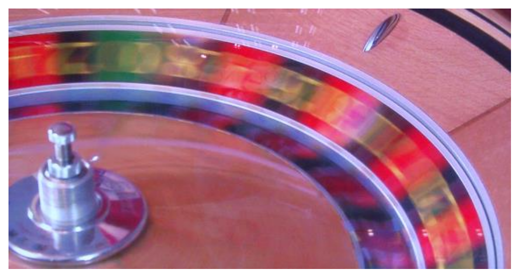


- International Committee for Display Metrology (ICDM)
  http://www.sid.org/ICDM/IDMSLicenseDownload.aspx
- K. Blankenbach: Display Metrology (with text), Veritas et Visus,
  http://eitidaten.fh-pforzheim.de/daten/mitarbeiter/blankenbach/vorlesungen/displays/Display_Measurement_VV.pdf
- K, Blankenbach: Display Metrology (video): adria
  http://eitidaten.fh-pforzheim.de/daten/mitarbeiter/blankenbach/vorlesungen/displays/Display_Metrology_ADRIA_2006.mp4
- RI color calculator (units, CIE color spaces, … free download)
  http://radiant-imaging-color-calculator.software.informer.com/2.0/

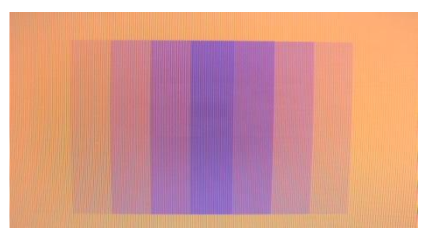
When Things Go Wrong* …

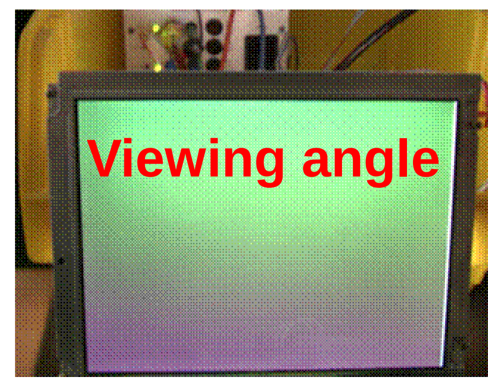
Ghosting





Response time





*: lyrics from “It hurts me too”, one of the most interpreted blues songs.

What is in a Specification ?

- Mechanical parameters
- Connectors
- Electrical interface
- Electrical characteristics
- Interface timing characteristics
- Absolute maximum ratings
- Backlight section for LCDs
- Optical characteristics
- Reliability tests
- Handling instructions

See WS term: Driving of FPDs

This chapter

Example of Optical Specification for AM LCD (I)

7.10 OPTICAL CHARACTERISTICS

Spec refers to measurement devices!

Remarks refer to measurement procedure ! Often no standard is used.

Measuring equipment:
Luminance, Chromaticity: TOPCON BM-7
Viewing Angle, Contrast: ELDIM EZContrast 160D

Ta = 25°C ± 2°CD, VDD = 5 V, fv = 60 Hz, f_{DCLK} = 32.5 MHz

Parameter		Symbol	Condition	Min.	Typ.	Max.	Unit	Remark
Viewing angle range	Horizontal	θ 21, θ 22	CR>10	60	70	-	Deg.	[Note1] [Note4]
	Vertical	θ 11		35	50	-	Deg.	
		θ 12		55	60	-	Deg.	
Contrast ratio		CRn	θ =0°	300	-	-		[Note2] [Note4]
		CRo	Optimum viewing angle	-	(600)	-		
Response time	Rise	τ r	θ =0°	-	10	-	ms	[Note3] [Note4]
	Decay	τ d		-	25	-	ms	
Chromaticity of white		x		0.263	0.313	0.363		[Note4] IL=6.0mArms f=60kHz
		y		0.279	0.329	0.379		
Chromaticity of red		x		(0.546)	(0.596)	(0.646)		
		y		(0.279)	(0.329)	(0.379)		
Chromaticity of green		x		(0.260)	(0.310)	(0.360)		
		y		(0.502)	(0.551)	(0.602)		
Chromaticity of blue		x		(0.117)	(0.167)	(0.217)		
		y		(0.132)	(0.182)	(0.232)		
Luminance of white		Y_{L1}		360	450	-	cd/m²	
White Uniformity		δW		-	-	1.25		[Note5]

Huge tolerance

Not guaranteed

[Note] The measurement shall be executed 30 minutes after lighting at rating. (condition:IL=6.0mA rms)
The optical characteristics shall be measured in a dark room or equivalent state with the method shown in Fig.3 below.

Example of Optical Specification for AM LCD (II)

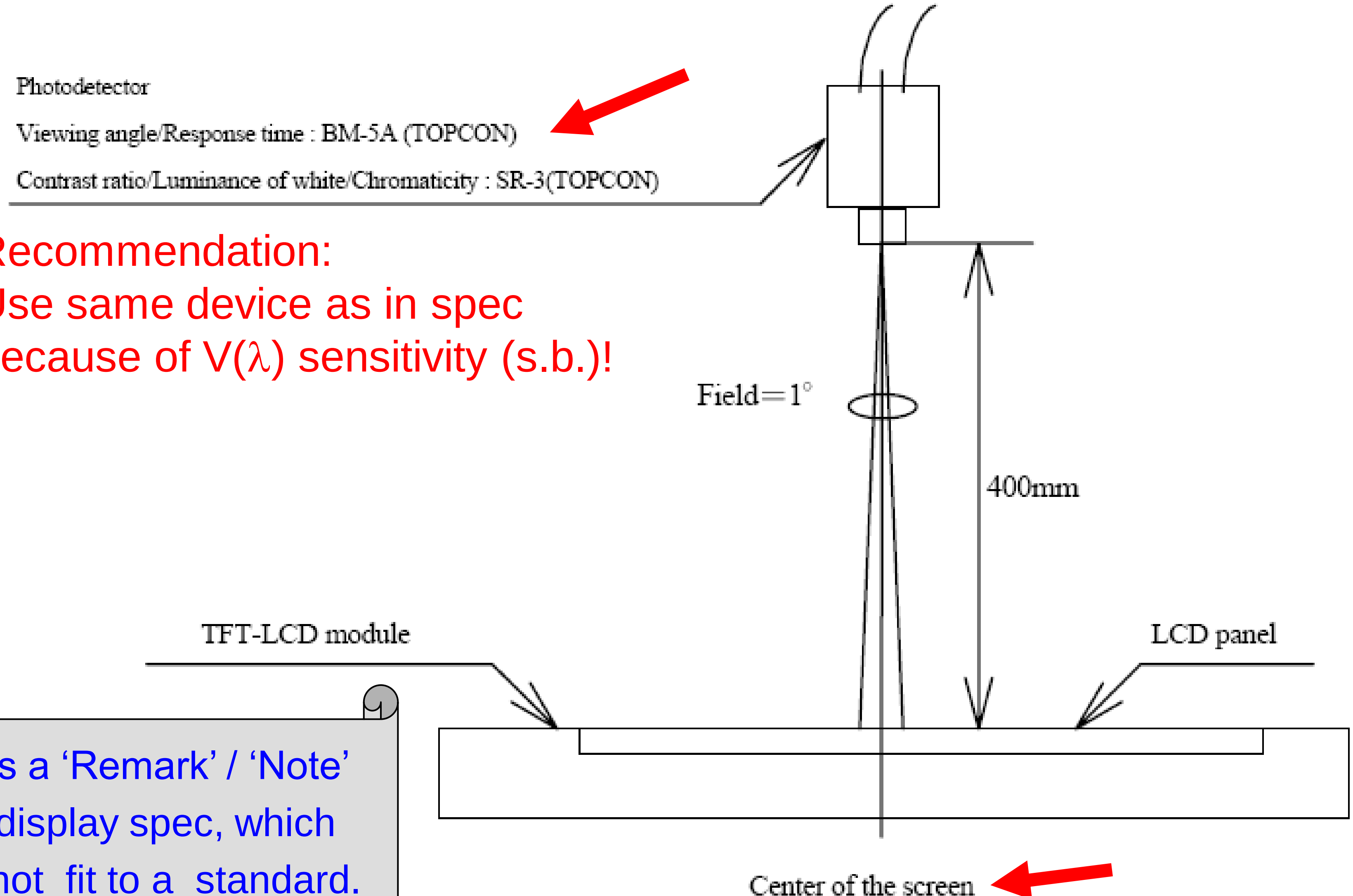
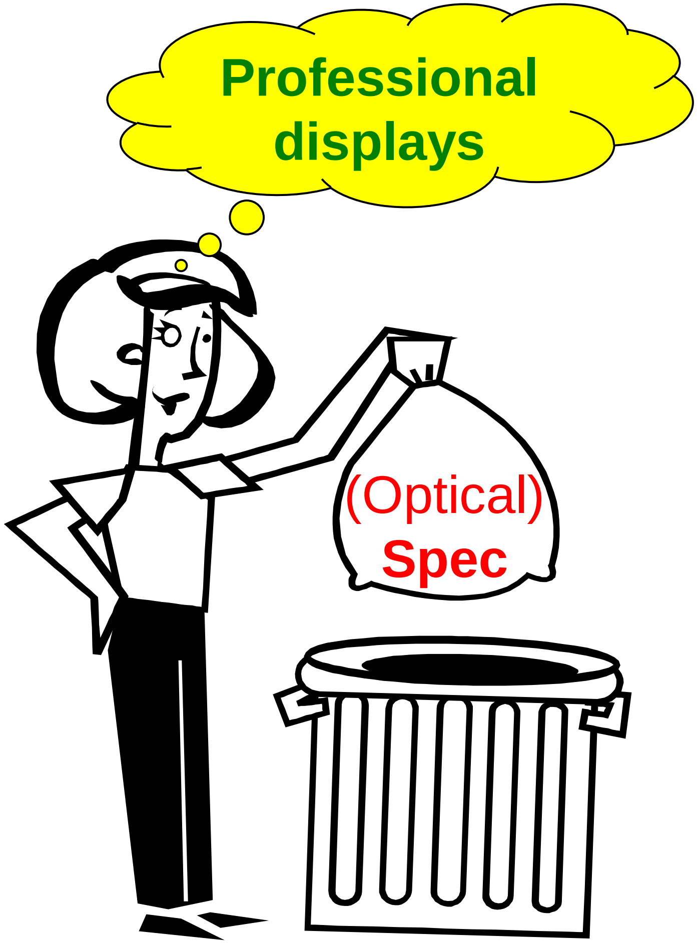


Fig.3 Optical characteristics measurement method

Recommendation:
Use same device as in spec
because of V(λ) sensitivity (s.b.)!

This is a 'Remark' / 'Note' of a display spec, which must not fit to a standard.

(Optical) Specifications - What are they good for ?



Why ?

- All optical measurements (contrast, color, …) are performed under dark room conditions
  ⇨ There is no serious extrapolation to ambient light (illuminance E) conditions
- Lifetime (LT): 25°C, full screen, permanent ON
  ⇨ This is not typical for most applications
- …

'here'

Evaluation for application requirements (LT, E, …) has to be done

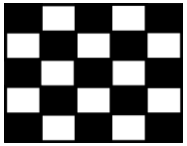
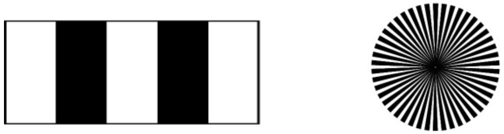
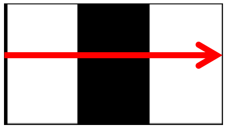
Typical Measurements

- Tests by **visual inspection** with dedicated test patterns:
  Full screen white, grey scale, color, resolution, motion, …
- Test by **measurement devices** with dedicated test patterns:
  Mostly full screen patterns
- **Basic Procedures**:
  - Spatial: Luminance, Contrast Ratio, Grey Scale, Color
  - Temporal: Response Time, Lifetime
  - Specific: Viewing Angle, Ambient Light, Touch, 3D, …
- **MEASUREMENTS CAN DAMAGE THE DISPLAY!**

What should be measured depends on display technology and application !

Typical Test Patterns

(examples see „testimages.exe“)

Measurement Task	**Recommended Test Pattern**	**Visualization**
Luminance, contrast ratio, grey scale, color, response time	Full screen	
Contrast ratio, Burn-In,	Checkerboard	
Modulation transfer function, sharpness	Resolution	
Motion blur	Moving bar	
Visual judgement	Text, full screen, motion, faces, …	 

Typical Measurements & Display Technology

Task	Lifetime	Response time	Ambient light	Viewing angle
Luminance	X (all)			X (LCD, LED)
Contrast ratio (black↔white)	X (all)	X (LCD, e-paper)	X (all)	X (LCD, LED)
Grey scale		X (LCD)	X (all)	X (LCD, LED)
Color	X (emissive)		X (all)	X (LCD, LED)

Usually in data sheets

X: should be measured
for () technologies

Only a few parameters are provided in specs / data sheets. Application relevant values have to be measured with display !

Typical Measurements & Application

Application	Lifetime	Response time	Ambient light	Viewing angle
Industry	X			
Automotive	X	X	X	X
White goods	X			
Medical	X	X		X
E-Signage	X	X	X	X

Most relevant: X

Why Measuring Electronic Displays ?

Merits of display metrology

- Human vision is only descriptive
- Standardized measurement setups and test patterns
- Specifications enable judging of displays
- Wide range of measurement procedures for many applications

Shortcomings of display metrology

- Ambient light (simulation) difficult, therefore most of the specified values are measured under dark room conditions
- Vision sees things that measurement can't capture and vice versa

Display metrology is also necessary because FPDs are mostly produced in Asia and designed in in Europe

Summary & Questions

- Take pictures of insufficient or badly working displays
- Download display specification (about 25 p.)
  - Try to understand each topic
  - Elaborate what could be missing for evaluation for of an embedded system for industrial, automotive, white goods, medical and e-signage applications
- Set up a list with measurements needed to evaluate this display and try to calculate how long this will last
- Write down examples for merits and shortcomings of display metrology

Overview Display Measurements

- Introduction
- Basic Parameters (Merits)
  - Luminance
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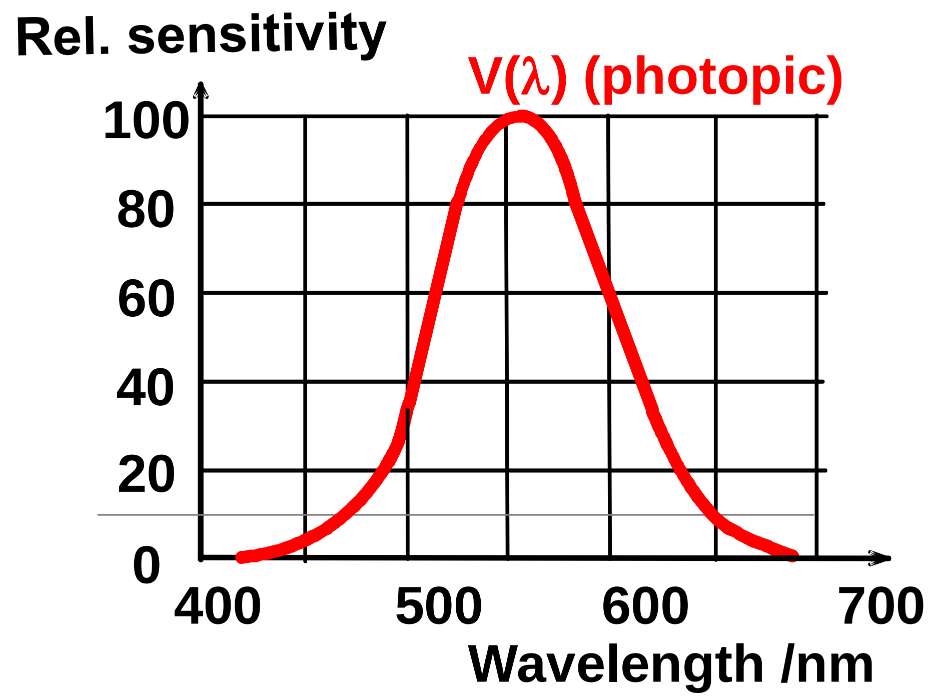
Basic Characteristics of Vision

Resolution	Spectral Sensitivity

- Angular resolution : 1‘
  at optical axis
  → 0.25 mm @ 1m = 100 ppi/m
- Time resolution ~ 50 ms (20 Hz),
  up to 100 Hz flicker sensitive
- ~ 500,000 colors can be
  distinguished
- … plus ‚signal processing‘ (brain)



V(λ) curve relevant for luminance measurements

Displays and metrology have to be matched to vision !

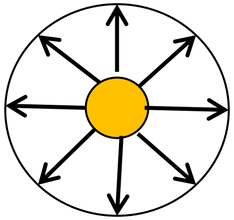
Photometric Units

Photometric unit are 'adapted' to vision, compare to physics units e.g. [W] for power

- **Luminous flux** (power) [Lichtstärke] : F / lm

  Value of total amount of light coming out of a light source

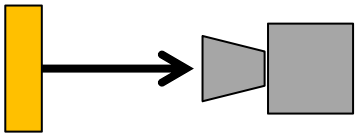
  Example: bulb, projector



- **Luminance** [Leuchtdichte] : L / $\frac{cd}{m^2}$ (emitter)

  Value of light of a light source emitted in one direction

  Example: luminance of a display

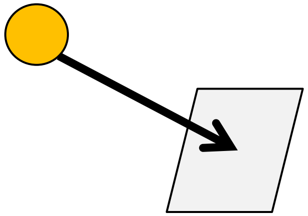


- **Illuminance** [Beleuchtungsstärke] : E / $lx = \frac{lm}{m^2}$ (receiver)

  Illuminance = power / area: $E = \frac{dF}{dA} = \frac{F}{A}$

  Value of light hitting a surface from any direction

  Example: Ambient light "illuminates" paper or display



Photometric Units Examples

See e.g. specs:

- Luminance L = 300 cd/m² for AMLCD

- Luminous flux F = 1,000 ANSI lm for projector

- Illuminance of 1,000 lm projector at 2 x 3 m²

$\rightarrow$ E = F / A = 167 lx

compare to 500 lx recommended at workplace!

Bright sunlight: 100.000 lx (reference for solar cells)

RI Color Calculator

Overview : Basic Parameters

- Photometric units are used instead of SI one's as "vision is implemented"
- The display measurement parameters ("Fab 4")
  - Luminance
  - Contrast Ratio
  - Grey Scale
  - Color

  are the fundamental procedures to specify and to characterise a display
- These 4 parameters are measured also under different conditions like lifetime, viewing angle, ambient light, …
- To compare displays and specifications, the measurement procedure (set-up and geometry) and instrument should be the same (and calibrated)
- The accuracy of display measurements is typically lower than for many other measurements due to deviations of spectral sensitivity ($V(\lambda)$, CMF)

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Luminance

Parameter	Symbol	Condition	Min.	Typ.	Max.	Unit
Luminance (center of screen)	Lw	at center	-	1600	-	cd/m^2

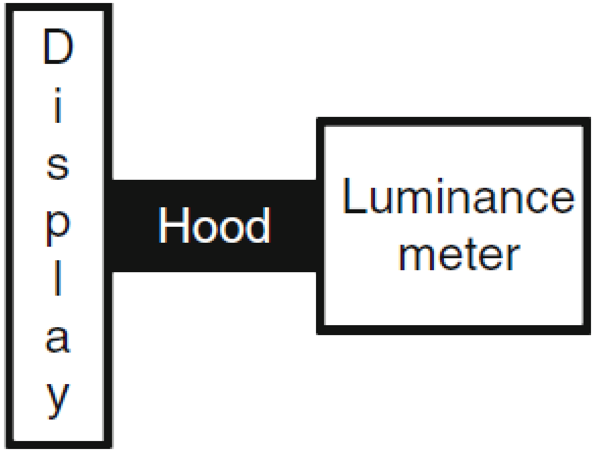
- [L] = cd/m^2
- Typical values : Displays 50 – 2,000 cd/m^2, bulb 10,000 cd/m^2
- Luminance (cd/m^2) is not brightness: see § Grey Scale & § CIE Lab Luv, brightness is "detected and described" by humans and has no unit
- Basic value for contrast, grey scale, uniformity, viewing angle, ...
- Luminance is one of three parameters for color measurements (Tristimulus)
- Major source of error: Deviations from V(λ) curve and SNR for black
- Measurement conditions (see above)
  - Dark room unless otherwise noted
  - Center of display, perpendicular incidence, 25°C
  - Mostly full screen white image, PDP: 1% white surrounded by black
  - Usually mean value of 500 pixel (FOV) for monitor

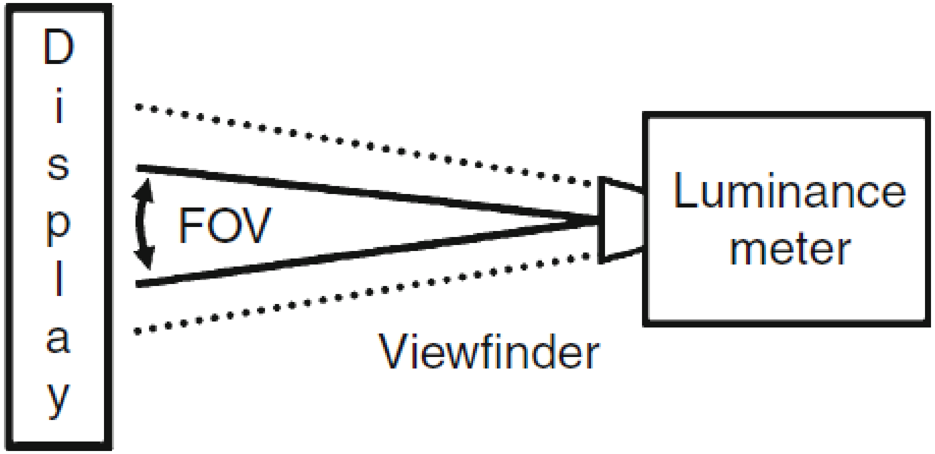
(Luminance) Measurement Devices (I)

There are basically two different principles for optical display measurements:

- Single detectors like spot meters integrate over many pixels (typically 25 to 500 pixel), aperture angle < 2°

- Area detectors in cameras can measure nearly single pixel luminance over the total screen





Measurement Devices Examples

Principles

- **Hood meter** (simple, low cost)

  Luminance or colorimeter

- **Meter with viewfinder** (ease of use)

- **Camera**-based meters (enable image processing) for monitors and segmented displays, avoid Moirè by e.gl. Defocusing, see TechnoTeam presentation

- **Spectrum**: Captures intensity over wavelength, highest precision

Devices

- Luminance meter (lower cost, limited use as no color)
- Color meter (color measurement capable, covers also L, higher cost)

Luminance Measurement and V(λ) Spectral Sensitivity

Silicon sensors (——— , ———)

of luminance meters have to be

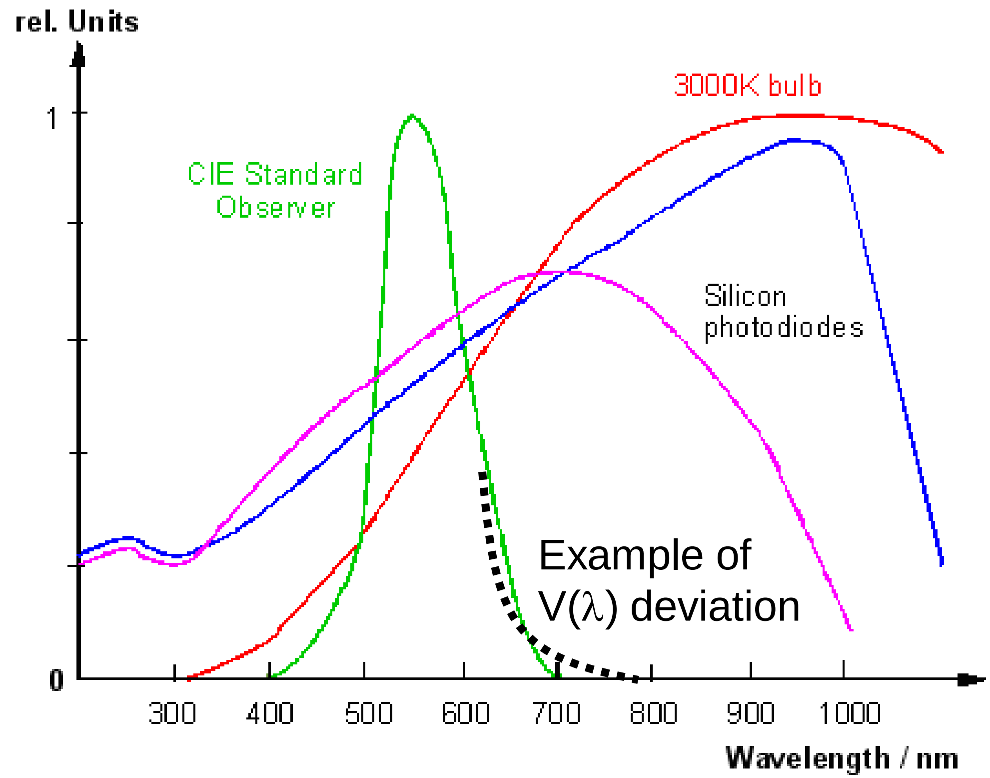
adjusted with optical filters to

human vision spectral sensitivity

(V(λ) – curve, CIE standard

observer, DIN 5032).

Color: Color Standard Observer

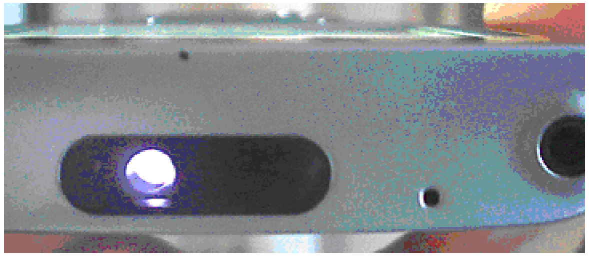


Example :

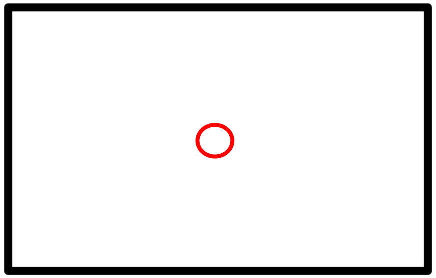
Test of IR-diode of remote control or IrDa

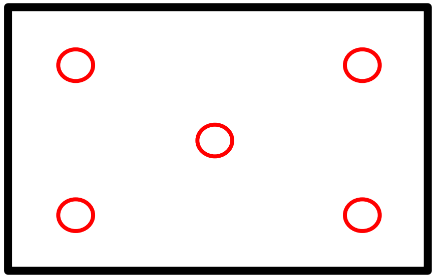
with digital camera because it is not

calibrated to V(λ), see also color management!



Test Patterns for Luminance Measurements



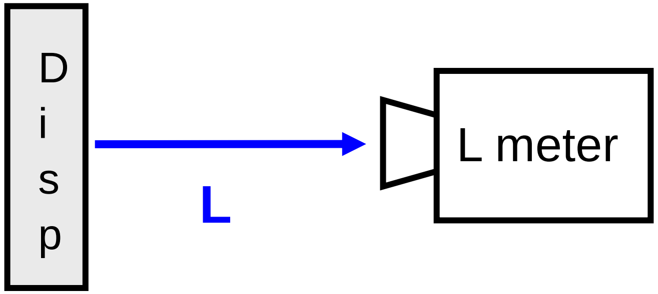


- Mostly full white screen
- Set-up: perpendicular, center of screen (o, see p 7)
- Uniformity: measure luminance at 5 or more locations (or camera)
- Contrast, grey scale and color base also on full screen showing white, black, grey, RGB
- Lifetime measurements (see § Common Issues) use often full white screen luminance measurement

"Luminance" - Measurements of Reflective Displays

- **Emissive displays (AM LCD, OLED):**

  Direct measurement of luminance **L**

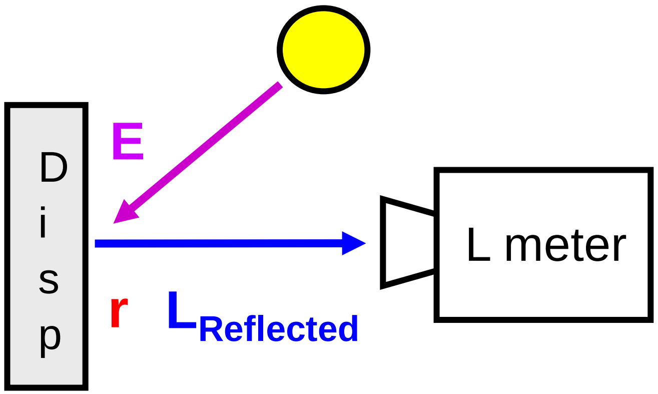


- **Reflective displays (E-Paper, refl. LCD):**

  Ambient light is reflected diffuse

  by display, luminance **L** is "generated"

  by reflectivity **r** of illuminance E



$$L_{Reflected} = \frac{r\ E}{\pi}$$

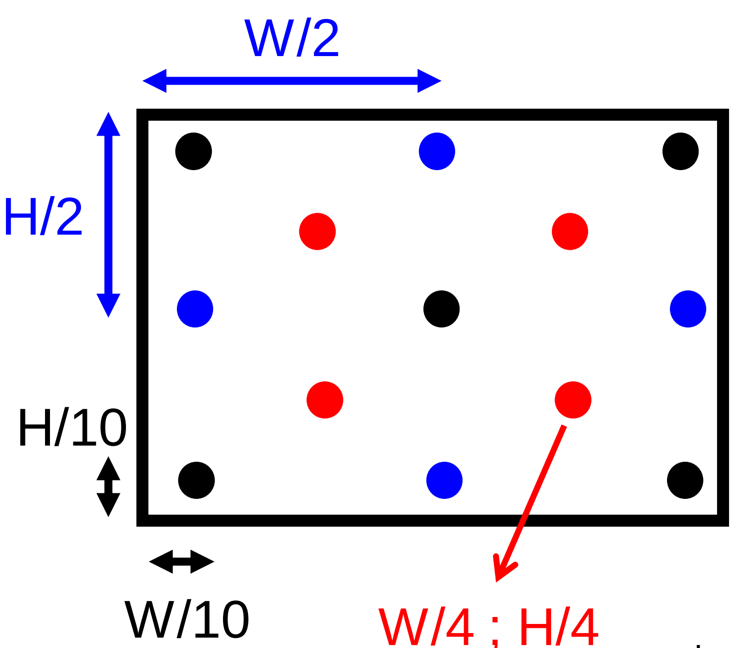
Typical reflectivity r: reflective LCD ~ 0.2 ; e-paper 0.4

Examples of Reflective Displays

Uniformity

Luminance of white	Y_{L1}		360	450	-	cd/m²
White Uniformity	δW		-	-	1.25	

- Deviation of a display parameter, e.g. luminance L within display area, also measured for CR, GS and color
- 5, 9 or 13 spots method (ISO 9241)
- Uniformity is easy to measure and complex to judge as vision is less sensitive as measurements

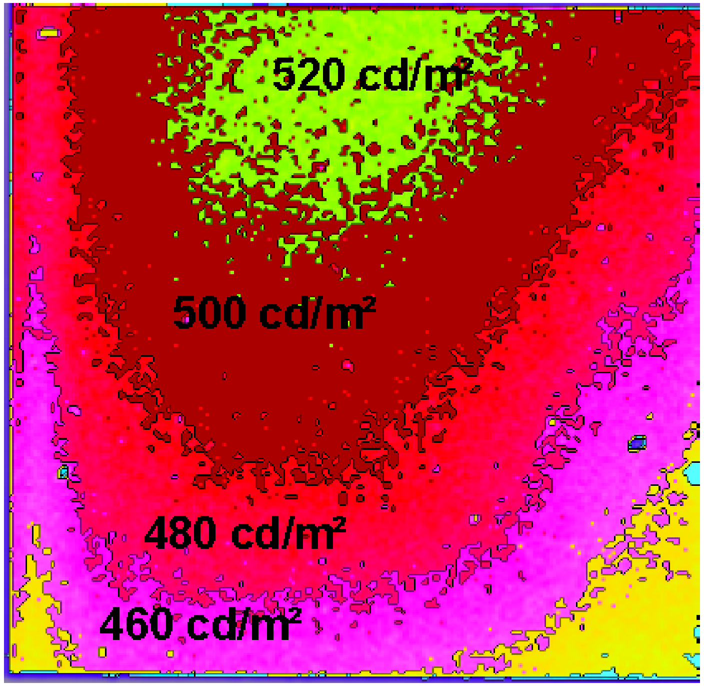


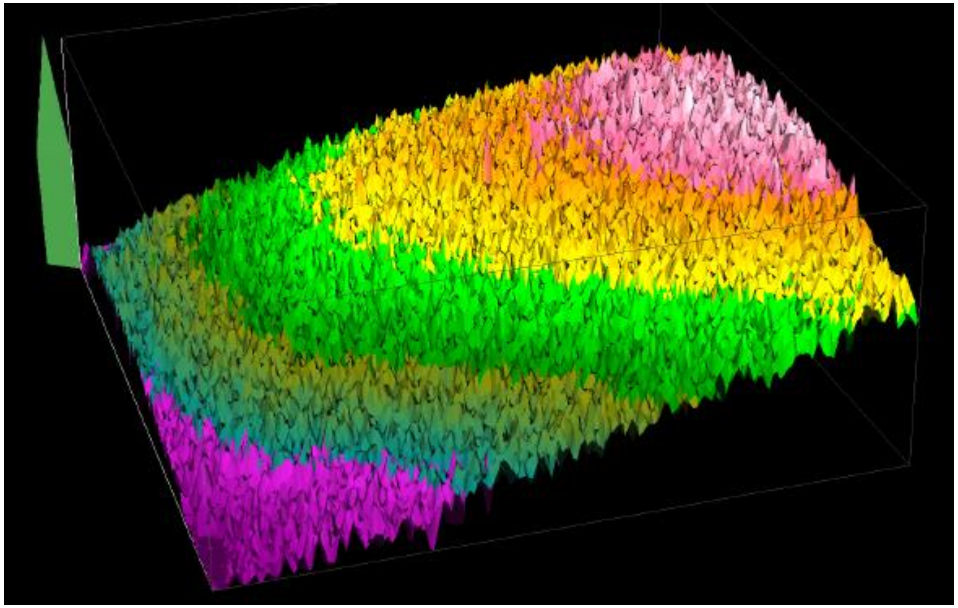
Definitions for L	Examples*
$\varnothing L \pm x\,\%$	190 cd/m² ± 5%
$100\,\dfrac{L_{max} - L_{min}}{L_{max}}$	10
$100\,\dfrac{L_{max}}{L_{min}}$	111%

*: L_{max} = 200 cd/m², L_{min} = 180 cd/m², equally distributed

Area Measurements with Luminance Camera

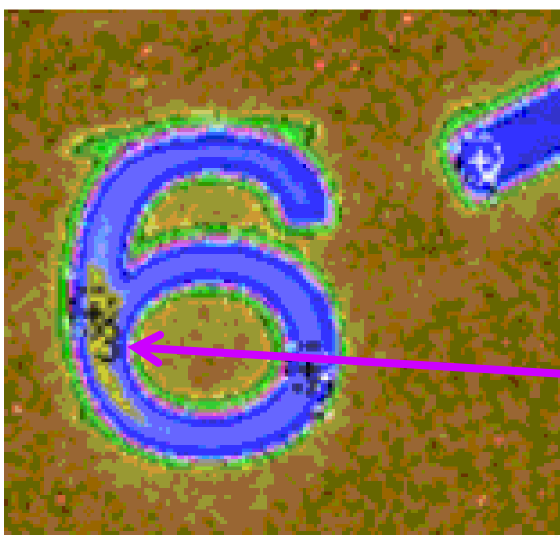
Area measurement examples





Area Measurements with Luminance Camera

- Camera detector with special filters (like colorimeter) can measure luminance (and colour) in a short time
- Used aslo for uniformity measurements of icons, etc
- Limited accuracy compared to other devices



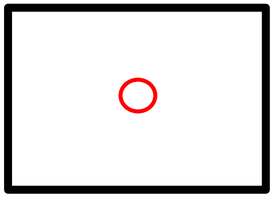
Object units:	pos [pixel]	radius [pixel]	Avg [cd/m²]	StdDev [cd/m²]	M [
cursor spot;	(1166,676);	5;	1,982;	0,05617;	1
spotmeter #1;	(1084,396);	5;	6,825;	0,8274;	2
spotmeter #2;	(1045,441);	5;	7,925;	1,306;	2
spotmeter #3;	(996,429);	5;	9,142;	2,309;	2
spotmeter #4;	(1098,640);	5;	2,070;	0,2466;	1
spotmeter #5;	(1073,691);	5;	1,667;	0,7365;	0

Efficiency

Efficiency η = "Light output per Watt"

„Go for Green"

- Measurement:
  Electric power consumption
  for "Full screen white"



- Projection and lamps: "Lumen per Watt"
- Displays: "Luminance per Watt", screen size to be normalized
- Viewing angle characteristics of light emission is a "weak point"
- Efficiency for lamps is key point, refers often to incandescent bulbs.
  Example left: same lumen
  Projection: F = 3,000 lm,
  P = 250 W ⇨ $\eta \approx 12$ lm/W

≈ 700 lm

	Incandescent	CFL	LED
Wattage	60W	13W	6W
Lifetime [2]	1 year	4 years	25 years
Average price	$1.00	$2.00	$29.95
Replacement cost per year [1]	$1.00	$0.50	$1.20
Energy consumption per year [2]	87.6kWh	18.98kWh	8.76kWh
Energy cost per year [3]	$10.51	$2.28	$1.05
Total cost per year [4]	$11.51	$2.78	$2.05

Emissive Displays Efficiency = "Light output per Watt"

Example of LCD

L_{white} ("set by vision")

Excerpt from data sheet

Item	Symbol	Condition	Min.	Typ.	Max.	Unit
Brightness of White	B	$\phi=0°, \theta=0°$	300	400	-	cd/m^2
Power Supply Voltage	VDD	-	3.0	3.3	3.6	V
Power Supply Current	IDD	VDD=3.3V	-	130	300	mA
LED Input Voltage	VLED	-	4.5	5.0	5.5	V
LED Forward Current (DIM control)	ILED	VLED = 5V	-	230	300	mA

LCD Active Area	A	71.04(W) mm x 53.28(H) mm

$$P_{LCD} = P_{electronics} + P_{backlight}$$

Efficiency $\eta = L_{white} / P_{LCD}$ (here ≈ 250 cd/m² W)

Here $\eta_n \approx 1$ cd/W

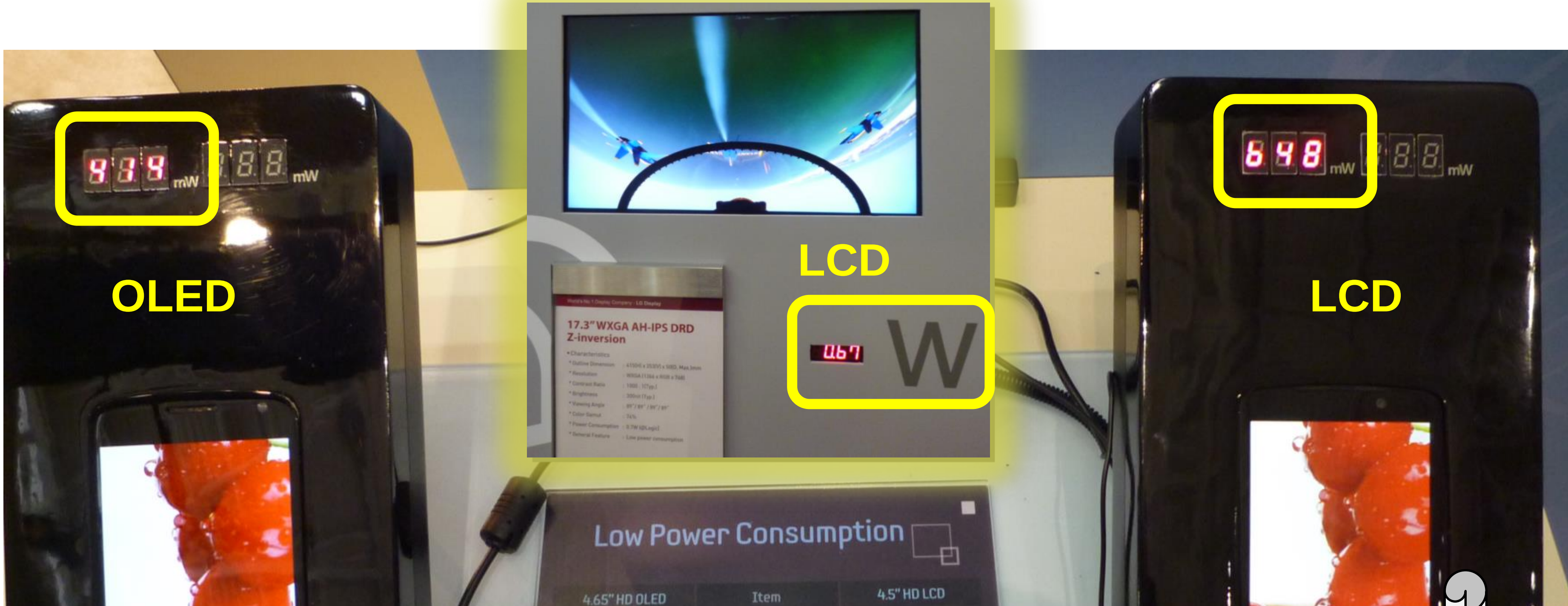
➡ **Display frontal intensity efficiency:**

$$\eta_n = \eta \cdot A = \frac{L_{white} \cdot A}{P_{LCD}}$$

- "Energy efficiency"
- Measure for efficiency for typical observer

Lighting: $[\eta]$ = lm/W
Not useful for displays because of viewing angle.

OLEDs vs. LCDs : Power Consumption



- OLED manufacturer: 4.5”: OLED: 0.41 W vs. 0.65 W for LCD
- LCD manufacturer: 17” LCD: 0.67 W

➡ η_n : 4.5” OLED: 4.1; 4.5” LCD: 3.5; 17” LCD: 47 / cd/W

η_n (17” LCD) > 10x 4.5” OLED

Summary & Questions

- Compare vision ‘detection’ with luminance measurement
- Photometric system easies display measurements
- What are the main topics of luminance measurements?
- Be always aware that most values in specs are measured under dark room conditions
- Set up a list with measurements needed to evaluate this display and try to calculate how long this will last
- Elaborate ‘detection’ and signal processing requirements for luminance meters. Hint: Black has low luminance, white ~ 1,000 cd/m² AMLCD is DC; PDP, PMOLED & CRT pulsed, …

Overview Display Measurements

- Introduction
- Basic Parameters (Merits)
  - Luminance
  - Contrast
  - Grey scale
  - Color
- Common Issues
- Display Technology Dependent Issues (Shortcomings)
- Summary

Contrast Ratio

… is not a measure for readability of text (fullscreen)!

- Luminance ratio of bright / white / max / ON to dark / black / min / OFF
- Various definitions, mostly contrast ratio used, MTF s. b.

- **Contrast ratio**

$$C_R = \frac{L_{bright}}{L_{dark}} = \frac{L_{white}}{L_{black}} \quad \ldots$$

Example

Paper $\approx$ 10 : 1

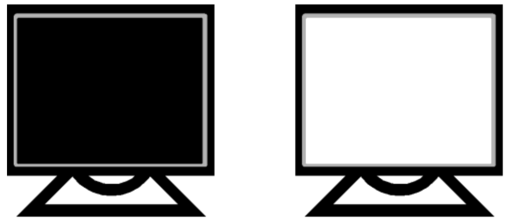
Remarks

- High C_R can be critical because of measurement error for L_{black}
- Vision range : C_R = 3 : 1 - 500 : 1; **30:1 is OK for multimedia!**
- $C_R \approx$ 10 : 1 recommended for non-fatigue reading (paper !)
- High C_R can bother (e.g. car headlights at night) !
- C_R in specs measured without ambient light ! $E\nearrow \rightarrow C_R\searrow$
- Various conditions like full screen, checkerboard, …

Contrast Ratio Test Patterns

Parameter	Symbol	Condition	Min.	Typ.	Max.	Unit
Contrast ratio	CR	∅y=-5°, ∅x=±0°	-	350:1	-	-

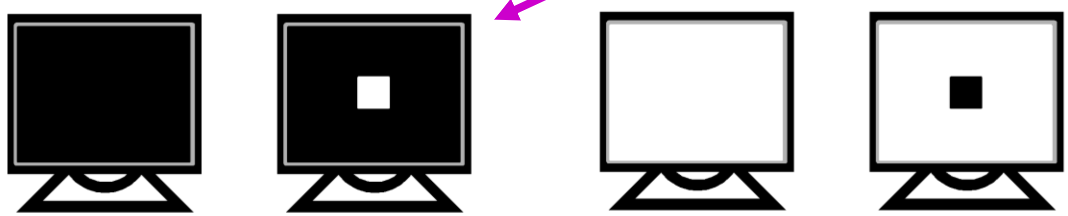
- Full screen



LCD, OLED, PDP $C_R \approx 100:1$

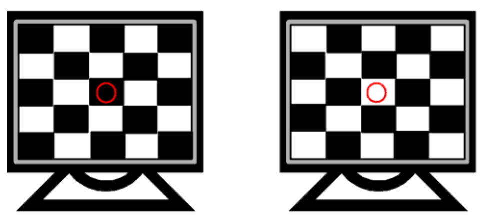
Used for PDP → $C_R \approx 1{,}000:1$

- Centered box



- Checkerboard

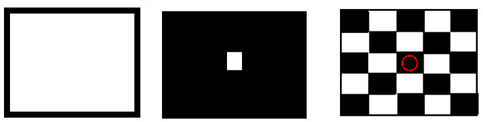
  (Projection)



- Intra-Character

C_R depends on test pattern, especially for
- PM drive (ghosting)
- PDP
- Projection

Examples of Contrast Ratio



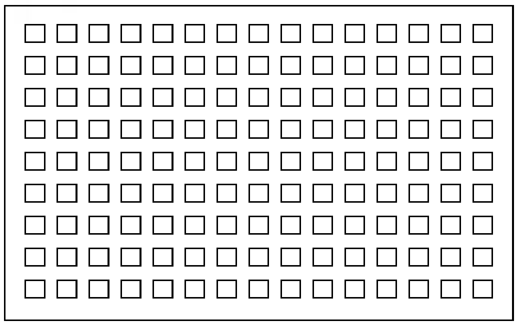
			Direct view		Projection
			LCD	PDP	DLP
L / cd/m²	White	Full screen	500	100	500
		Highlight 1 %	500	500	500
		Checkerboard	500	150	500
	B Black	Full screen	1.0	0.1	0.5
		Checkerboard	1.25	0.5	2.0
C_R		Full screen	500	1,000	1,000
		Highlight 1 %	500	5,000	1,000
		Checkerboard	400	300	250

Remarks:

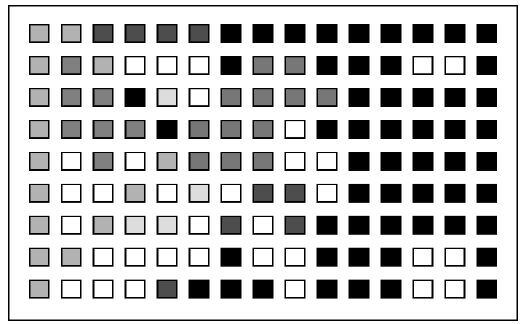
- Full screen white << highlight (1%) white for PDP, other technologies nearly indep.
- Checkerboard black >> full black for projection systems (lens flare, …)
- Checkerboard C_R << highlight C_R for PDP and projection

LED LCD - Backlight Improvements : Local Dimming

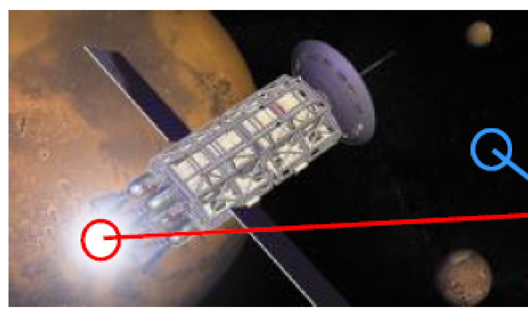
Traditional Full-On LED



Individual LED On/Off & Level Control



High Contrast



L_{max} = 630 cd/m^2

L_{min} = 0.03 cd/m^2

→ C_R = 630 / 0.03

= **21,000 : 1**

Power saving 50% average (image dependant)

Examples for Luminance and Contrast Ratio

	Display 1			
L_{white}				
L_{black}				
Contrast ratio				
Comment				

Summary & Questions

- Contrast ratio is measured under dark room conditions as ratio of white luminance divided by black luminance
- Test patterns for contrast ratio is mostly full screen but some use checkerboard (projection) or 1% white (PDP)
- Contrast ratio is not a measure for readability or sharpness
- What is the basic procedure to measure contrast ratio ?
- Why and where depends the contrast ratio on test pattern ?
- Why is contrast ratio not meaningful for real world applications ?

Overview Display Measurements

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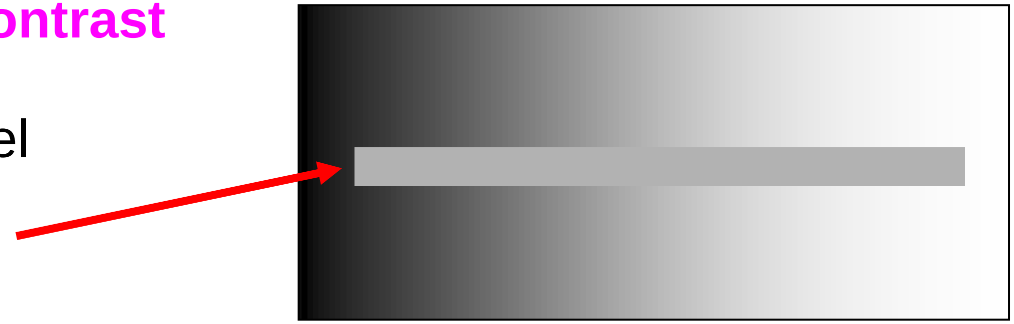
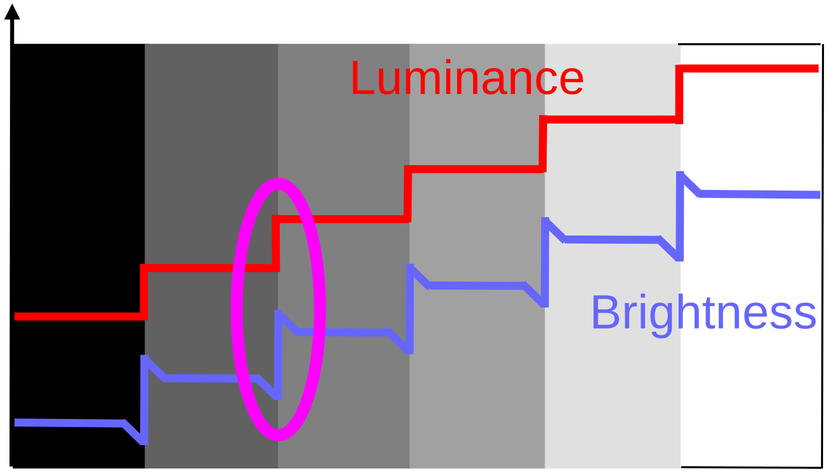
Visual Effects of Grey Shades

- **Simultaneous Brightness Contrast**

Bar has constant grey level (luminance) but appears brighter on the left !



- **Mach Band Effect**



The grey bars appear brighter on their left side and darker on the right !

Grey Shades and Vision

- Grey shade is a definition for an observer,
- Grey level is a definition for a digital grey level of a display pixel

- The ‚eye‘ shows a non-linear sensitivity of luminance ≡ perceived brightness

- Digital data (grey level) should be recognized in a ‚linear‘ way !

(digital grey levels for a display e.g. 6, 8, 10 Bit [per color])

→ Displays have to be adapted to vision and digital requirements!

This adaptation is expressed by a parameter/ value called **gamma**.

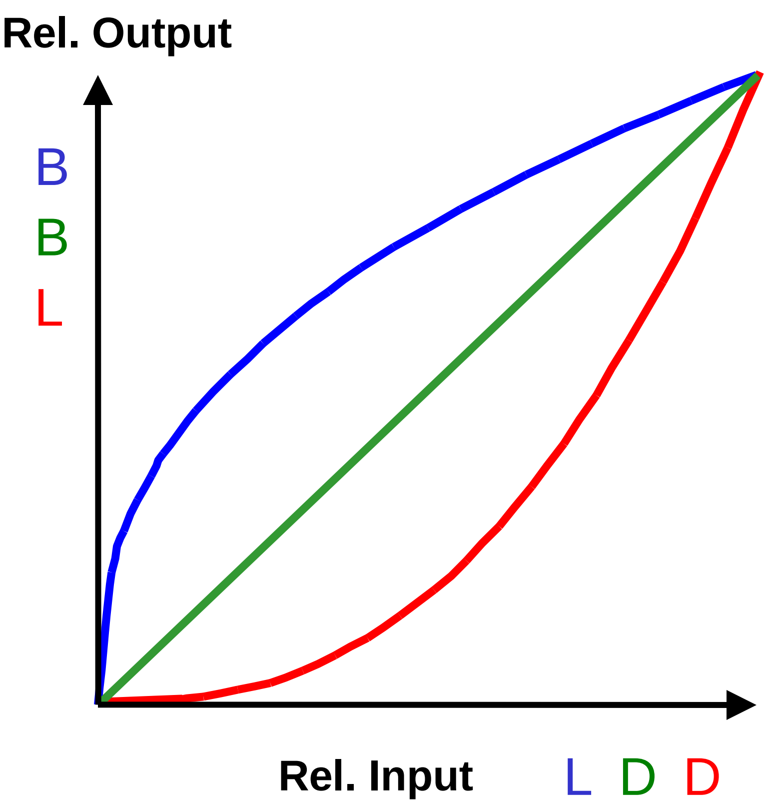
It is implemented in the operating system and/or graphics adaptor.

This is also valid for printers, ...

Digital Data - Perceived Brightness

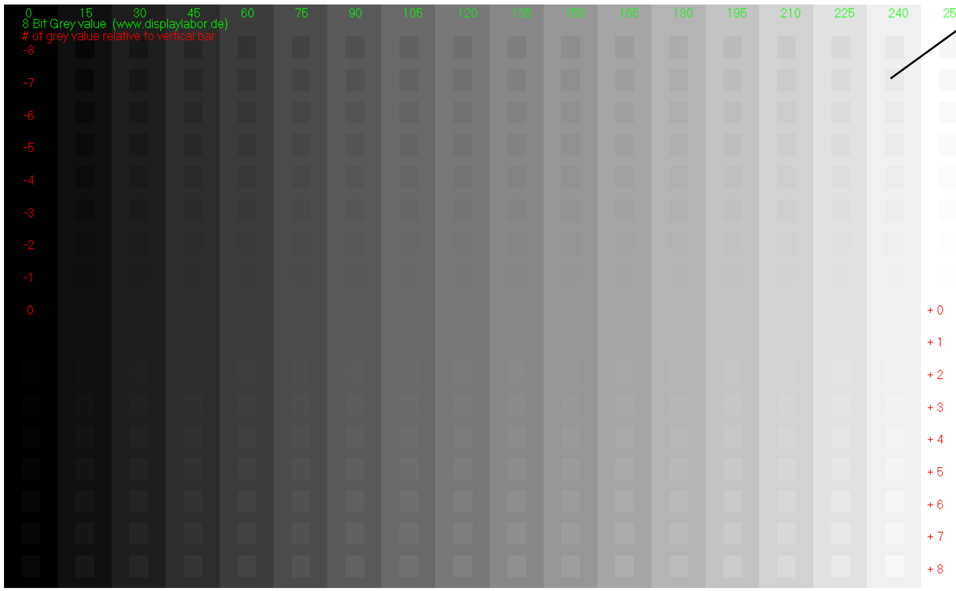
- Perceived brightness B by human vision (typ.) **$B \sim L^{0.44}$**
- Brightness B and Grey shade D should be proportional **$B \sim D$**
- Luminance L of a display depends on grey shade D **$L \sim D^{\gamma}$**
- Gamma value (γ) for linear relationship :

$B \sim D \rightarrow B \sim L^{0.44} \rightarrow B \sim D^{\gamma \, 0.44} \rightarrow \gamma \approx 2.3$



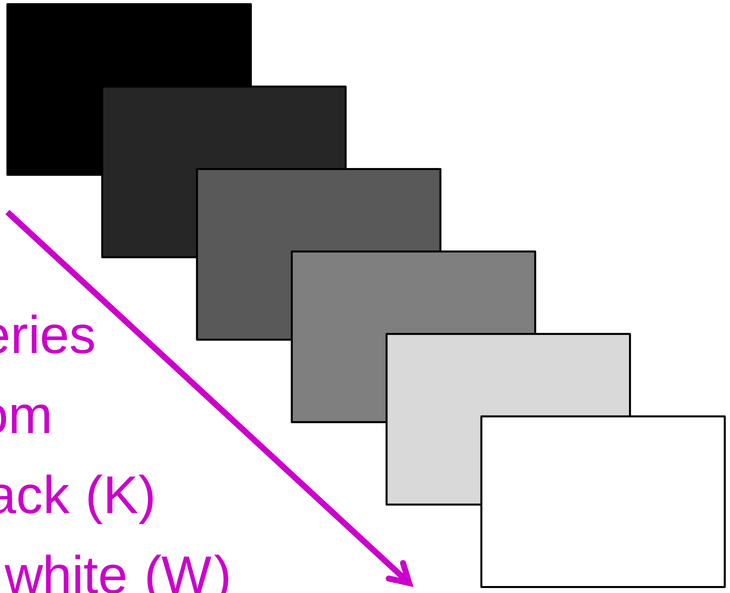
WINDOWS : $\gamma = 2.2$
MAC OS : $\gamma = 1.8$

Test Patterns for Grey Scale



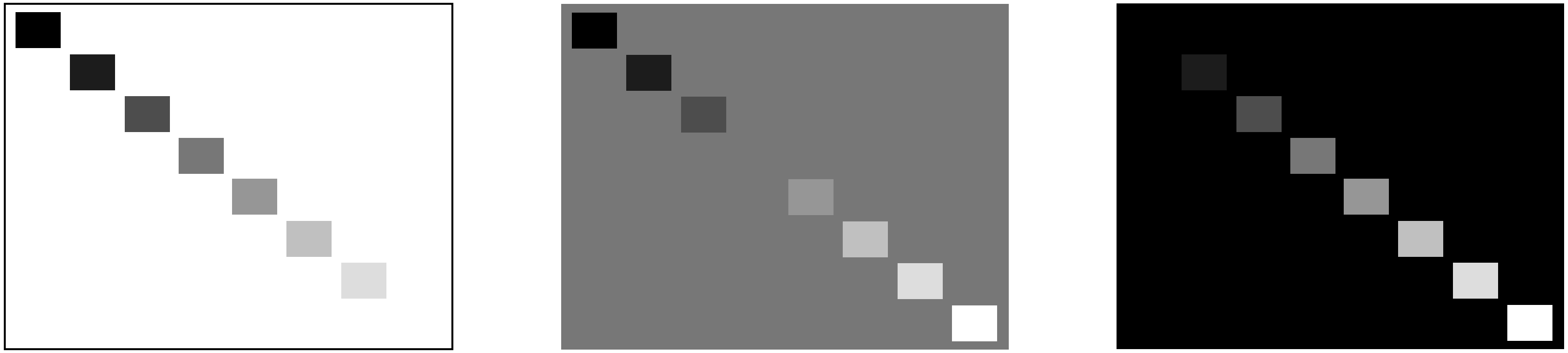
Boxes in vertical bars with ±1, ±2, ±3, … grey levels.
±1 is often not noticeable thus reducing visible „grey levels“.

Visual inspection for grey level resolution, “vanishing of neighbouring grey levels”, influence of e.g. ambient light, …



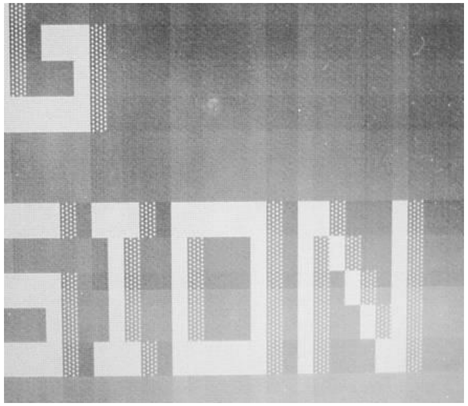
Series from black (K) to white (W) for **measurements**

Visual Test Patterns for Grey Scale



Shadowing of grey levels:

- Measurement or visual inspection
- Mainly critical for Passive Matrix LCDs and Passive Matrix OLEDs

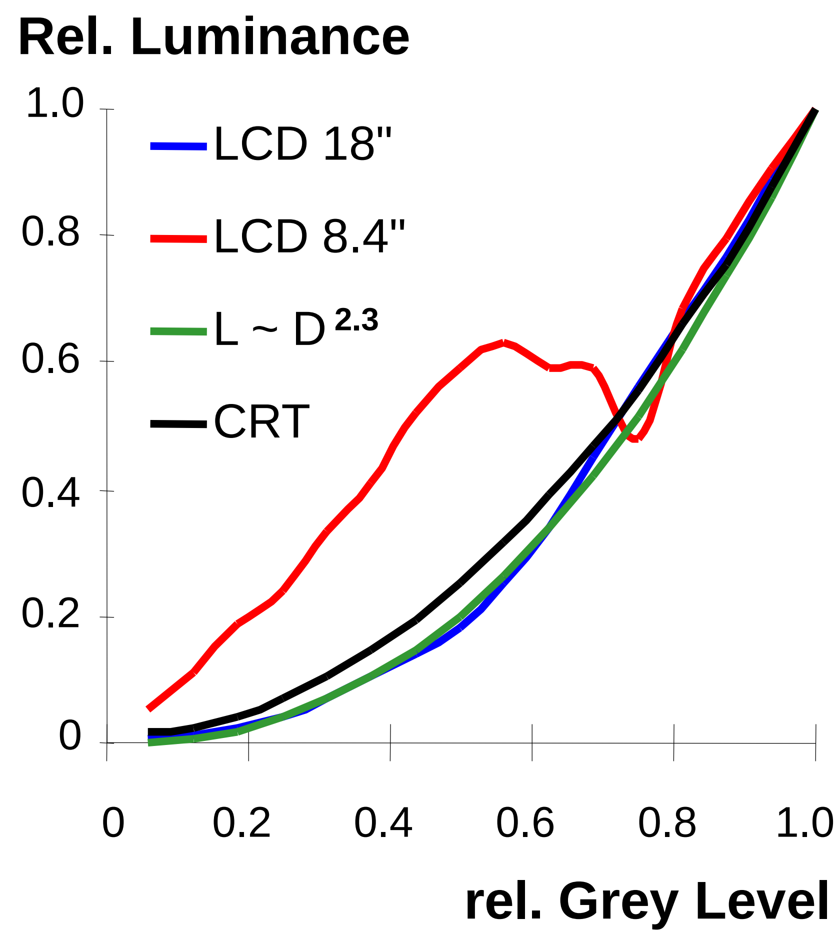


Examples of Grey Scale

- Measure full screen luminance (s.a.) from black to white for typically 10 grey levels and plot (right)

- Example values

Grey scale	Luminance
0	1.4
15	1.7
31	2.4
47	4.1
63	7.7
79	13.6
95	20.5
111	27.0
127	35.7
143	48.7
159	66.1
175	87.5
191	109.0
207	130.0
223	149.0
239	173.0
255	195.0

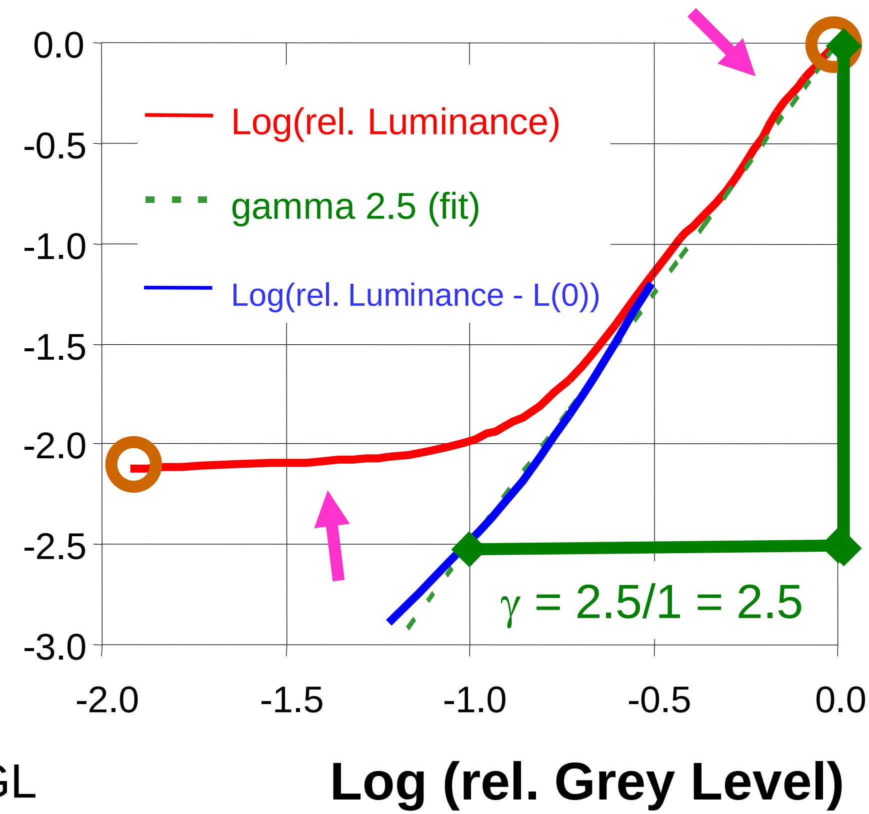


Remark: Linear chart of luminance over grey level is only rarely used → see next slide.

Gamma Measurement

Gamma mostly not specified for professional displays

- Greyscale for images, …
- Measurements: L(GS) @ 0 … 255
- Test patterns:
  - Visual: Grey bars (left)
  - Measurement: Full screen
- Measure luminance L for about 10+ grey levels e.g. 0, 15, 31, …
- Plot in double log chart, L(GS) – L(0) is helpful
- Results:
  - Gamma value by fit as log slope ΔL / ΔGL
  - GS resolution, deviations, …



Deviations from ideal curve !

Rem.: Contrast ratio represents only the min and max (o) of grey scale!

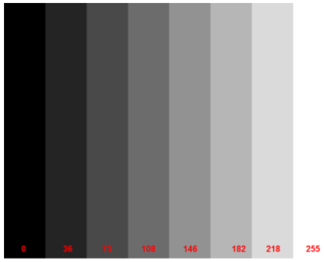
Gamma Measurement Example Data

Grey scale	Luminance	log (Grey scale)	log(Luminance)	log(Luminance - L(0))
0	1.4	-2.75	-2.14	
15	1.7	-1.22	-2.07	-2.89
31	2.4	-0.91	-1.92	-2.30
47	4.1	-0.73	-1.68	-1.86
63	7.7	-0.60	-1.41	-1.49
79	13.6	-0.51	-1.16	-1.20
95	20.5	-0.43	-0.98	-1.01
111	27.0	-0.36	-0.86	-0.88
127	35.7	-0.30	-0.74	-0.75
143	48.7	-0.25	-0.60	-0.61
159	66.1	-0.20	-0.47	-0.48
175	87.5	-0.16	-0.35	-0.35
191	109.0	-0.13	-0.25	-0.26
207	130.0	-0.09	-0.18	-0.18
223	149.0	-0.06	-0.12	-0.12
239	173.0	-0.03	-0.05	-0.05
255	195.0	0.00	0.00	0.00

This can be easily done by MATLAB, EXCEL, ...

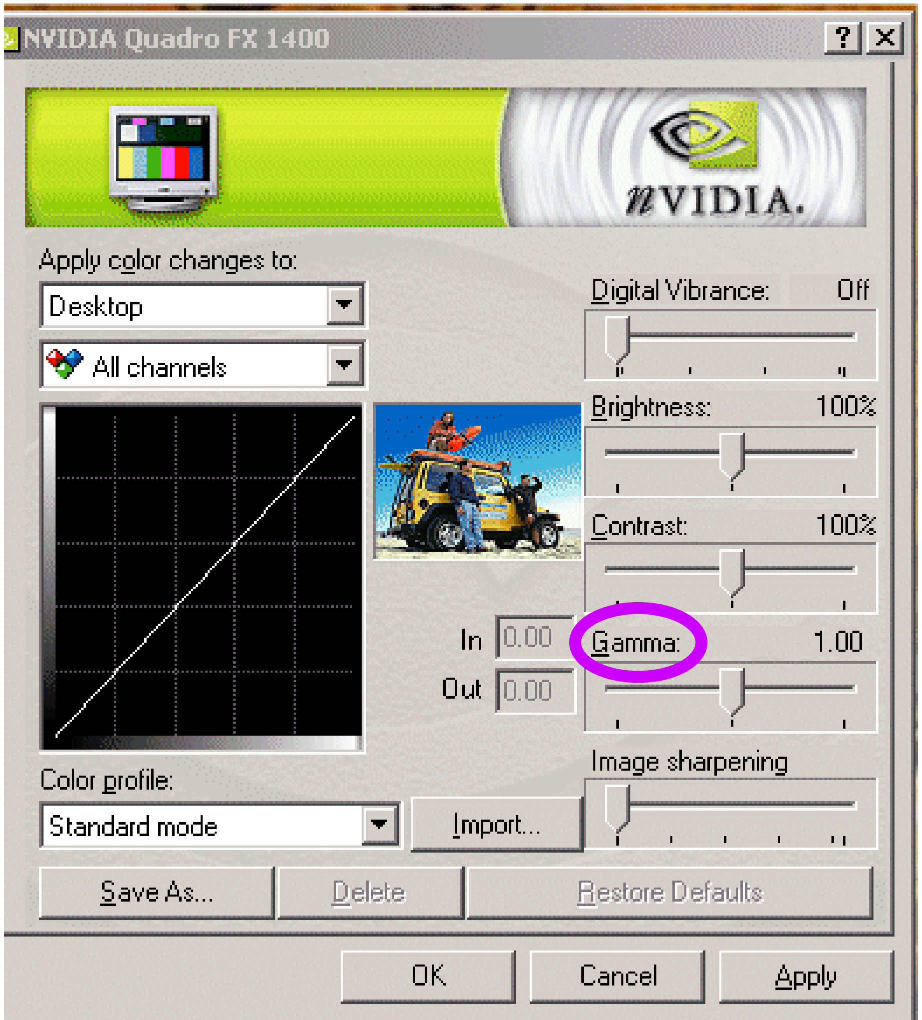
Example for Grey Level & Gamma

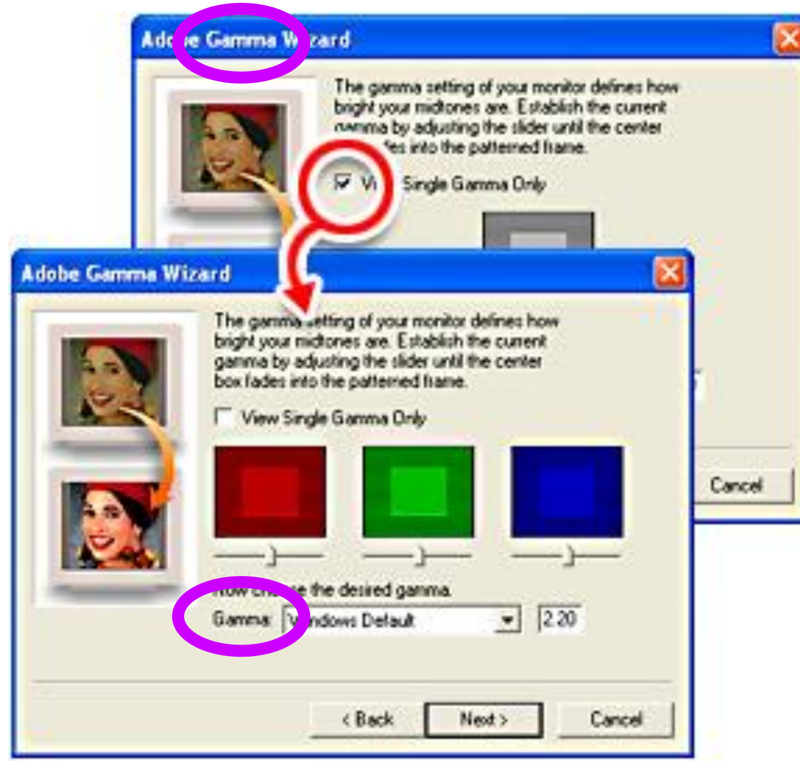
NIST
Testbilder



Grey level	Display 1 L /cd/m²	Display 2 L /cd/m²
0		
36		
73		
108		
146		
182		
218		
255		

Gamma in PC Hard- and Software





Note that Gamma value is mostly relatively used. A value of “1” means no change.

Summary & Questions

- Human vision (brightness) has a nonlinear relationship to luminance
- Gamma value combines grey scale to luminance $L \sim GL^{\gamma}$
- The gamma value is measured by a series of grey levels and plotted in a double logarithmic graph
- EO-Characteristic of displays have to be adapted to gamma curve
- Why is the contrast ratio not meaningful for image rendition quality ?
- How significant or visible are deviations from ideal gamma curve?

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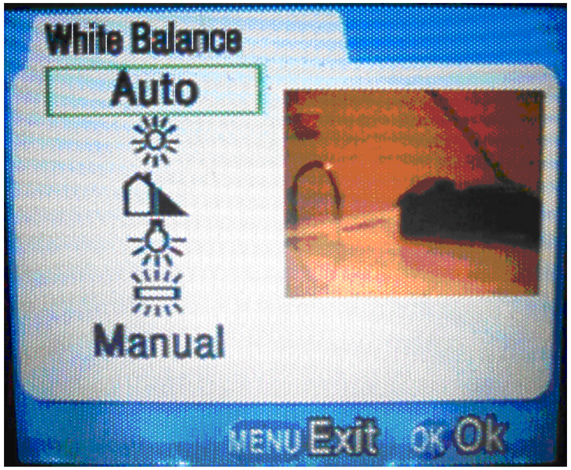
Why Color Measurements ?

… because vision is adaptive to color !

Examples

- Reddish illumination in supermarket for fruit and meat elsewhere white
- Woman's clothes shops have windows for daylight
- Cars: Xenon headlight is seen bluish compared to H4 bulb
- ‚Analogue' films : daylight and tungsten light

- Digital cameras have white balance, ‚Auto' should resemble vision but often fails



Colors Reproduction

... via color mixture !

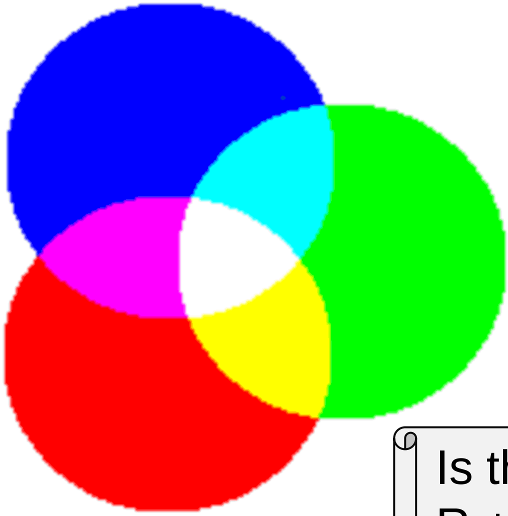
- Additive color mixture

e.g. displays : R + G + B = W

including 3-panel projection

(black can't be 'displayed' on

(white) screen !)



Is this valid?
R + G + B = W ?

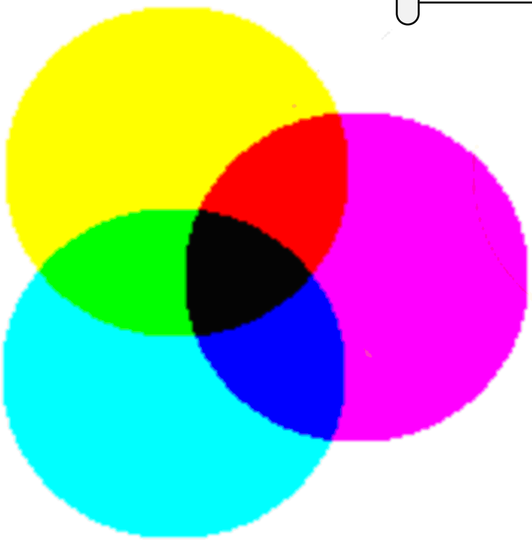
- Subtractive color mixture

e.g. printer and stacked displays:

C + M + Y = K

(cyan, magenta, yellow, K for blac<u>k</u>)

(no printing of white ≡ paper 'color' !)



Color Vision

Natural Spectrum

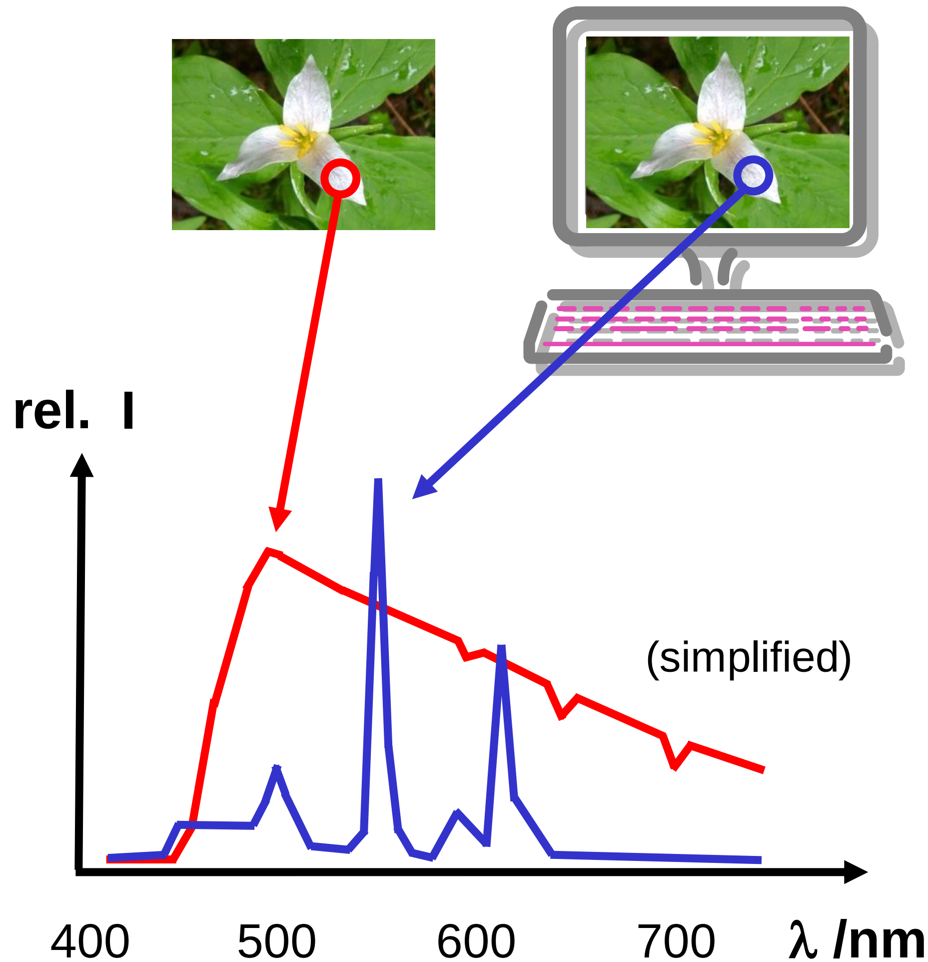
(chart intensity over wavelength)

Reflected sunlight from white leaf

Captured by digital camera
and display on a monitor:

‚Artificial' Spectrum

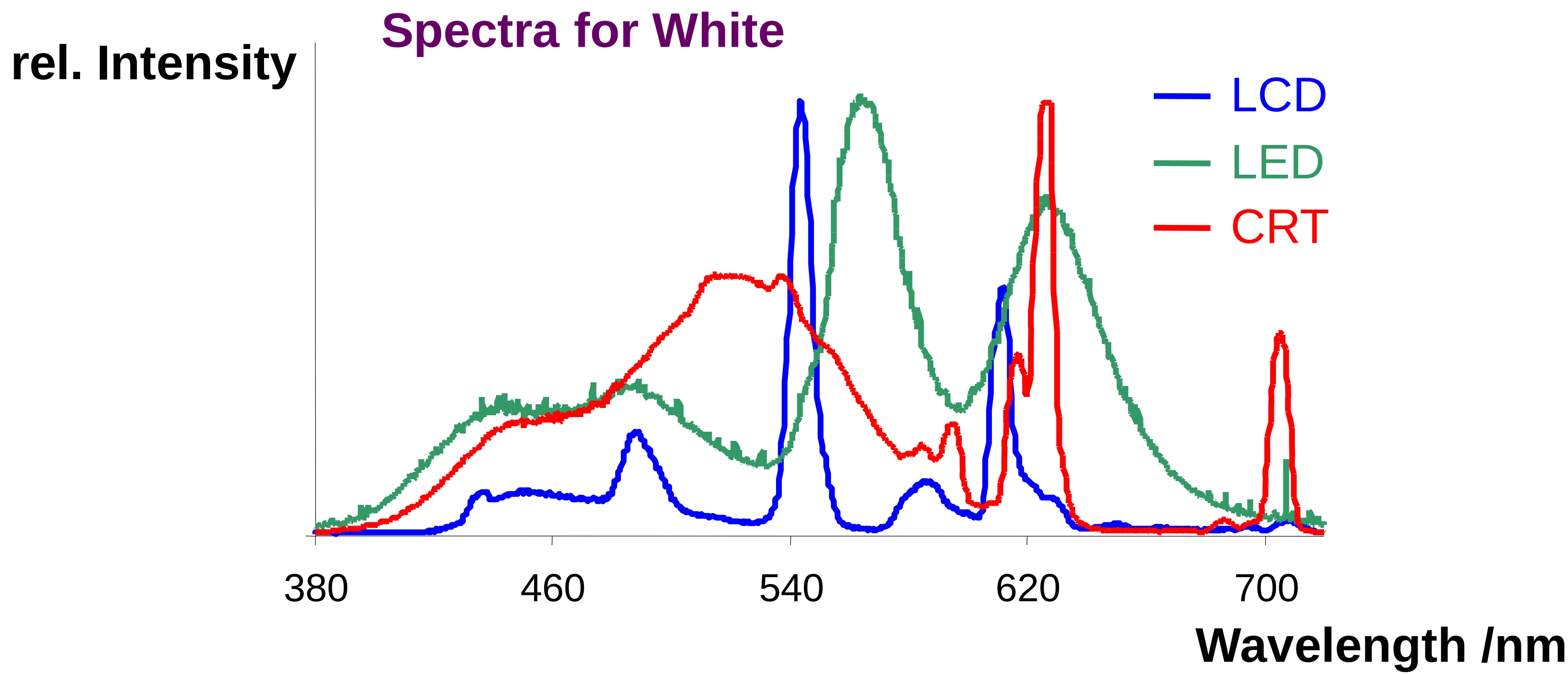
Emission of white leaf from display



Both spectra result in the same color impression !

(if calibrated devices were used)

Spectra of Different Display Technologies



→ Vision recognizes all the displays in white color

- Color systems for measurement and comparison are therefore necessary!
- Measurements and calculations via Color Matching Functions and Tristimulus values X, Y, Z (see below)

Color Measurements

- Human vision is only descriptive
- Color impression depends on illuminance
- Different spectra can produce the same color (impression)

- **Color measurements for displays are necessary for**
  - Color space calculations
  - Color gamut, white point
  - Color Management
  - Viewing angle effects mainly of LCDs
  - Color coding for Human Machine Interface (HMI, MMI)
  - Influence of illumination

see specs

- **Color measurements devices**

Same principles as for luminance but 3 sensors (one for luminance) or spectrometer (measures intensity for each wavelength)

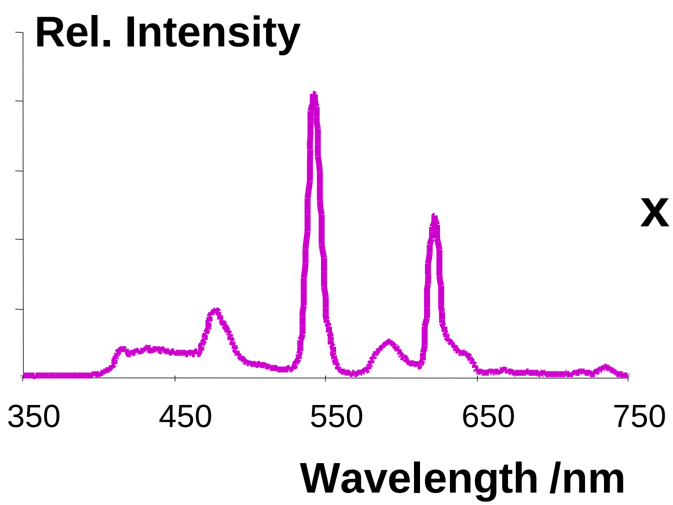
Most Wide-spread Color Spaces

- Displays : CIE xxxx : Commission Internationale d'Éclairage
  xxxx : year of standardization
- Software : RGB (red, green, blue)
- Printing : Munsell, Natural Color System (NCS),
  Hue Saturation Lightness (HSL, also in software), ...

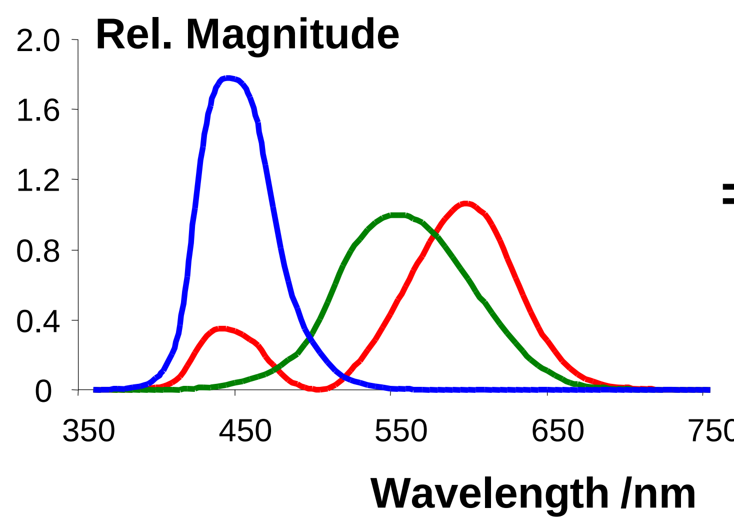
Measurement and Calculations of Color Co-Ordinates

Example for emissive display and measurement of spectrum:

The spectrum is captured and the intensity of each wavelength is multiplied with the Color Matching Functions (CMF, weighting function of human eye, often 2° values) and summarized. This results in Tristimulus values which are the basis of all (CIE) color spaces and calculations.



x



= X Y Z (from measurement device)

Spectrum x **‚Eye'** = **Tristimulus**

(Color Matching Functions) (math)

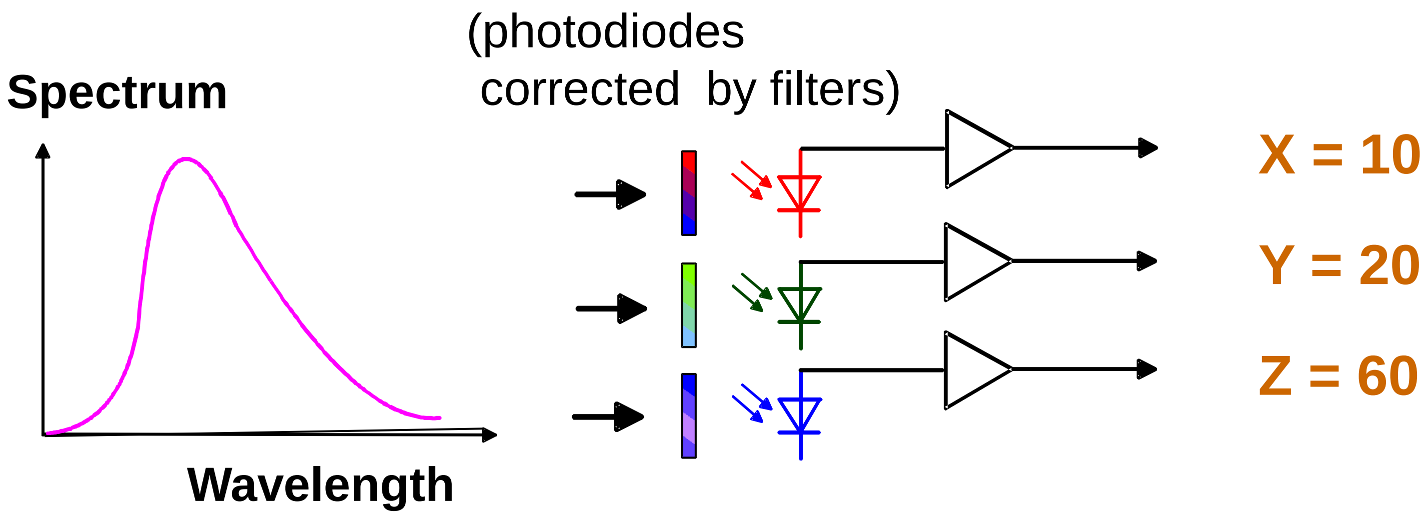
Tristimulus Color Co-Ordinates

- X, Y (= L) and Z are the very basic co-ordinates for all CIE color spaces
- X, Y, Z are then transformed to 2D color spaces like CIE 1931
- Tristimulus values are the only color space where calculations (addition, matrix, …) can be made!
- Example: Mixing of two light sources 1 and 2
  - $X_M = X_1 + X_2$
  - $Y_M = Y_1 + Y_2$
  - $Z_M = Z_1 + Z_2$

  The “mixed” co-ordinates can then be transformed to other CIE spaces
- **Examples:**
  - White point adjustment
  - Ambient light color wash out

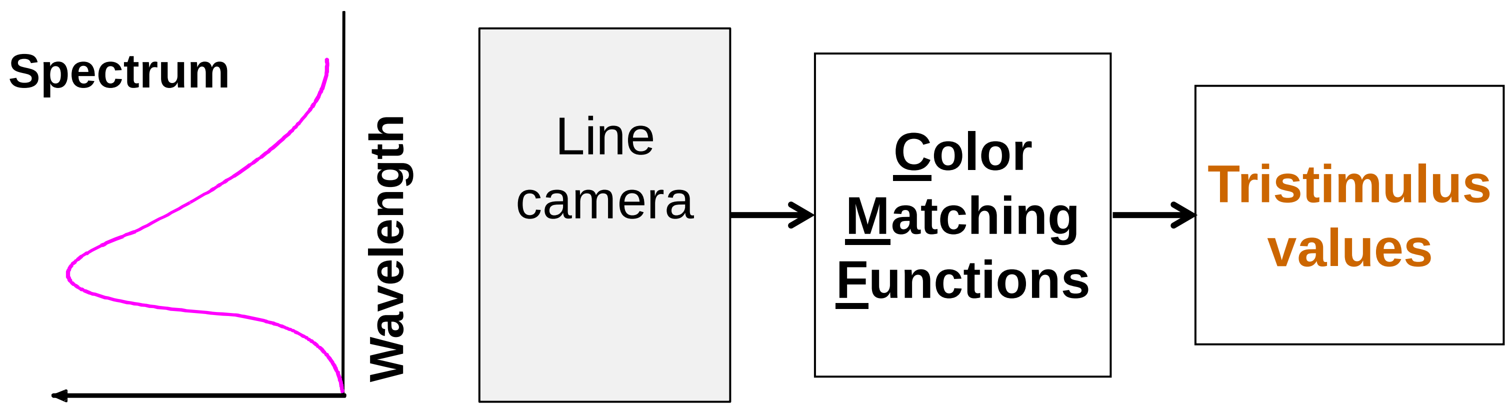
Principle of Colorimeters and Spectrometers

Colorimeter



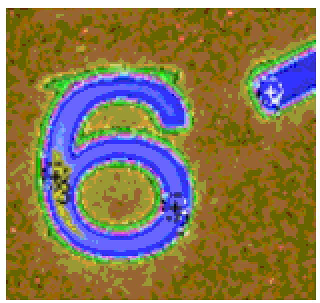
Spectrum x Color Matching Functions = Tristimulus values

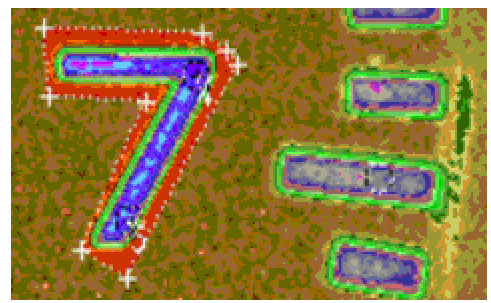
Spectrometer



Area Color Measurements with Special Camera

- Camera detector with special filters (like colorimeter) can measure luminance and colour in a short time
- Used for uniformity measurements of pixels or clusters etc.
- Limited accuracy compared to other devices





Spotmeters:

Object	pos	radius	Avg	StdDev	Min	Max	pixels	x	y	z	Ldom	pur
units:	[pixel]	[pixel]	[cd/m²]	[cd/m²]	[cd/m²]	[cd/m²]	[#]	[1]	[1]	[1]	[nm]	[1]
cursor spot;	(1166,676);	5;	1,982;	0,05617;	1,808;	2,081;	83;	0,6488;	0,3183;	0,0328;	616,2;	0,901
spotmeter #1;	(1084,396);	5;	6,825;	0,8274;	2,866;	7,361;	83;	0,3301;	0,3319;	0,3379;	486,1;	0,011
spotmeter #2;	(1045,441);	5;	7,925;	1,306;	2,924;	8,951;	83;	0,3279;	0,3226;	0,3493;	432,6;	0,032
spotmeter #3;	(996,429);	5;	9,142;	2,309;	2,223;	10,51;	83;	0,3313;	0,3314;	0,3372;	478,1;	0,008
spotmeter #4;	(1098,640);	5;	2,070;	0,2466;	1,090;	2,276;	83;	0,6448;	0,3208;	0,0342;	615,1;	0,897
spotmeter #5;	(1073,691);	5;	1,667;	0,7365;	0,07480;	2,364;	83;	0,6450;	0,3190;	0,0359;	616,0;	0,892

Color Space CIE 1931

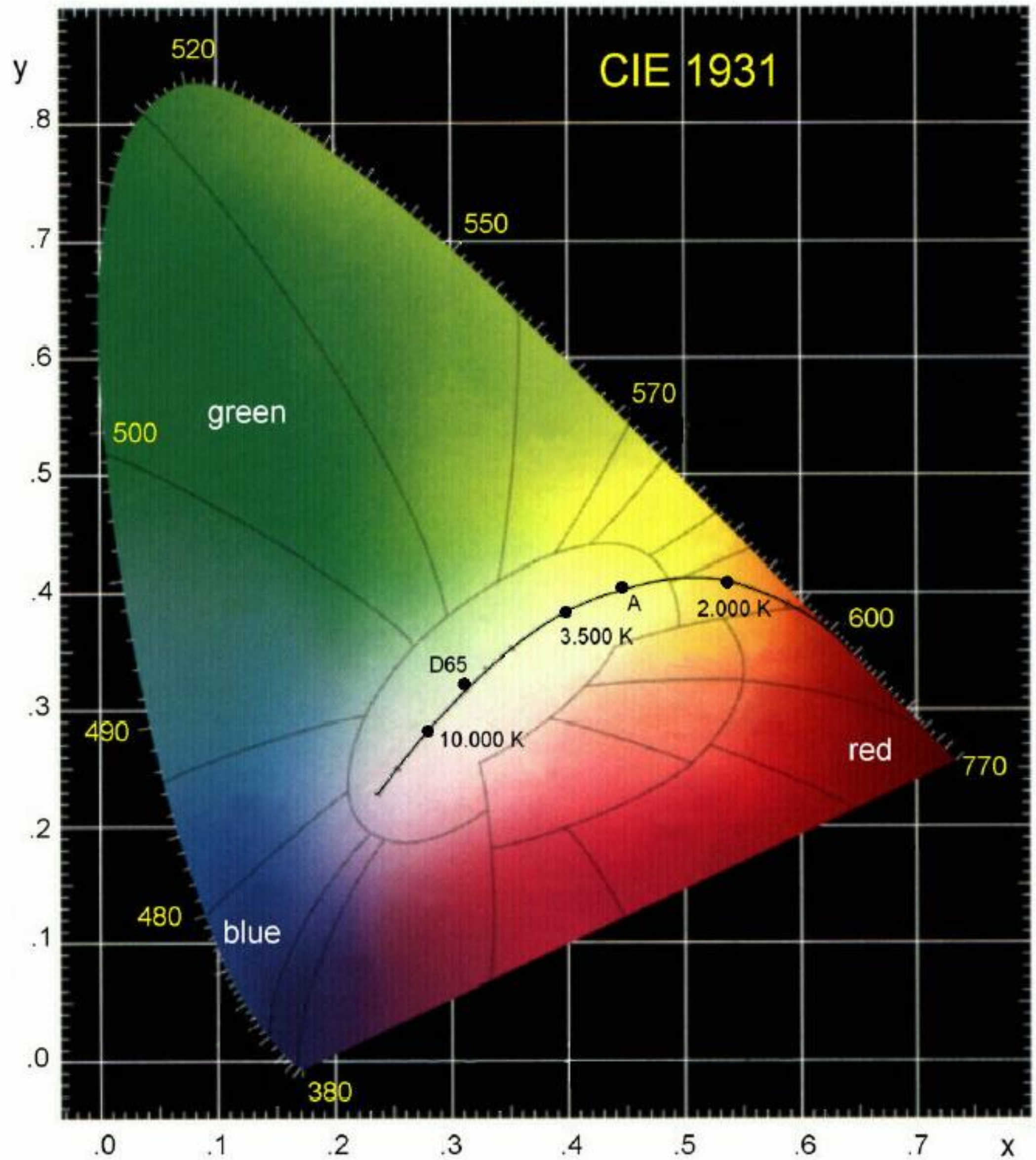
- Oldest CIE standard
- Still in use today
- Full screen test patterns

- Problem: Co-ordinate differences ≠ color differences (Mac Adam)
- Linear transformation of Tristimulus values, L = Y

$$x = \frac{X}{X+Y+Z} \; ; \; y = \frac{Y}{X+Y+Z}$$

RI Color Calculator

3. co-ordinate : Luminance L = Y



LCD CIE 1931 Specification

Ta=25℃

Item	Unit	Conditions	Min.	Typ.	Max.
Color / Chromaticity Coordinates (CIE 1931)		White x	0.26	0.31	0.36
		White y	0.27	0.32	0.37
		Red x	0.56	0.60	0.64
		Red y	0.31	0.35	0.39
		Green x	0.31	0.35	0.39
		Green y	0.53	0.57	0.61
		Blue x	0.11	0.15	0.19
		Blue y	0.08	0.12	0.16
Color Gamut	%		-	50	-

Plot these tolerances in CIE 1931 with △x and △y = 0.1 !

Color Space CIE 1931

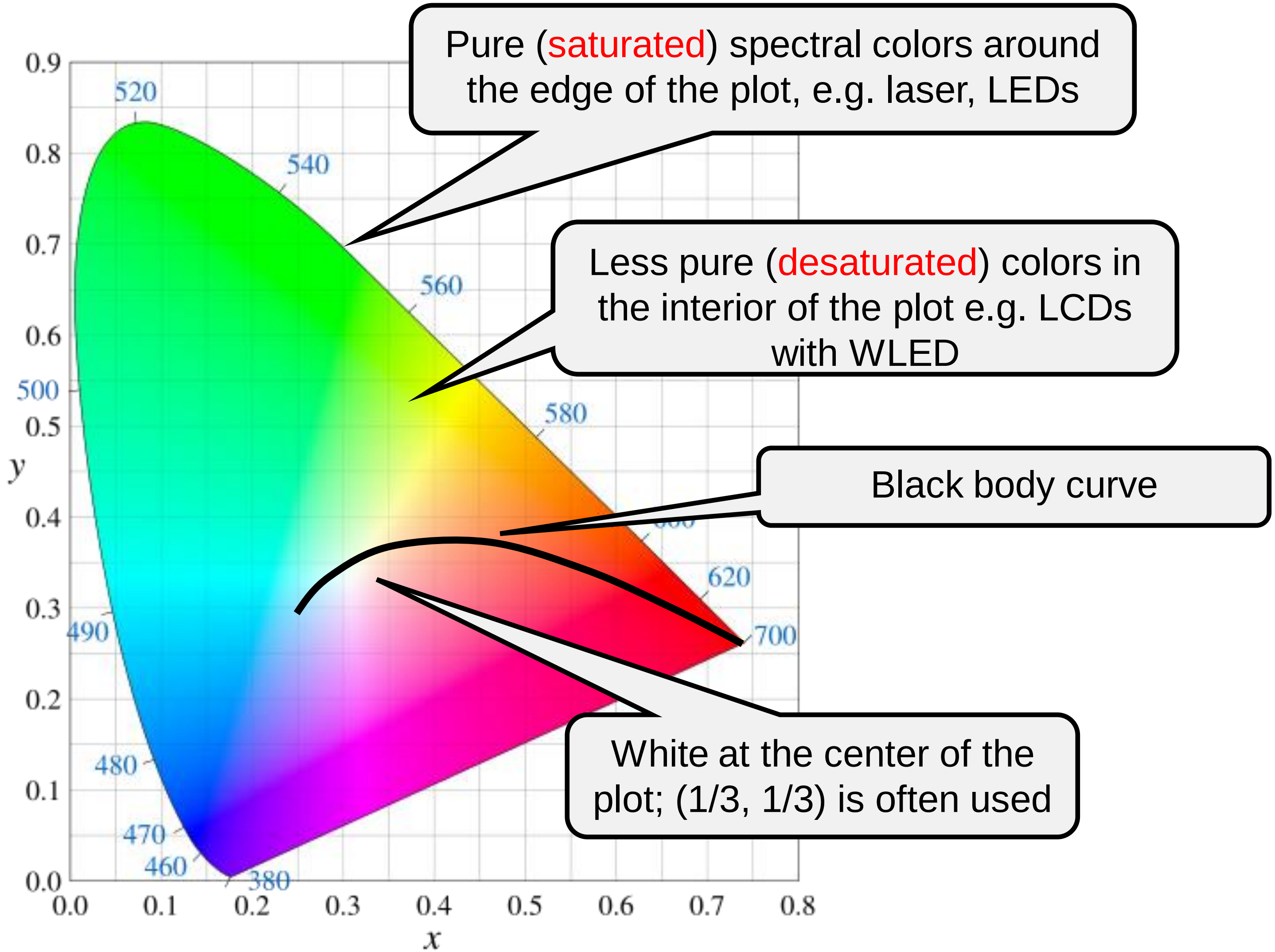


Image from www.wikipedia.com

Correlated Colour Temperature

- Description of white point

- Formula

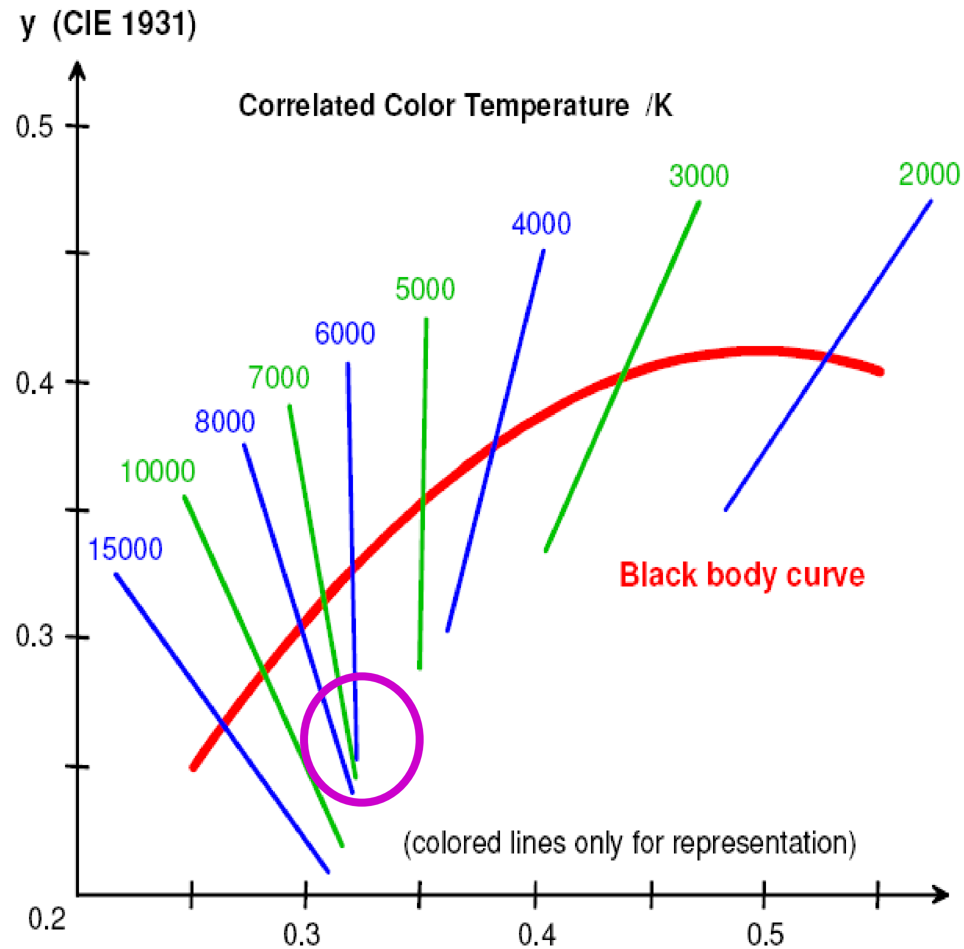
$$T_C = 437\, n^3 + 3601\, n^2 + 6831\, n + 5517$$

where - $n = \dfrac{x_n - 0.3320}{0.1858 - y_n}$

- x_n, y_n : colour co-ordinate of white

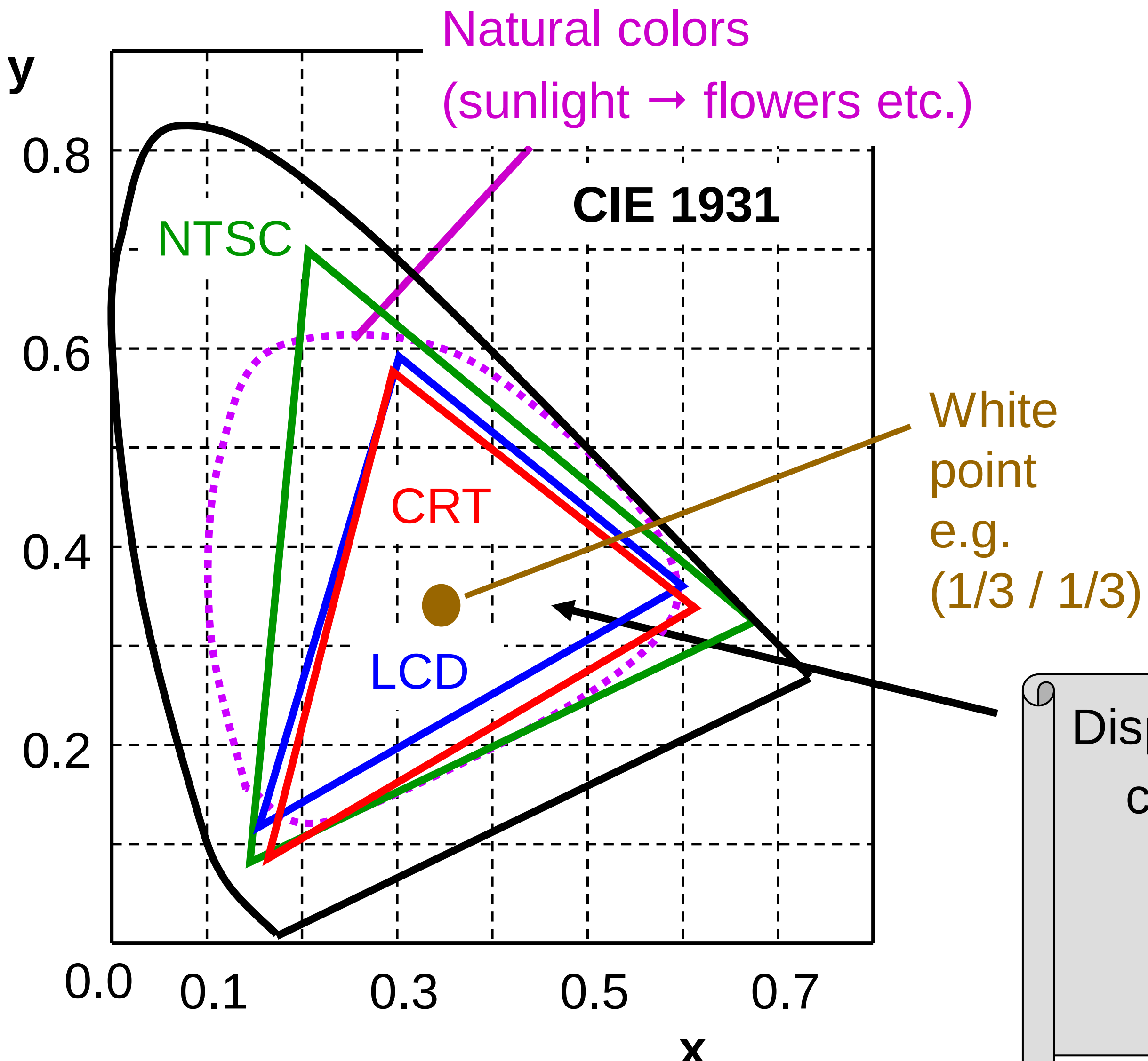
- Formula is good for 2,000 … 10,000 K

- Example x = y = 1/3 → : $T_C \approx 5487$ K



CCT can overlap in color co-ordinates !

Color Gamut

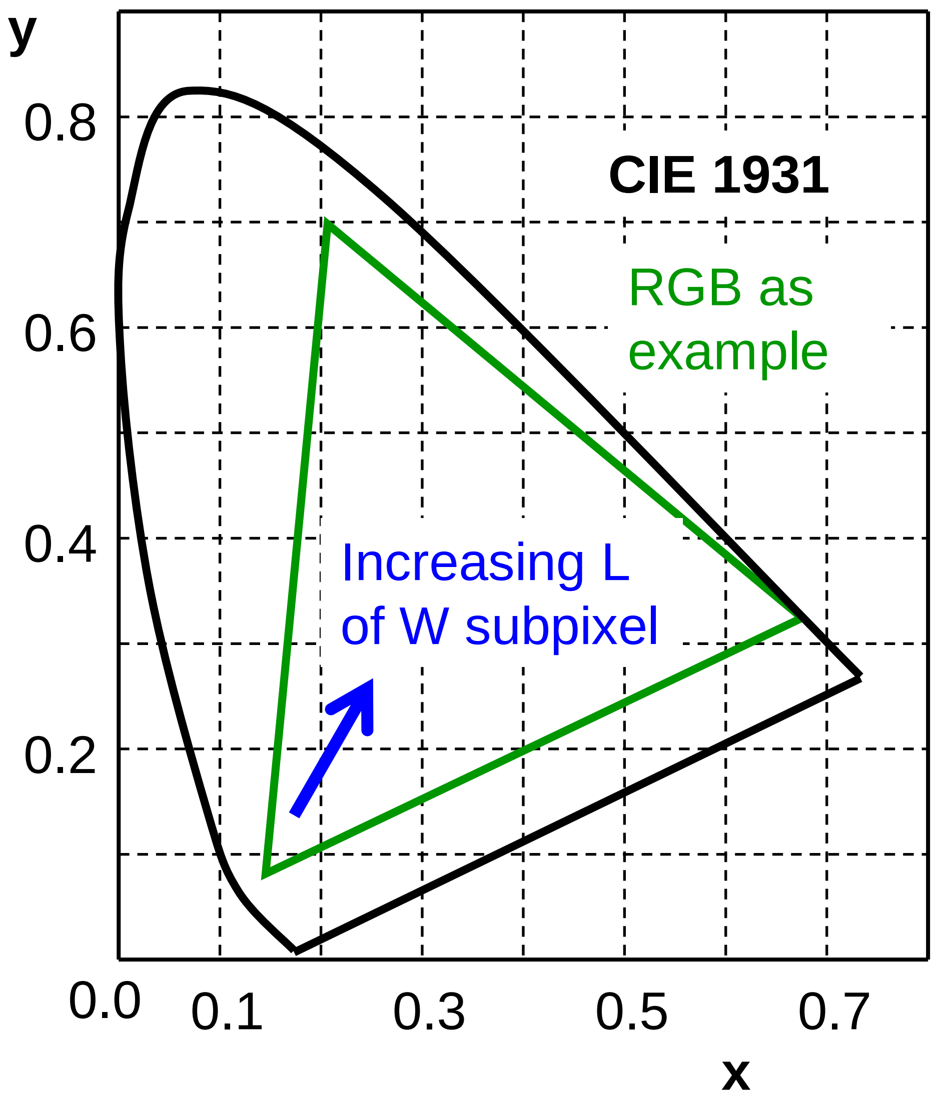


Remarks:

- Color management: Same co-ordinates throughout the system
- Gamut calculation see formula of CIE 1976 UCS

Display can only reproduce colors within the RGB triangle (gamut) by variations of RGB grey levels.

Color Gamut for RGBW



RGBW has 4 subpixels:

- W subpixel is highly transparent enhancing white luminance
- Advantage: Higher L and efficiency
- Issue: W lowers gamut

White Point Adjustment

- Color coordinates of "White point" can differ even within the same display lot.

- If these displays or different display types have to be mounted next to each other, the white point has to be adjusted to the reference value.

- White point is set by RGB color coordinates x, y and their luminance L_{RGB}

- Calculation only in Tristimulus space:

$X_W = X_R + X_G + X_B$; $L_W = Y_W = Y_R + Y_G + Y_B$; $Z_W = Z_R + Z_G + Z_B$

Tristimulus from CIE 1931: Y = L , $X = \frac{Y}{y}x$, $Z = \frac{Y}{y}(1-x-y)$

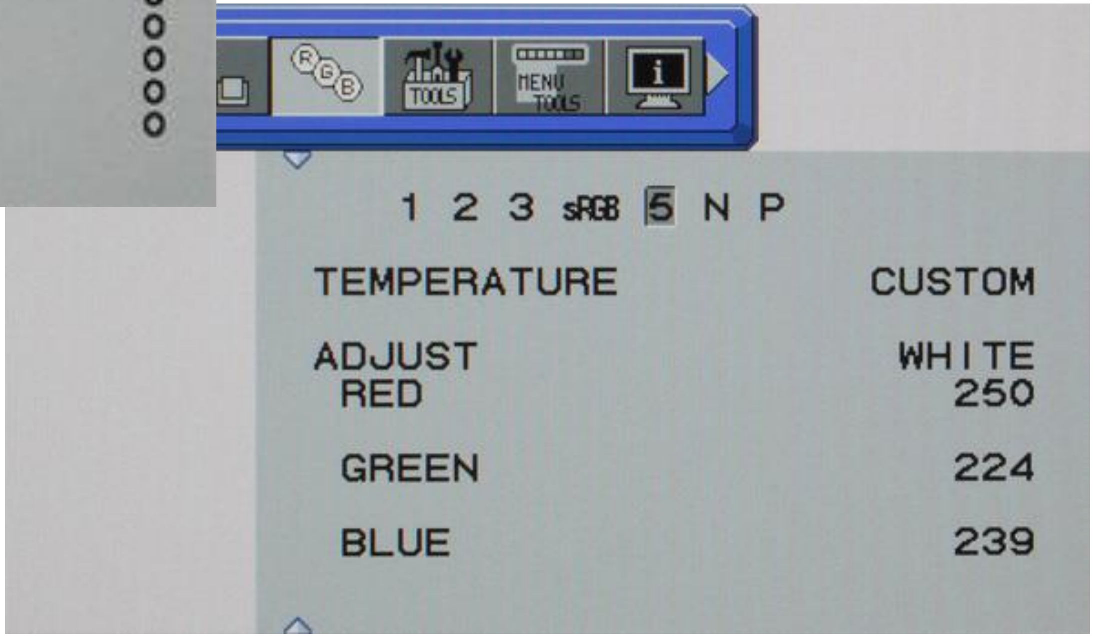
- Color coordinates are "fix" only RGB luminance can be adjusted. This is often done within the Timing Controller of the display as "offset"; other possibility by remapping of grey levels e.g. G 0 … 255 → G 0 … 200 if white has is somewhat greenish.

White Point Adjustment

Examples:

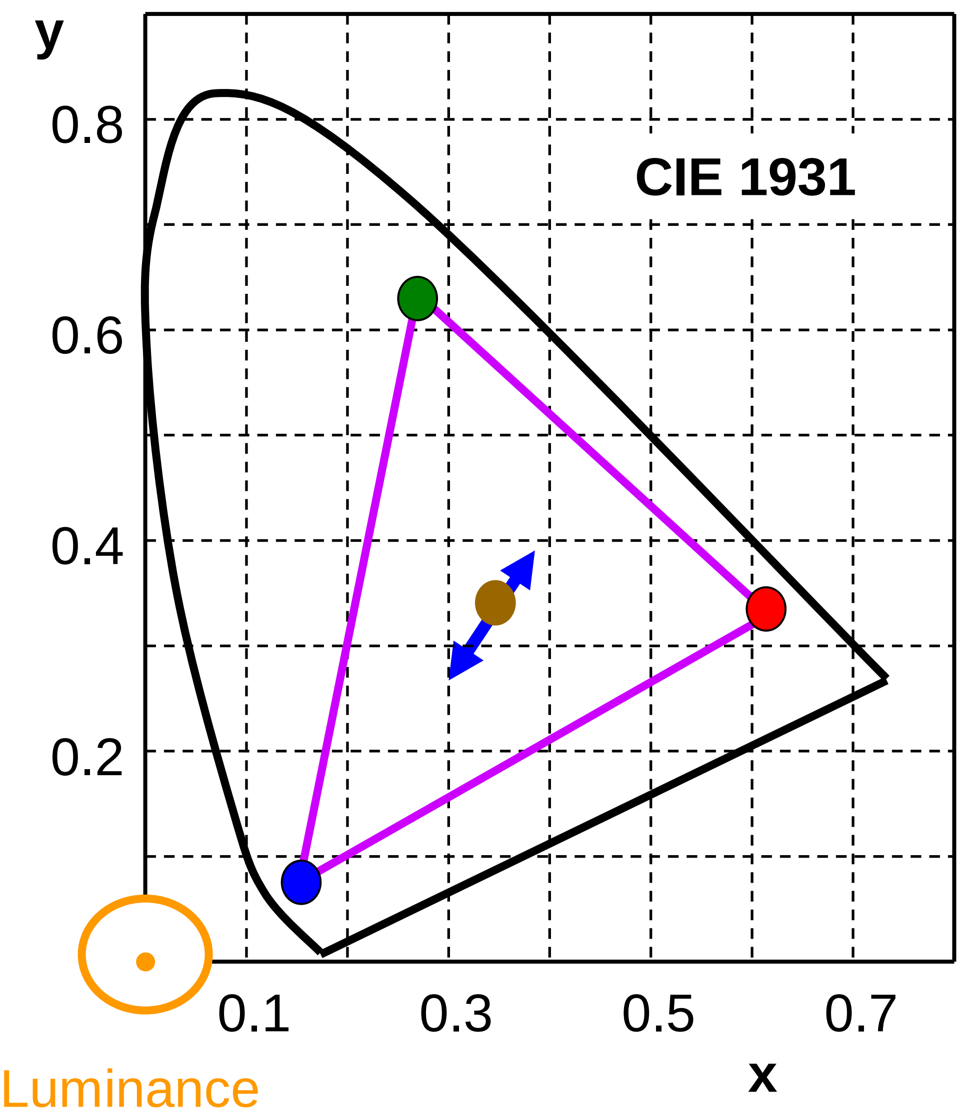
White point via CCT
(here 6500 K)

White point via RGB



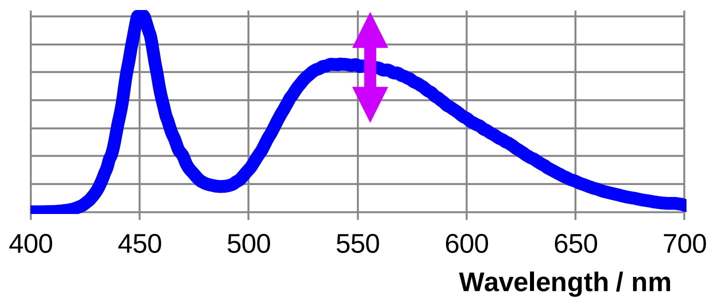
White Point Fundamentals

- Typical luminance relationship for white:
  $R \approx 0.3\ L_W$
  $G \approx 0.6\ L_W$
  $B \approx 0.1 L_W$
- If one primary is “stronger” or “weaker”, the white point shifts to or from the original locus. Example in chart for blue
- Luminance is the third coordinate of CIE 1931 and mostly never plotted (direction to viewer).



Example: White LED

- White LED consists of a blue LED and a yellow conversion phosphor (some have RG phosphors)

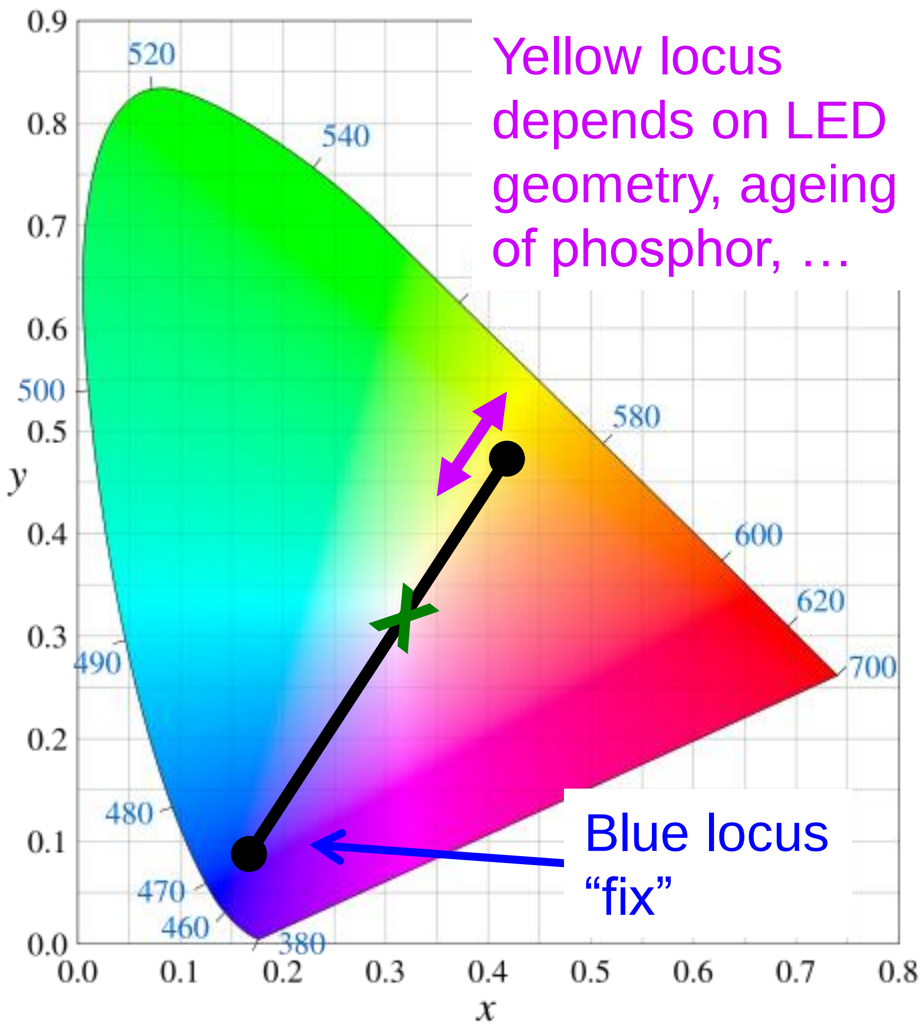


- Some blue light is converted to yellow → Tristimulus color mixing
- Calculation in Tristimulus space:

$X_W = X_B + X_Y$; $L_W = Y_W = Y_B + Y_Y$;

$Z_W = Z_B + Z_Y$ → CIE 1931 x_W , y_W

Image from www.wikipedia.com

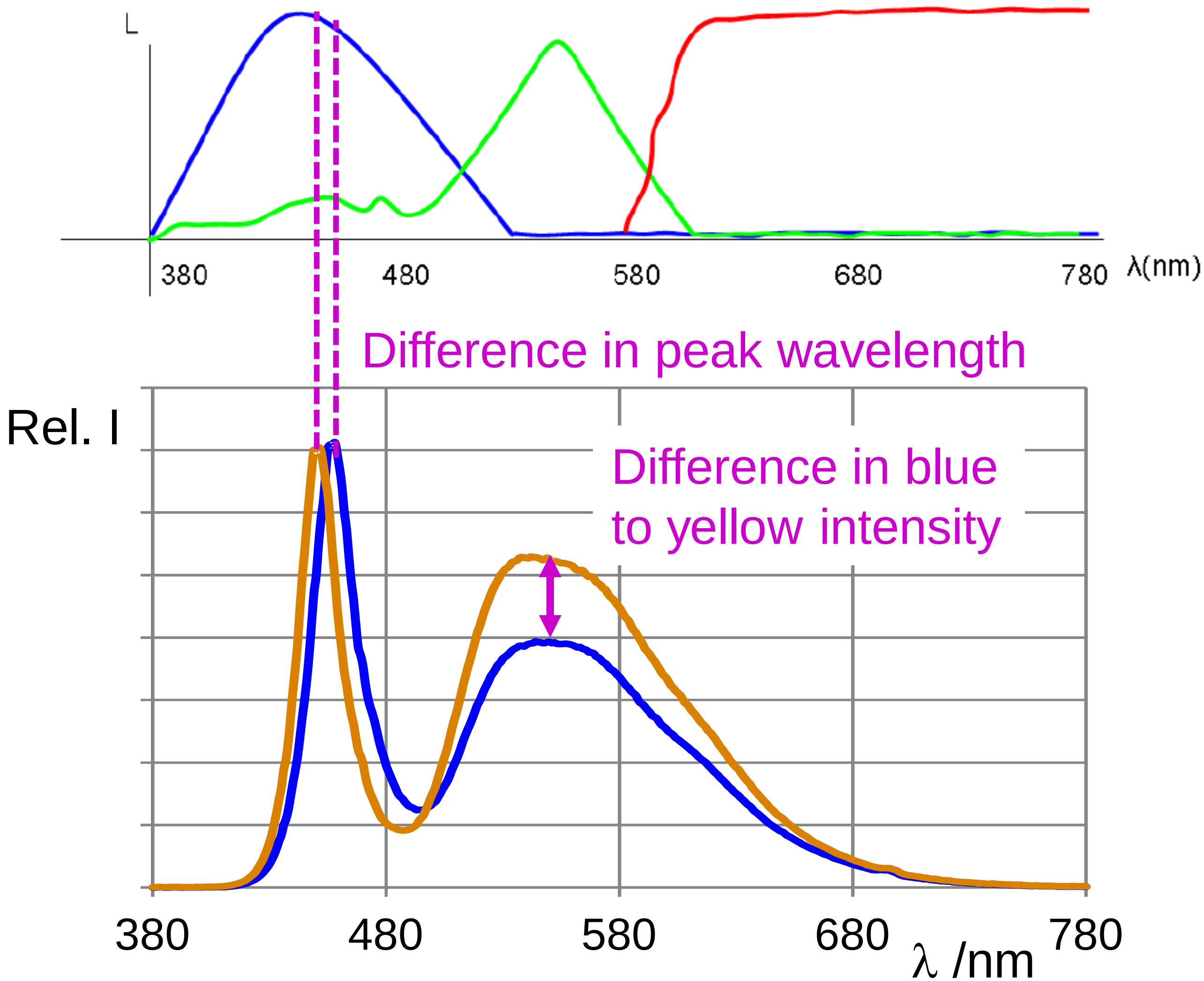


- Intensity ratio of blue to yellow set white point on line

White Point Shift for LCDs with White LED Backlights

… due to variations in color filter and LED

- **LCD filter**
- **Spectra of white LEDs**



Color Differences in CIE 1931

- Blue : high sensitivity

  for small Δx and Δy

- Green : medium sensitivity

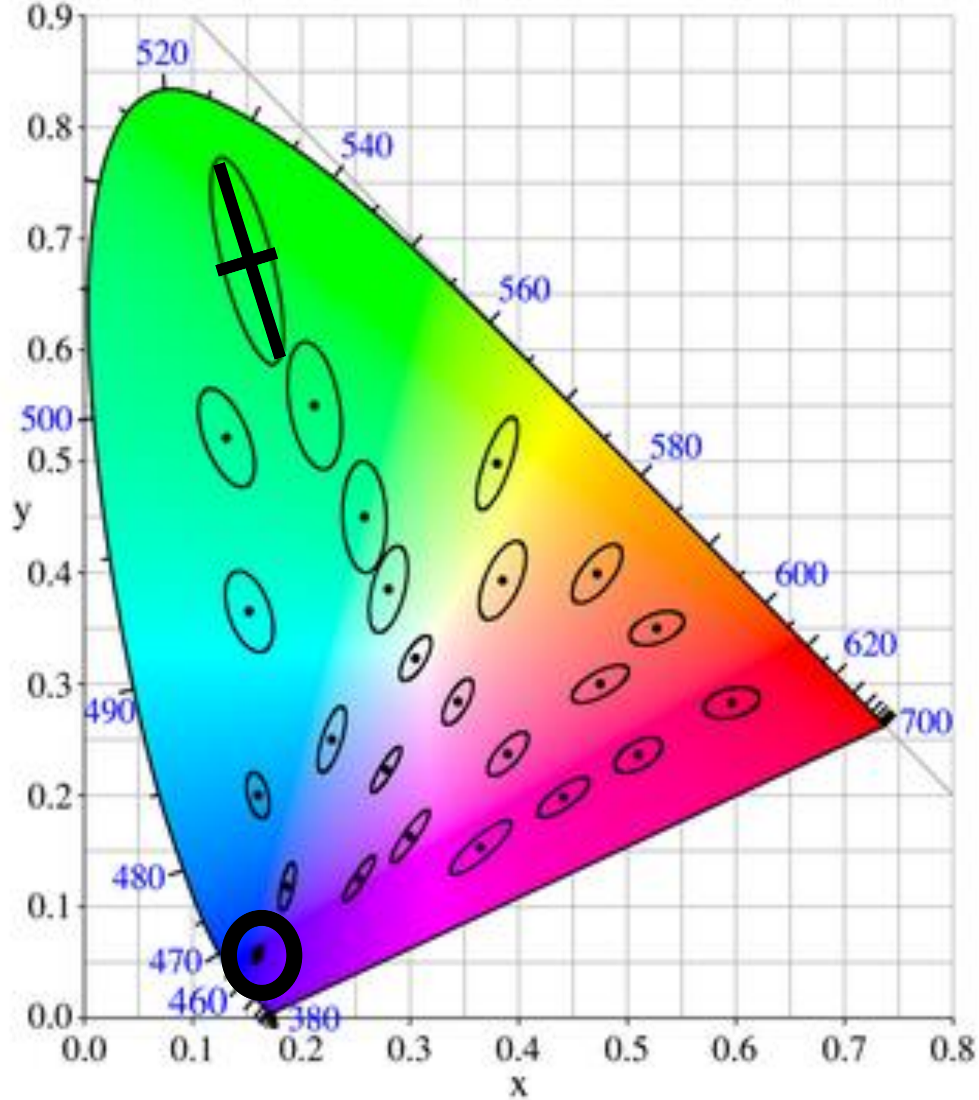
  for Δx and lowest for Δy

  → ‚lack of gamut' for green

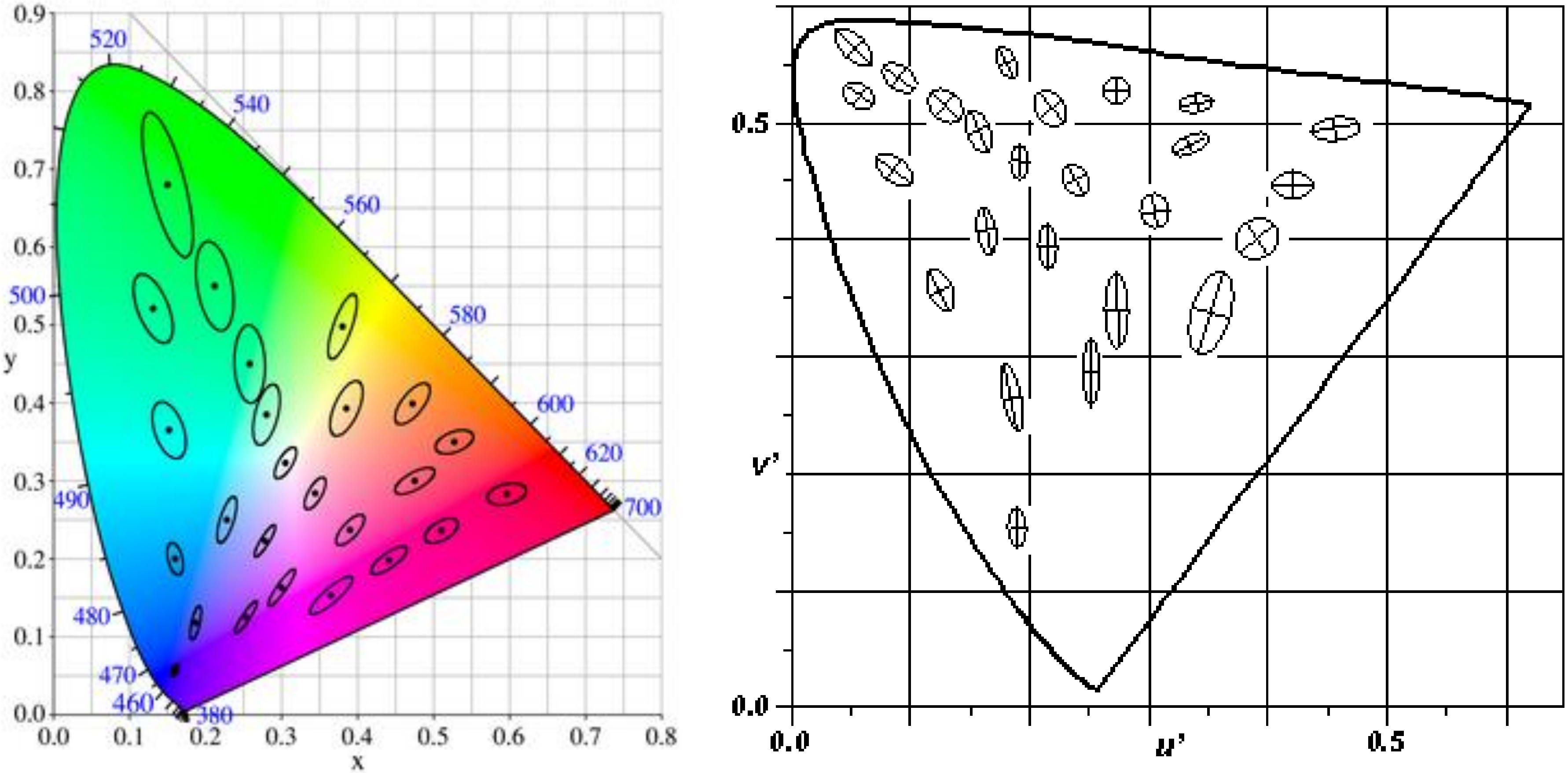
  mostly not recognizable

- CIE 1931 shouldn't be used but is mentioned in nearly all display specs

- New measurements : CIE 1976 !



Color Spaces CIE 1931 vs. 1976



The 10x Mac Adams JNDs of CIE 1931 are transformed to CIE 1976 UCS.

It is clearly visible that the ellipse for green shrinks while the blue one is significantly enlarged and therefore better to capture by vision

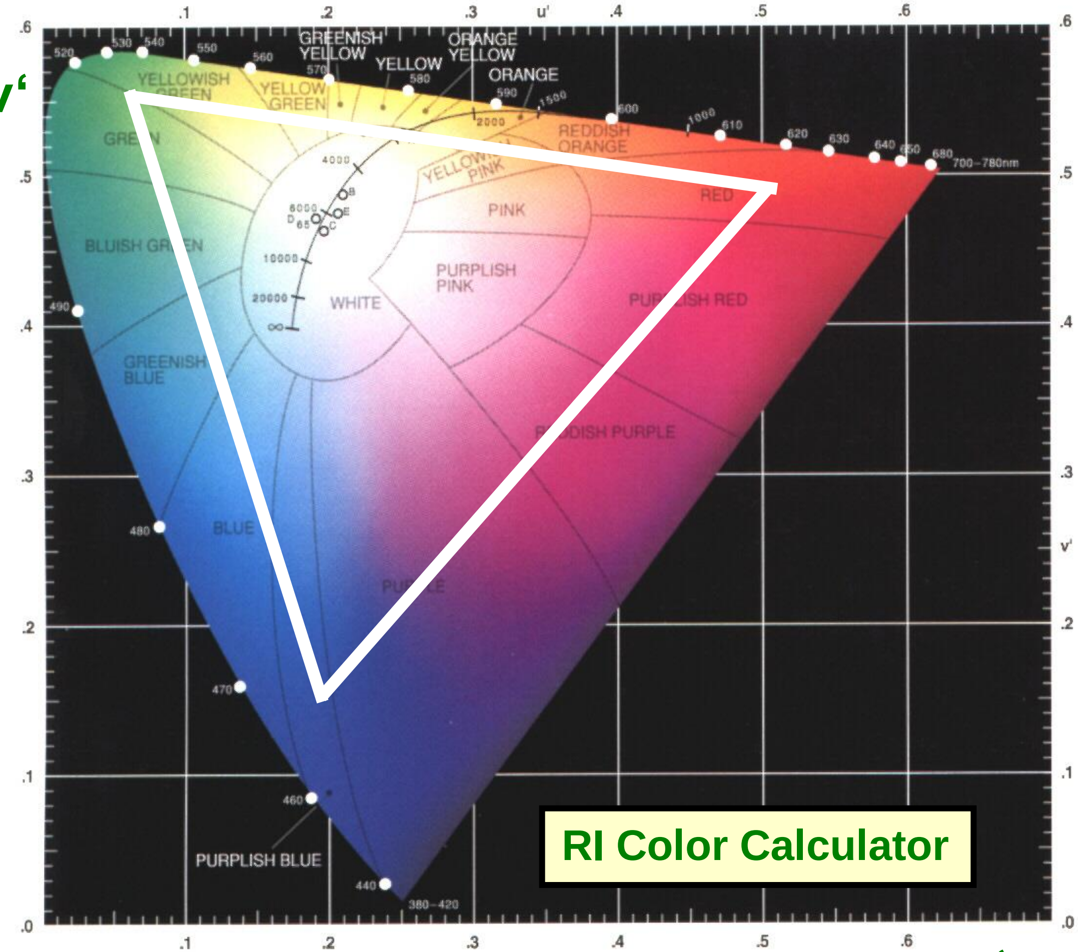
Color Space CIE 1976 UCS

3. co-ordinate : Luminance L = Y

- CIE 1976 UCS recommended for metrology !
- “Characterisitcs similar to CIE 1931, e.g. black body
- Co-ordinate differences ≈ colour differences
- Linear transformation

$$u' = \frac{4X}{X+15Y+3Z} = \frac{4x}{-2x+12y+3}$$

$$v' = \frac{9Y}{X+15Y+3Z} = \frac{9y}{-2x+12y+3}$$



- Gamut (100% usually refers to NTSC)

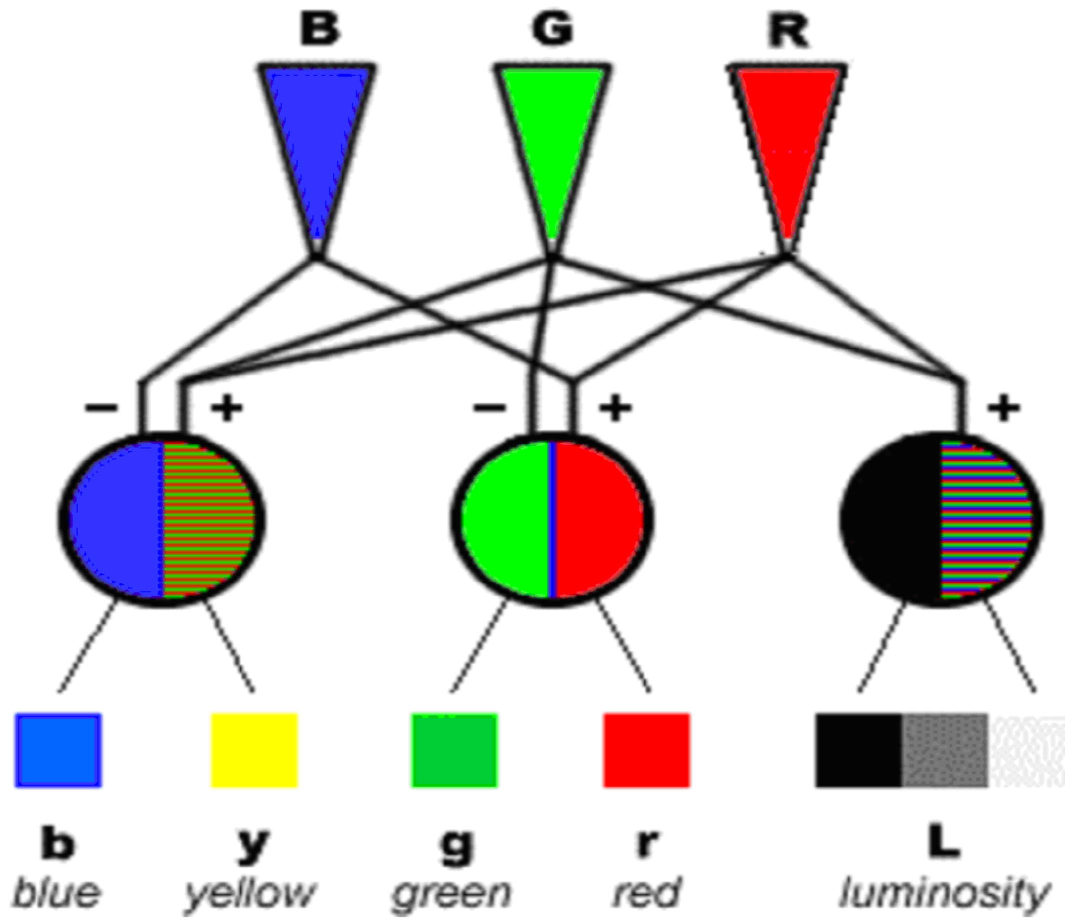
$$A = 256.1\ \left[(u'_R - u'_B)(v'_G - v'_B) - (u'_G - u'_B)(v'_R - v'_B)\right]$$

CIE 1976 LAB, LUV

Approach

Approximation of human ‚signal processing‘, which distinguish mainly :

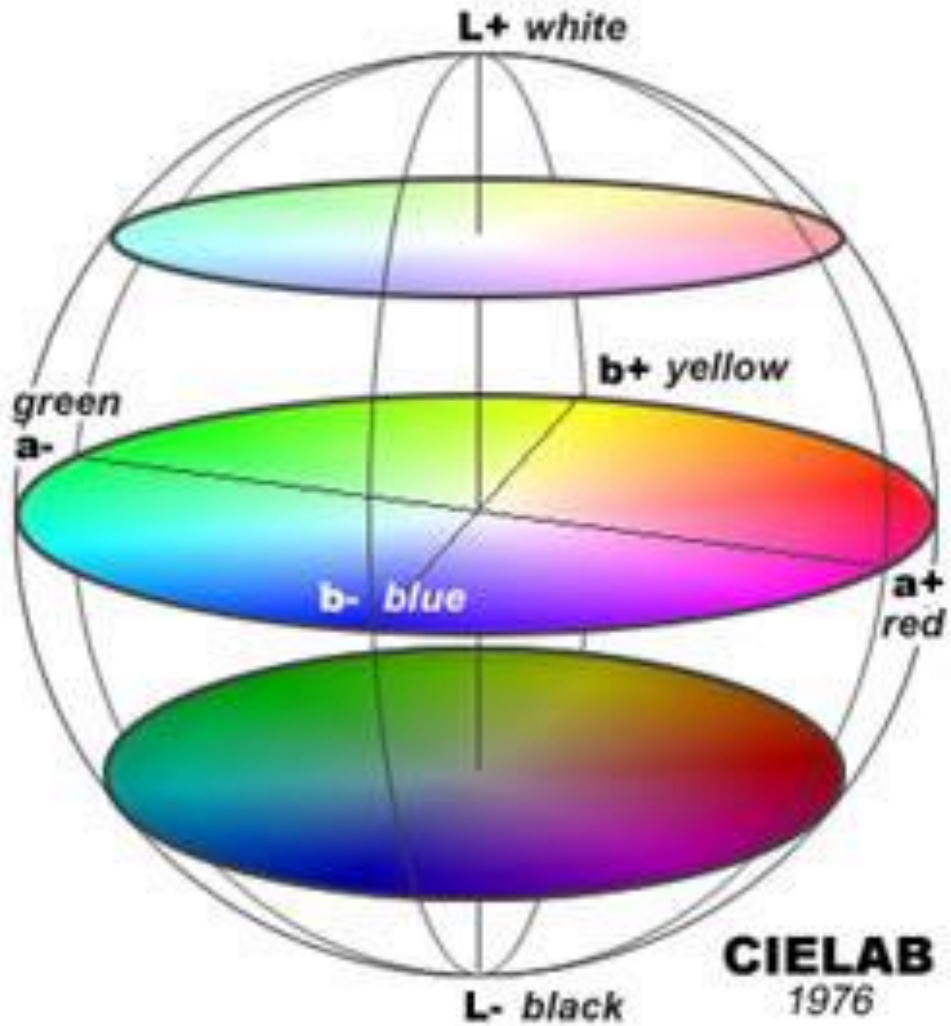
- bright - dark (L)
- red - green (g – r)
- blue - yellow (b – y)



Merits : - Brightness adapted to vision
- Color differences (ΔE) can be calculated !

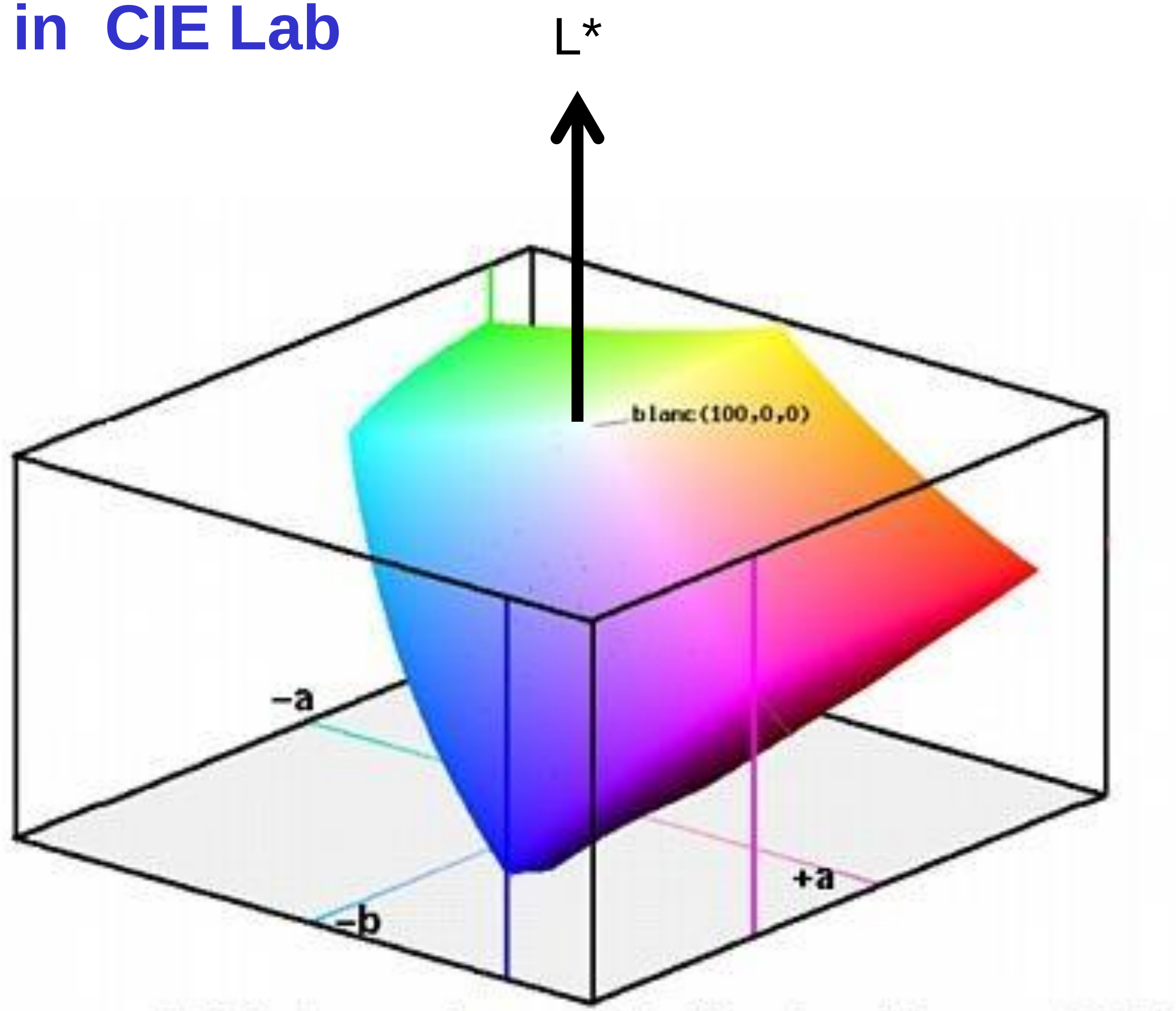
CIE 1976 Lab for Reflective Displays and Printers

- Sphere-like representation
- Color gamut only in 3D
- L* is not luminance and therefore not a direct measurement parameter



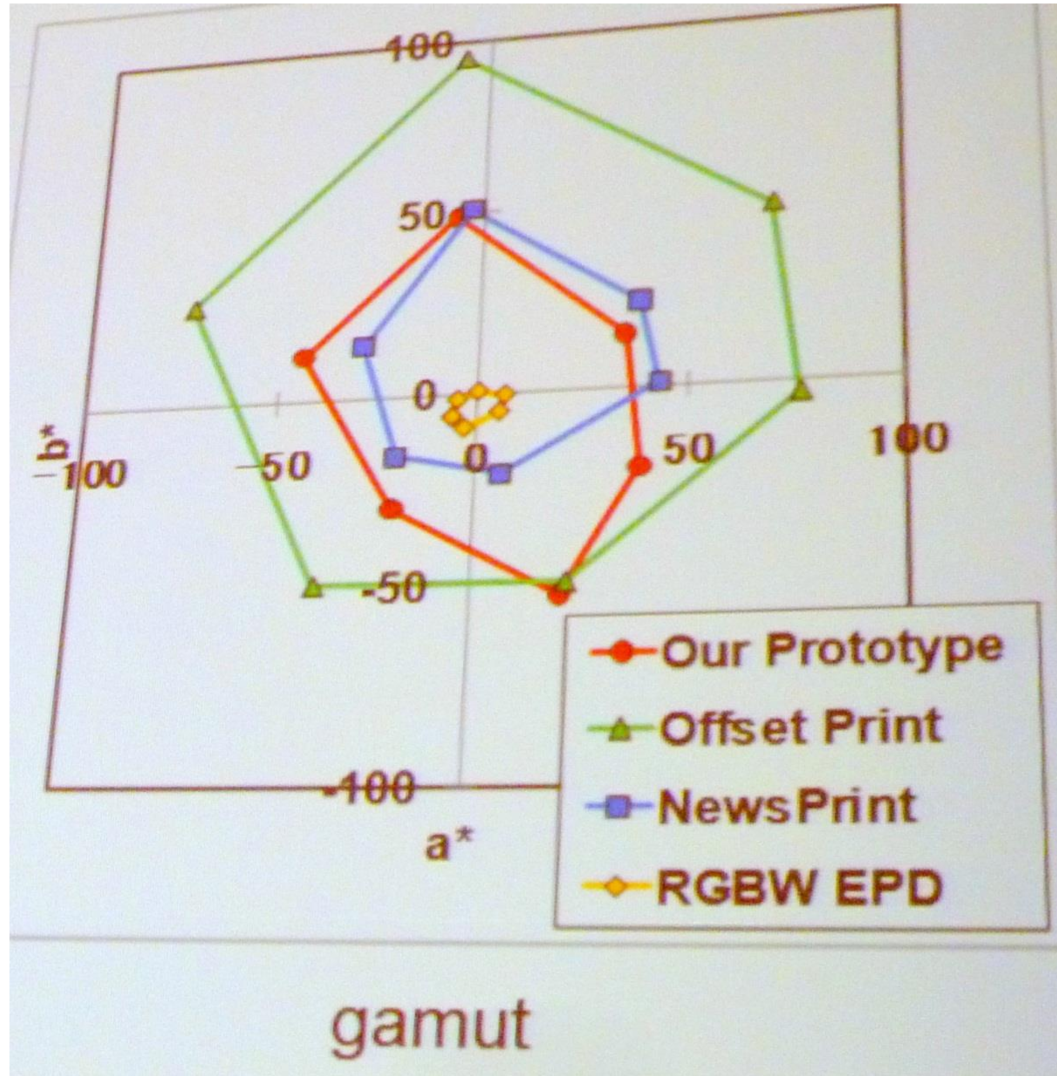
Color Gamut of LCD in CIE Lab

- Color gamut in 3D
- Difficult to interpret and to compare
- Often 2D plots for certain L* are used



Color Gamut of LCD in CIE Lab

- Color gamut in 3D
  for L* = 0
- Color gamut for
  reflective E-INK
  (EPD) too low,
  see photo:



CIE 1976 Lab / Luv

Non-linear transformation

CIE Lab (reflective displays, printer)

$$L^* = 116 \cdot \left[f(Y, Y_n) - \frac{16}{116} \right]$$

$$a^* = 500 \cdot \left[f(X, X_n) - f(Y, Y_n) \right]$$

$$b^* = 200 \cdot \left[f(Y, Y_n) - f(Z, Z_n) \right]$$

$$\text{with } \frac{Y}{Y_n} \begin{cases} > 0.008856: & f(Y, Y_n) = \left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} \\ \leq 0.008856: & f(Y, Y_n) = 7.787\left(\frac{Y}{Y_n}\right) + \frac{16}{116} \end{cases}$$

$f(X, X_n)$ and $f(Z, Z_n)$ acc.

Color difference:

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

'n' refers to white point

CIE Luv (emissive displays)

$$L^* = 116 \cdot \left[\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - \frac{16}{116} \right]$$

$$u^* = 13\, L^* \cdot (u' - u'_n)$$

$$v^* = 13\, L^* \cdot (v' - v'_n)$$

u', v': 1976 CIE UCS

Color difference:

$$\Delta E^*_{uv} = \sqrt{\underbrace{(\Delta L^*)^2}_{\text{Luminance}} + \underbrace{(\Delta u^*)^2 + (\Delta v^*)^2}_{\text{Color}}}$$

Merit of CIE Lab & CIE Luv:

Color difference formula $\triangle E$

Characters and Color

ISO 15008 for automotive infotainment, also used for public displays

4.4 Colour

4.4.1 Colour combinations

When a symbol and its background are of different colours, minimum luminance contrast (see 4.3.1) shall be provided. For physiological and psychological reasons, not all symbol/background colour combinations are acceptable. Because of this, when selecting colours in full multicolour displays, symbol/background colour combinations should be chosen in accordance with Table 1.

Table 1 — Symbol/background colour combinations

Background colour	Symbol colour						
	White	Yellow	Orange	Red[a], Purple	Green, Cyan	Blue[a], Violet	Black
White		–	o	+	+	++	++
Yellow	–		–	o	o	+	++
Orange	o	–		–	–	o	+
Red[a], Purple	+	o	–		–	–	+
Green, Cyan	+	o	–	–		–	+
Blue[a], Violet	++	+	o	–	–		–
Black	++	++	+	+	+	–	

++ Preferred

\+ Recommended

o Acceptable with high saturation differences

– Not recommended

[a] Pure red and blue should be avoided because the eyes may have trouble focusing on these colours because of eye chromatic aberration.

4.4.2 Colour discriminability

For minimum colour discriminability, there shall be a minimum colour difference of $\Delta E_{UV} = 20$, in accordance with the ΔE_{UV} colour difference metric defined in the CIE 1976 colour space model CIELUV (See CIE 15.2:1986). Reference white is the white produced by the display. The measurement shall be taken using a colour meter with a FOV of 20′ with the same geometry used for the luminance contrast measurement, and shall be performed for all colours intended to be used for colour coding, both in night and day conditions. All relevant pairs of colours shall be evaluated using this ΔE_{UV} colour difference metric. Reference white is the white produced by the display in each condition.

Color Differences acc. CIE 1976 Lab / Luv

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \qquad \Delta E^*_{uv} = \sqrt{\underbrace{(\Delta L^*)^2}_{\text{Lightness}} + \underbrace{(\Delta u^*)^2 + (\Delta v^*)^2}_{\text{Color}}}$$

- ΔE : Difference of two color co-ordinates incl. lightness
- Δ E = 1 : Just Notable Difference, minimum difference to distinguish two ‚colors' (lightness and/or color co-ordinates)
- Δ E = 5 : Difference which is recognized by nearly everybody. This value is regarded practically as maximum tolerable difference

Example : Black - yellow ($\Delta L \neq 0$ und $\Delta C \neq 0$) can generate a larger ‚color contrast' as black – white ($\Delta L \neq 0$, $\Delta C = 0$ because of same co-ordinate) $\rightarrow$ better readability for yellow on black (next slide)

Color Differences acc. CIE 1976 Lab / Luv

Example : Black - yellow ($\Delta L \neq 0$ <u>und</u> $\Delta C \neq 0$) can generate

a larger ‚color contrast‘ as black – white

($\Delta L \neq 0$, $\Delta C = 0$ because of same co-ordinate)

$\rightarrow$ better readability for yellow on black

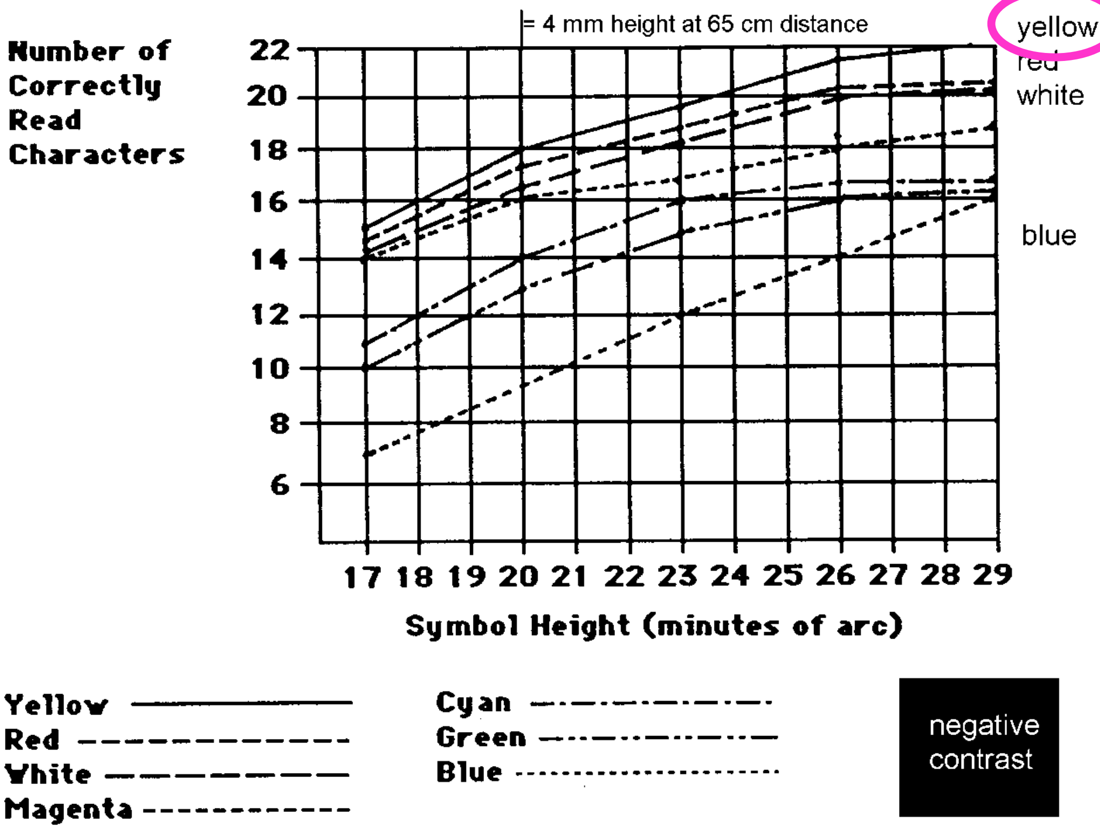
Measured UCS	**L /cd/m²**	**u’**	**v’**
White	100	0.2	0.45
Black	1	0.2	0.45
Yellow	90	0.25	0.53

Calculated CIE Luv	**L***	**u***	**v***
White	100	0	0
Black	9	0	0
Yellow	96	62	100

$\rightarrow \Delta E^*$ (black - white) = 91 ; ΔE^* (black - yellow) = 146 !

Color Differences acc. CIE 1976 Lab / Luv

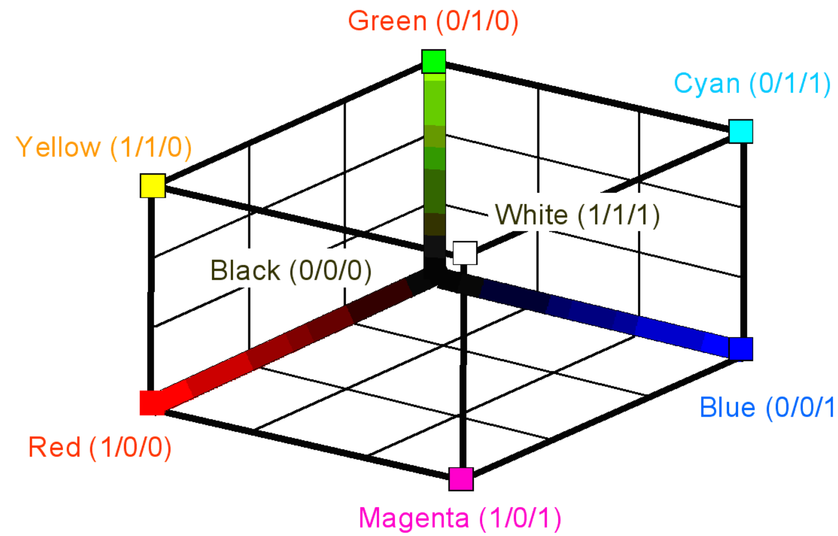
… see ‚Introduction – Ergonomics‘



negative contrast

CIE vs. RGB Colour Space

- Image is captured or designed in RGB
- Display shows this via RGB data on display (printer uses CMY)
- Display is characterized in CIE

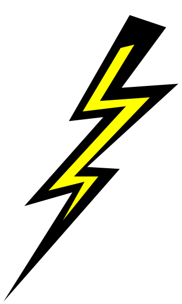


→ Maths CIE ↔ RGB

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{pmatrix} \cdot \begin{pmatrix} R^\gamma \\ G^\gamma \\ B^\gamma \end{pmatrix}$$

Tristimulus values of the primaries

$\gamma = \gamma = \gamma$!



- RGB is a device dependant colour space
- CIE is a absolute colour space
- **RGB should be transformed to CIE via calibration (ICC/ICM files, …)**

⇨ Color shifts
⇨ Color management

Diamond Compatible 9300K G2.2.icm
ADOD6522.ICM

CIE vs. RGB Colour Space

Tristimulus coordinates of RGB of a display, e.g. via “reverse” CIE formula

$$\begin{pmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{pmatrix} = T\text{(abbreviation for Tristimulus matrix)}$$

RGB → CIE

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = T \cdot \begin{pmatrix} R^\gamma \\ G^\gamma \\ B^\gamma \end{pmatrix}$$

Calculate color coordinate for given RGB grey levels and gamma

CIE → RGB

$$\begin{pmatrix} R^\gamma \\ G^\gamma \\ B^\gamma \end{pmatrix} = T^{-1} \cdot \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

Calculate RGB grey levels for given color coordinate and gamma

This is more important:

Task: “The display should show exactly this color coordinate!”

Note: R, G, B are normalized to 1

TV Color Spaces

- **YIQ : NTSC**

$$\begin{pmatrix} Y \\ I \\ Q \end{pmatrix} = \begin{pmatrix} 0.30 & 0.59 & 0.11 \\ 0.60 & -0.28 & -0.32 \\ 0.21 & -0.52 & 0.31 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

- **YUV : PAL, SECAM**

$$\begin{aligned} Y &= 0.30\,R + 0.59\,G + 0.11B \\ U &= 0.493\,(B - Y) \\ V &= 0.877\,(R - Y) \end{aligned}$$

- **YCbCr : ITU-R BT.601, 709 HDTV**

$$\begin{pmatrix} Y \\ Cb \\ Cr \end{pmatrix} = \begin{pmatrix} 0.30 & 0.59 & 0.11 \\ -0.17 & -0.33 & 0.50 \\ 0.50 & -0.42 & -0.08 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

- All parameters are normalized
- $Y \equiv$ Luminance, same formula for all TV color spaces
- Luminance is set by about 30% R, 60%G and 10% B
- IQ, UV, CbCr $\equiv$ Chrominance

Case Study : White Color Adjustment

- **Task**

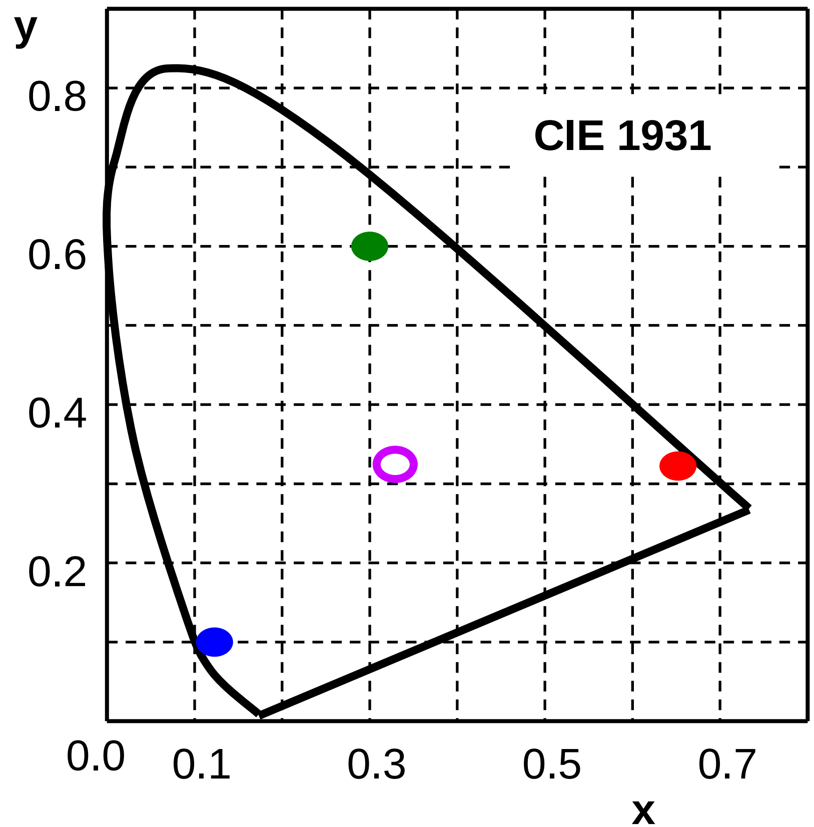
  Adjust display to “given” white point

- **Conditions**:

  “Dark room”, RGB LEDs with PWM dimming, RGB co-ordinates given as Lxy, …

- **Solutions**:

  - “Try and measure”
  - “Measure and calculate”



Color Space Summary

	CIE 1931	CIE 1976 UCS	CIE Lab CIE Luv	RGB
Tristimulus transformation	Linear	Linear	Non-linear	n. a.
Luminance	Yes	Yes	No	n. a.
Plot	2D	2D	3D	3D
Pros	history	Δco-cord. ≈ Δcolor	JNDs	SW
Cons	Δco-cord. ≠ Δcolor (Mac Adams)	L not brightness	3D, L* ≠ L	Device specific
Used for	Specs	Specs (recomm.)	ΔE	SW

Summary & Questions

- Human vision is represented as Color Matching Function in CIE
- Various CIE standards exist, 1931 mostly used, 1976 UCS recommended
- CIELAB and CIELUV are used for color difference formula; they also provide brightness – luminance relationship
- Color is measured in CIE and programmed by RGB
- Color management leads to better results but is not very common in public
- Color tolerances is specs are noticed depending on color due to Mac Adam
- What are the influences of spectral sensitivity of color measurement devices on the color co-ordinates?
- Is CCT (/K) and Gamut (/%) very meaningful ?

Overview

Some selected topics,
others can be also relevant!

- Introduction
- Basic Parameters (Merits)
- Common Issues
  - Spatial domain: Uniformity
  - Time domain:
    Lifetime, burn-in, IS…
  - Ambient light
  - Signal processing (see § TV)
- Display Technology Dependent Issues (Shortcomings)
- Summary

Overview : Parameters - Common and Display- Specific

- The basic display measurement parameters

  Luminance, Contrast Ratio, Grey Scale, Color

  are used to evaluate the application-specific performance of displays

- These parameters are e.g. lifetime, viewing angle, ambient light, …

- However most of these measurements and therefore data in specs are often “too simple” for applications like

  - Luminance & lifetime (Contrast ratio is better for LCDs)
  - Contrast ratio & ambient light (grey levels and color vanish)
  - Contrast ratio & viewing angle (grey levels and color degrade also)

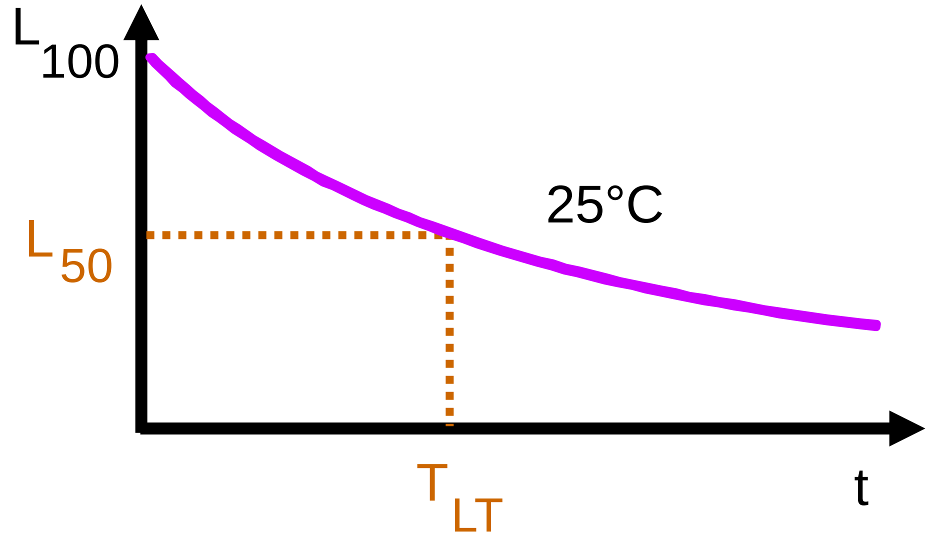
- Some of these “advanced” measurements are “dedicated” to display technologies like Differential Aging for emissive displays and viewing angle for LCDs

Lifetime Overview

Definition: Lifetime T_{LT} is half (L_{50}) of initial value L_{100}

Measured and specified usually for

- Full screen white luminance
- 25°C (often extrapolated)
- Ideal operating conditions (full screen, power always on)



Are those data 'good' for professional display applications ?

- Static content (neighboring pixels have different operating time, …) :
  - Emissive displays like PDP: Burn-In, Differential Ageing
  - LCDs: Image Sticking

No !

- Many displays are switched ON and OFF, only a few are permanent ON
- Many displays are exposed to mostly higher temperatures as 25°C

Issues of Lifetime in Specifications

- Lifetime measured at ~ 75°C and extrapolated to 25°C in specs!
- Temperature in application is higher than 25°C thus reduced lifetime:
  Temperature ↑ → Life time ↓
- Lifetime is mostly measured for static white image luminance
- When static images are shown, effects like Burn-In
  (emissive displays : Grey level ↑ → Life time ↓)
  and Image Sticking (LCDs) are likely to occur (see below)
- Lifetime is therefore also specified for 20% drop (80% of L_o) for
  e-signage and automotive displays
- Lifetime has to be evaluated for specific applications incl. content shown
- Full white luminance is often not the best test pattern:
  - Emissive displays: checkerboard
  - LCDs: Colored boxes and text, test on medium grey

Other Lifetime Measurement Parameters

- **LCDs**

Symbol	Min	Typ	Max	Units	Remark
Operating Life	30000	-	-	Hrs	$\boxed{Ta = 25\ ℃}$, I_{LED} = 25mA Note 3,4

Note 3: If G043FW01 V0 module is driven by high current or at high ambient temperature & humidity condition. The operating life will be reduced.

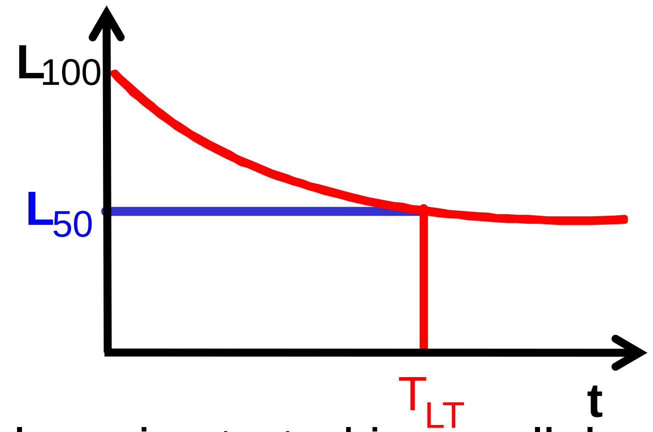
Note 4: Operating life means brightness goes down to 50% initial brightness. Typical operating life time is estimated data.

LCDs at extreme conditions (high temperatures, humidity):
Measured additionally Contrast Ratio (as polarizer may degrade)

- **Emissive Color Displays**

Measure luminance and color (white point and/or RGB)
due to Differential Aging

Lifetime – Measurement Procedures and Issues



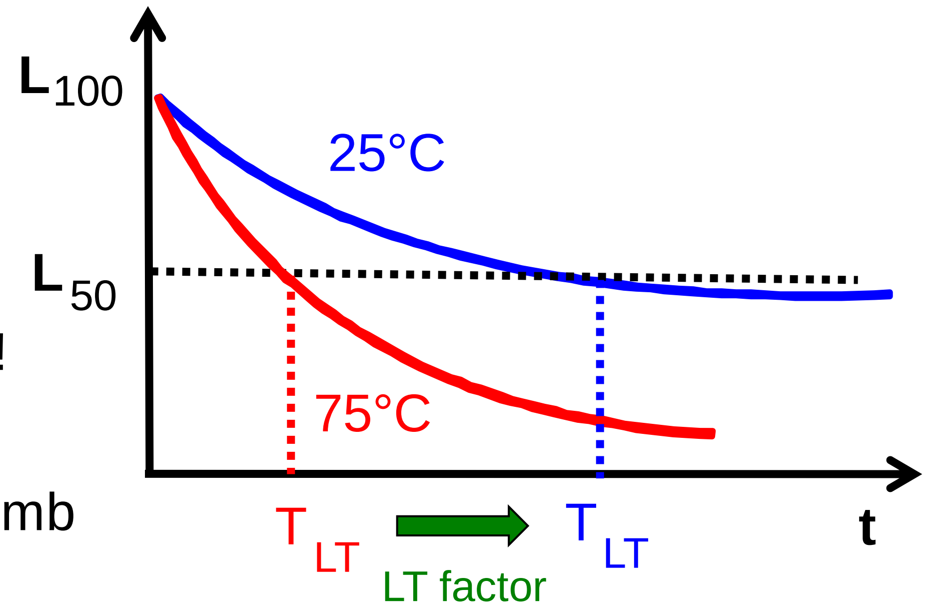
- Life time is measured in climate chamber, mostly at elevated temperatures (e.g. 60°C) and extrapolated to 25°C.
- This is reasonable as 25°C lifetime is in the range of several 10,000 h.
- Often measurements with a large number of displays is started in parallel for 25 and 60°C. Results are then compared and used for extrapolation from 60°C to 25°C lifetime, see next slide “LT factor”.
- Display must mostly be removed from climate chamber for measurements due to optical measurements. When the measurements can be quickly performed (less than 3 mins), the measurement at elevated temperature can be used. If longer, wait for about 30 mins until the displays have adapted to room temperature.
- > 3 samples of the same display should be tested.

Lifetime – Measurement Procedures and Issues

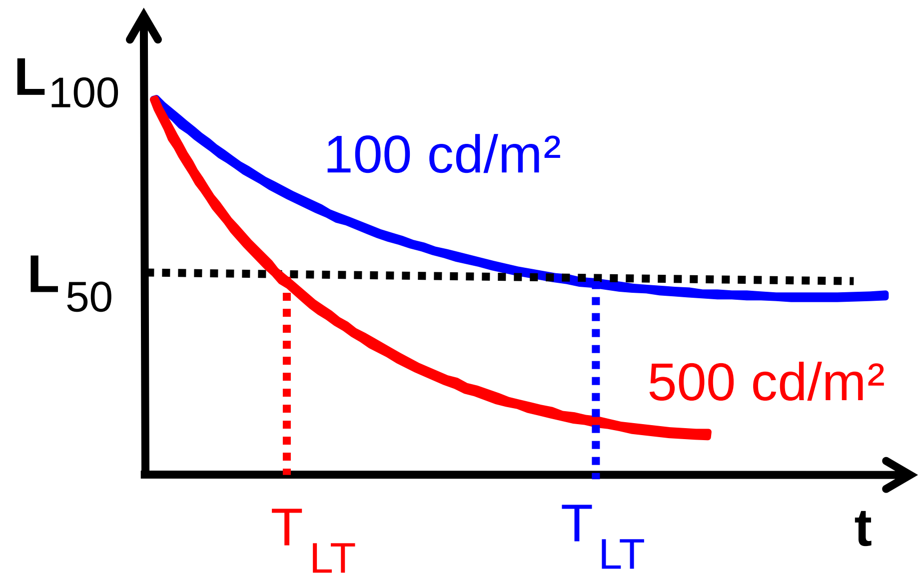
- Lifetime is measured mostly for full screen white luminance.
- This “lifetime” does not apply for mostly static content is shown on displays, as neighboring pixel have very different operating time.
- When those pixels show the same grey level (or color), lifetime degradations for emissive displays become noticeable (burn-in, see below). Even a luminance difference of about 10% of neighboring pixels is seen by everybody.
- So a specified lifetime (50% of initial luminance) of e.g. 50,000 h can result in significant degradation of image quality after 10,000 h.
- High luminance, temperature and humidity typically reduce the lifetime.
- For many displays like LCDs, contrast ratio should be measured as well over time.
- LCD luminance lifetime is mostly influenced by LED backlight degradation.

Lifetime Dependencies

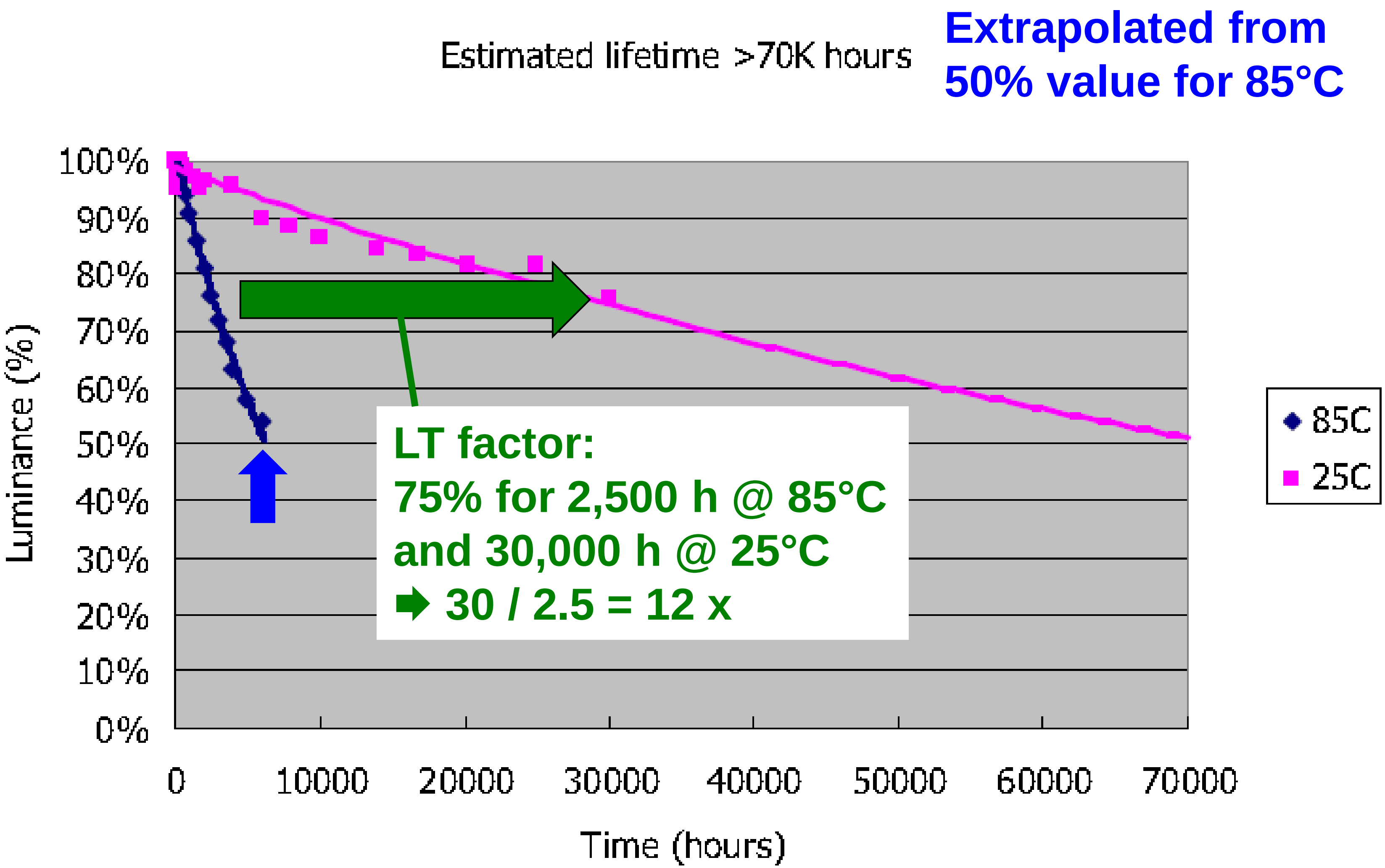
- **Temperature**
  Life time is measured at elevated temperature (e.g. 75°C) and extrapolated to 25°C for specs!
  Reason: 50.000 h ≈ 5y
  Problem: Extrapolation is rule of thumb



- **Luminance**
  Emissive displays: Life time is measured at a certain (low) luminance. Higher luminance (e.g. for outdoor use) reduces lifetime.
  "Uneven" load (grey level, time) of pixels will lead to "Burn-In" (s.b.)



Luminance Lifetime of OLEDs

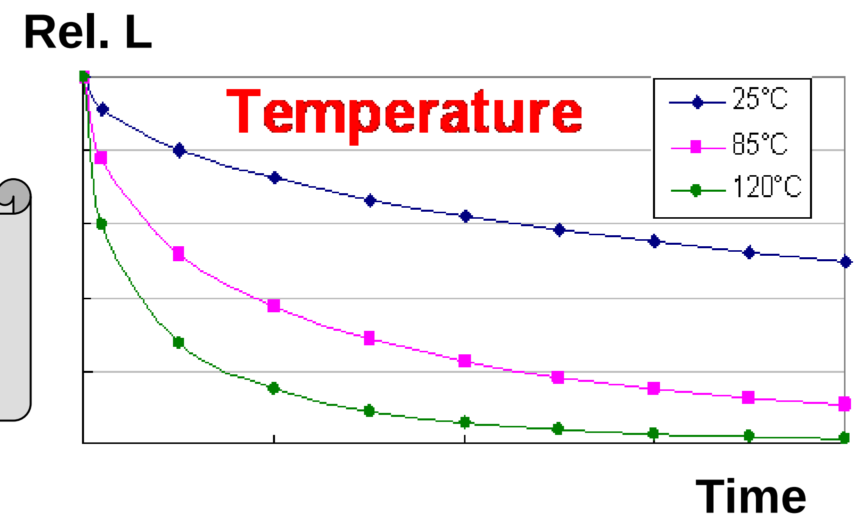


Source: WSI

Lifetime Examples

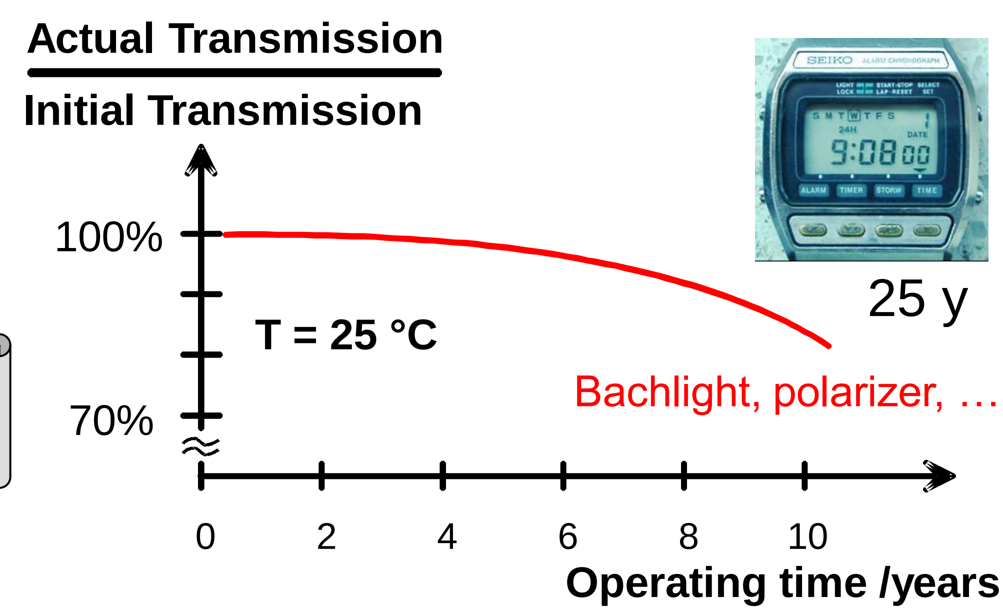
OLED

Emissive displays degrade because of aging of the light emitting material



LCD

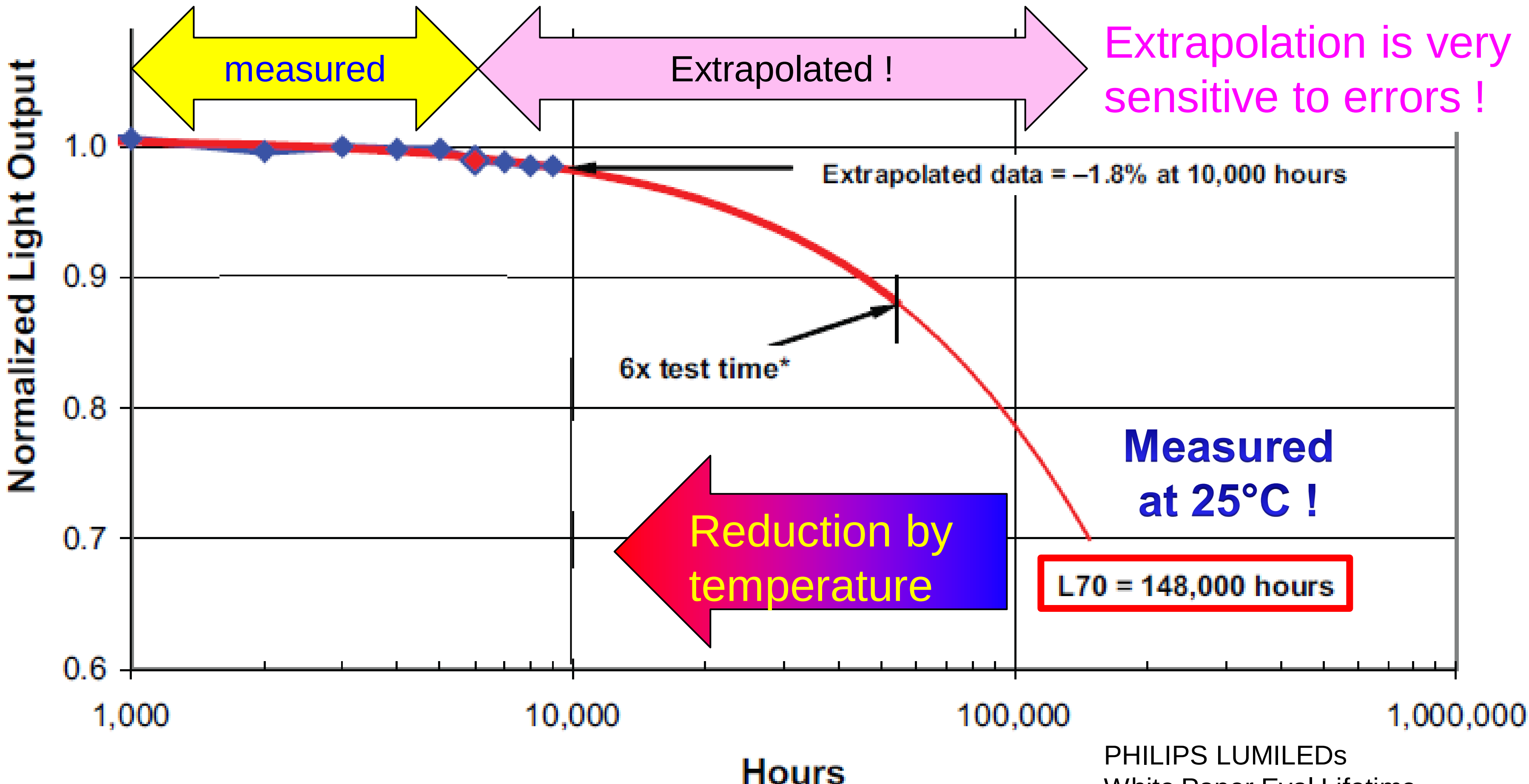
LCD: mainly backlight



25 y

IESNA LM-80 LED Lifetime Measurement

- 6,000 hours of testing with a minimum of 25 samples
- Extrapolated lumen maintenance behaviour mostly ‘exponential’ model.



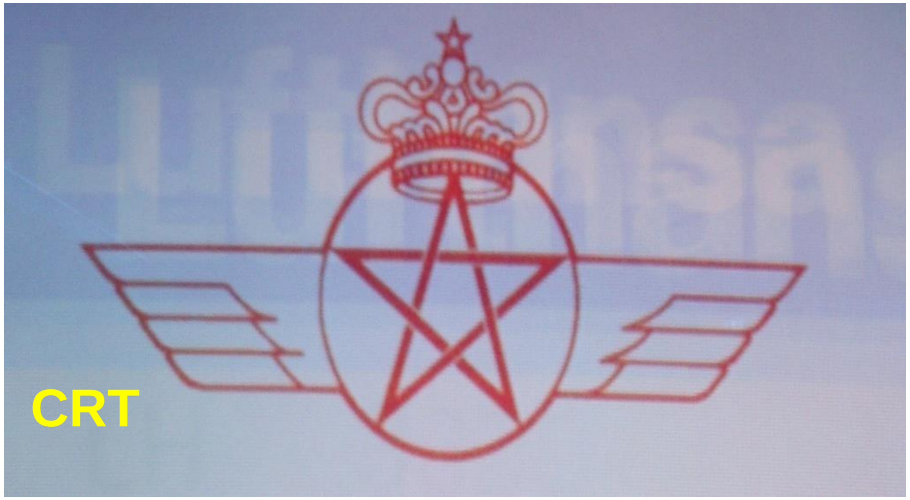
PHILIPS LUMILEDs
White Paper Eval Lifetime

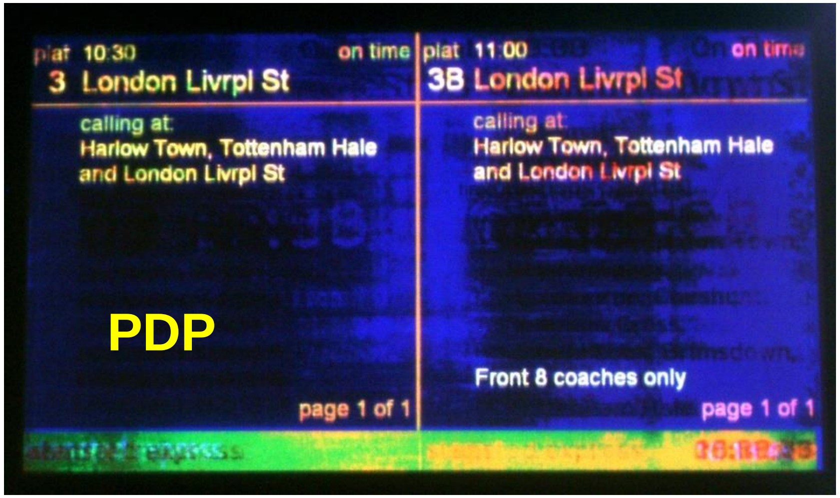
Example Procedure for Lifetime Measurement

LT requires time and money

1. Prepare climate chamber, displays and measurement devices
2. Prepare measurement document with all topics listed
3. Warm-up climate chamber
4. Warm-up displays (incl. electronics) at room temperature (RT)
5. Measure via IR-meter front surface temperature (FST) of display at RT
6. Measure all optical parameters needed. LT measurements are usually performed for dark room conditions.
7. Put display into climate chamber.
8. Measure display parameters (white luminance at first and last, white luminance is reference) and FST in climate chamber after 30 mins. immediately after door is opened.
9. If FST lowers during necessary measurements for more than 5°C, close doors and wait for 30 mins. and continue acc. 8.
10. If displays must be removed from climate chamber, wait until FST is settled in the range of RT. Then perform measurements.
11. Repeat all measurements: Every 12h for first 5 days, then 24h until 10 days, …

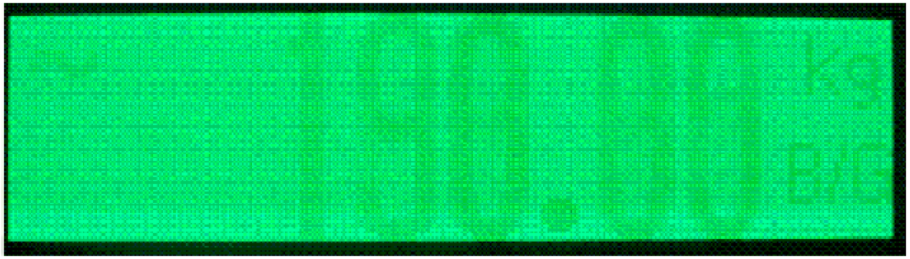
Burn - In of Emissive Displays





… Burn-in is the reason for using screen savers on PC monitors because first technology was CRT

OLED



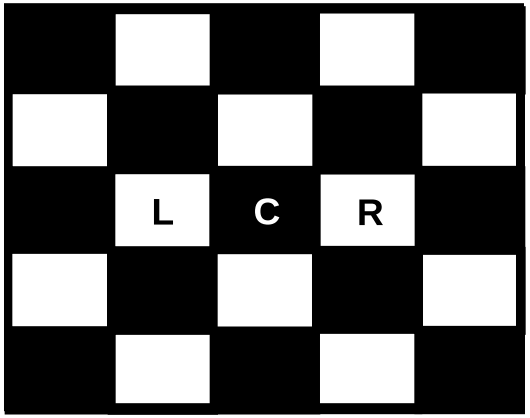
Today: Caution for information systems with static content like airport, railway, … or zoom of 4:3 SD TV to 16:9 for PDP TVs

Burn-In with Checkerboard

Typical measurement procedure

Idea: Compare 100% ON to OFF pixels

- Design a 5x5 checkerboard
- Select e.g. middle line 3 boxes (2 white, 1 black)
- Measure the 'initial' luminance at the three marked positions for black $L_0(K)$ and white $L_0(W)$
- T = 0 : Display checkerboard for a long time
- Wait x hours (can also be repeated)
- Measure luminance L' of the boxes at the same locations for full screen white
- Calculate Burn-In by $L'_0(W) / L'_0(K)$
- Further calculations possible



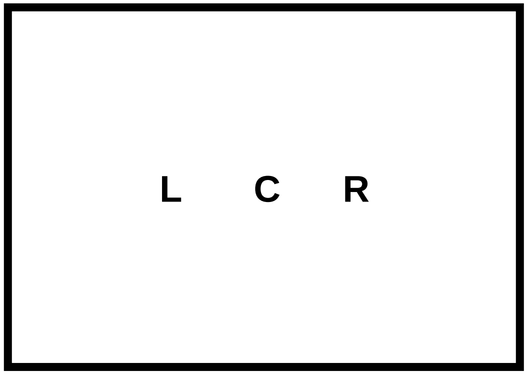
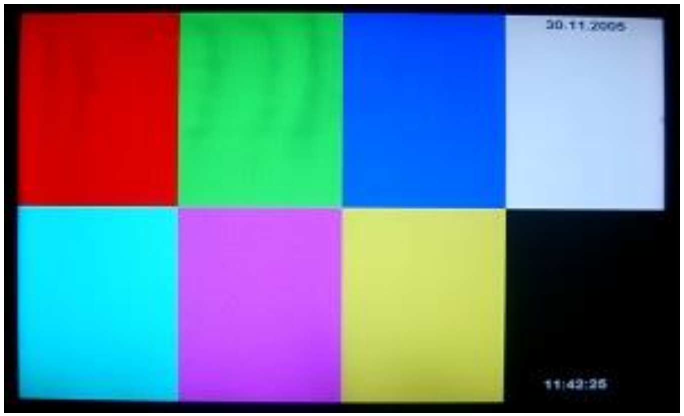
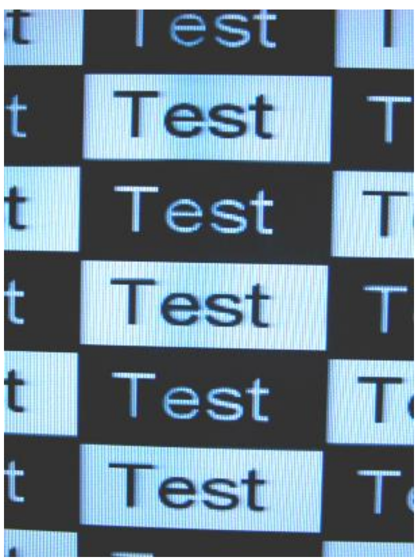


Image Sticking of LCDs ('Burn In' of LCDs) > 20"

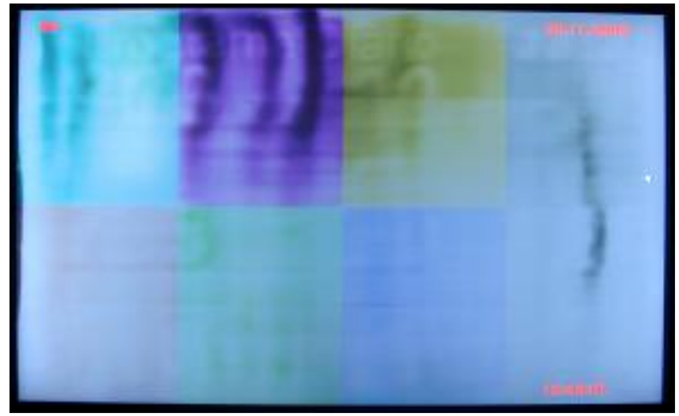
After power on





After 3 hours

Grey 60 of 255 is displayed



Inverted color:

R ↔ C

G ↔ M

B ↔ Y

B and W minor

Area IS

Inverted text:

B ↔ W,

borders visible,

background

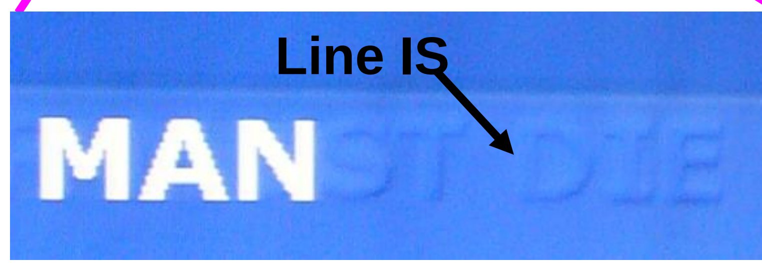
minor

Line IS

Image Sticking Examples

Mura IS

Line IS



Best ‚optical' test: Full screen low grey level like 60 (8-Bit)

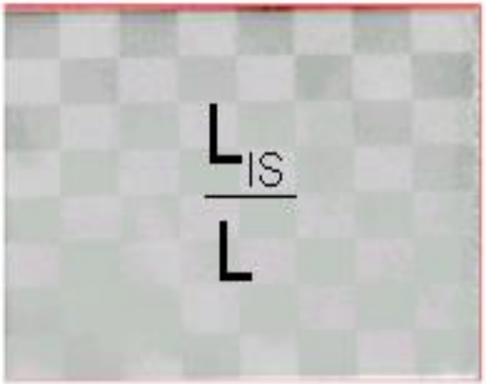
Image Sticking Measurement

Display Checkerboard for long time and switch (measure) at medium grey level (e.g. 60 of 255)

Medium grey level

(a) Before image sticking test

(b) after image sticking test

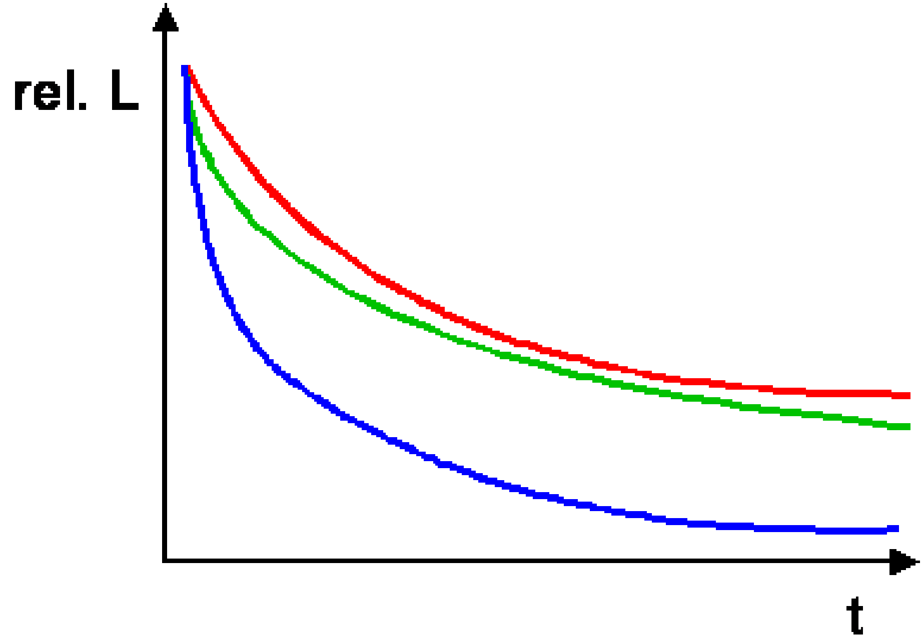


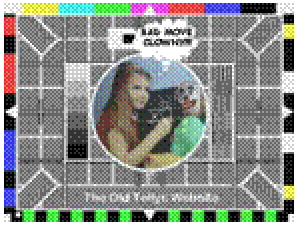
(c)Normalized data set

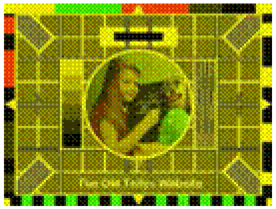
Measure at different locations at the positions of W and K of the checkerboard

Color Shifts due to Differential (RGB) Ageing

- Differences in life time of RGB emitters lead to color shifts
- This can also be forced by different ‚loads‘ (grey level, ON-time)
- Differential aging is different to Burn-in because Differential Aging occurs only on color displays
- Sensible to Differential Aging are mainly emissive displays like CRT, PDP, OLED, ...
- This lowers the useful lifetime significantly
- Test pattern like Burn-In + RGB





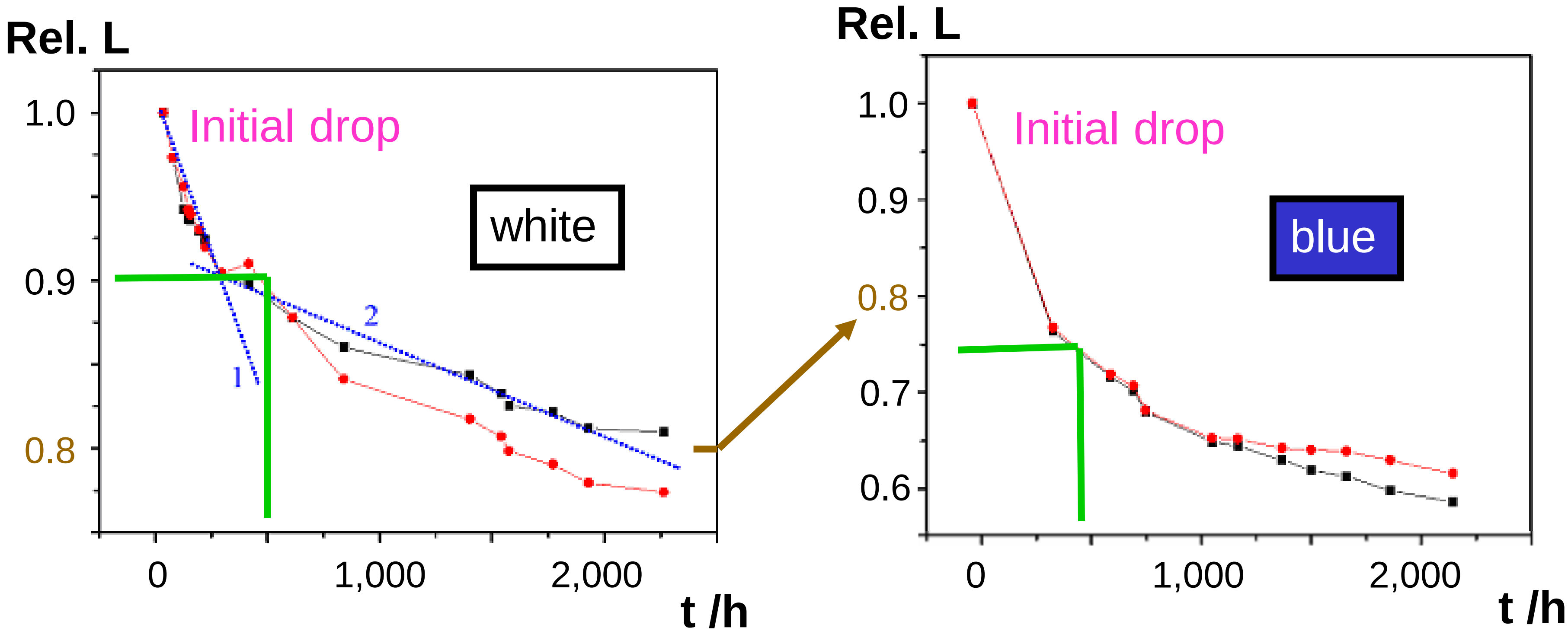


B has typically shortest lifetime

→ white becomes yellowish

Background: see White point

Color Shifts caused by Differential Ageing of PDP



Luminance decrease

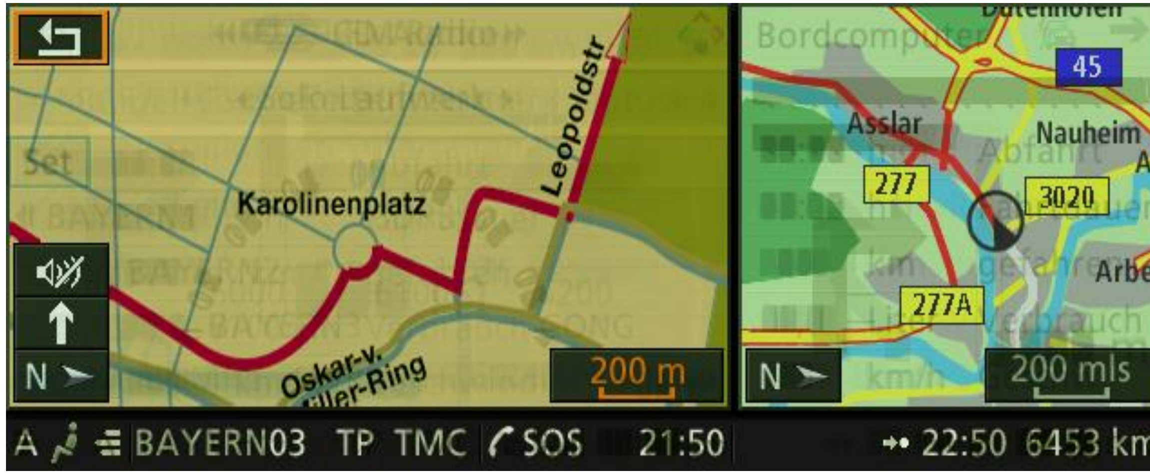
- White (left, 500 h ≡ 90% incl. blue)
- Blue (right, 500 h ≡ 75%) → yellowish

Never use static image for the first 1,000 h of PDPs

OLED - Simulation of Burn - In and Differential Ageing

A. Donath, K. Blankenbach
SID ME, 3/2004, Frankfurt

- **Simulated image**



Color difference is the only method for judging Burn-in and Differential Aging

- **False color acc.**

ΔE (CIELUV)

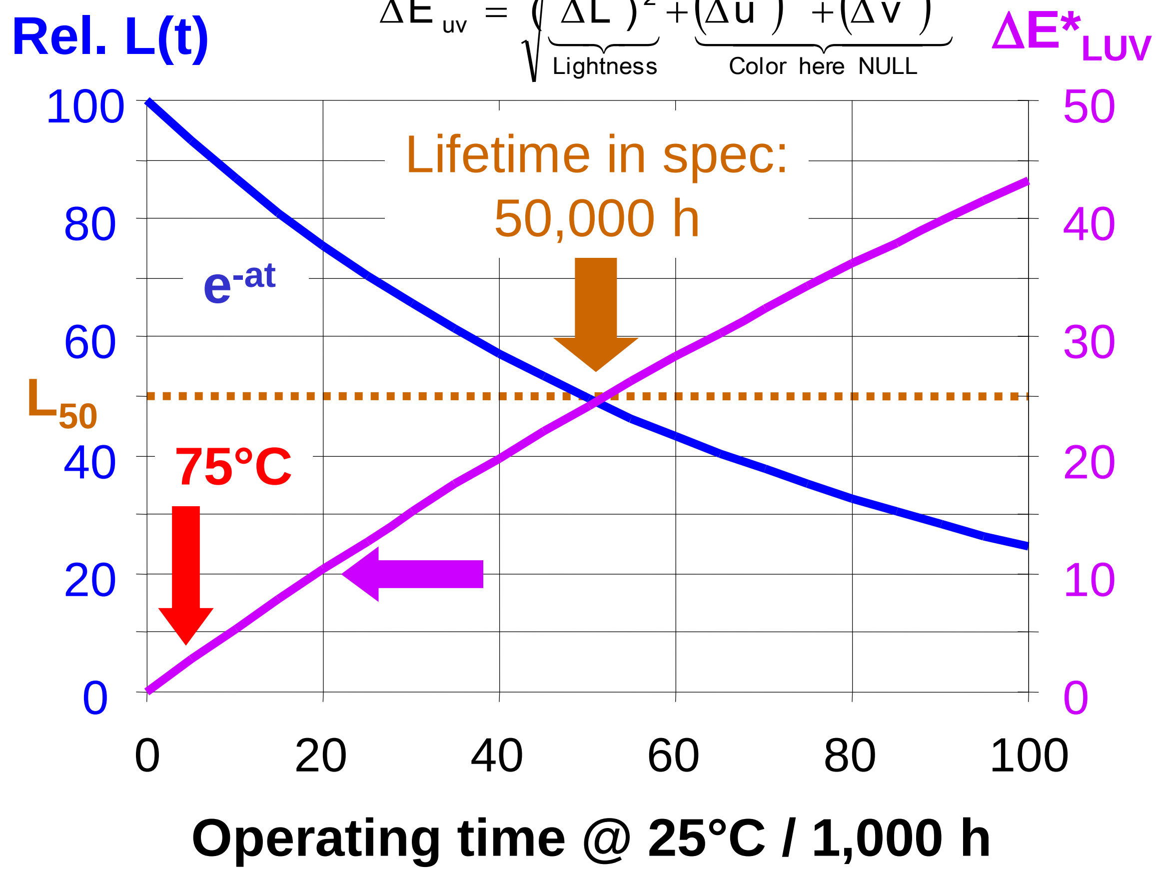
5 ΔE

Suitable for evaluation of necessary lifetime and optimization of GUI

Reduction in 'Useful Lifetime' for Emissive Displays

- Lifetime given in spec: 50.000 h @ 25°C
- $\Delta E^*_{LUV} = 10$ is clearly visible for neighboring pixel (100% ON vs. OFF)
- This results in 20,000 h 'useful lifetime' @ 25°C
- Operating at 75°C lowers lifetime by e.g. a factor of 4 down to 5,000 h which is only 10% of spec ! Further reduction by differential ageing.

$$\Delta E^*_{uv} = \sqrt{\underbrace{(\Delta L^*)^2}_{\text{Lightness}} + \underbrace{(\Delta u^*)^2 + (\Delta v^*)^2}_{\text{Color here NULL}}}$$



High temperature reduces 'useful lifetime' significantly. Evaluate at operating temp!

Lifetime & MTBF Bathtub Curve

Source: SIEMENS

The Mean Time Between Failures (**MTBF**) is a statistical mean value for error-free operation of an electronic device. The specification of this statistical value in years often leads to it being wrongly interpreted as the **service life** of the component.

What is to be understood by service life?

The service life is the time for which the device or component is designed to function. This, therefore, is the time up to the beginning of the wear-and-tear phase through a physical law or aging due to chemical reactions. In the case of devices with electromechanical parts (relays), the service life is mainly defined by the number of operations and the load connected.

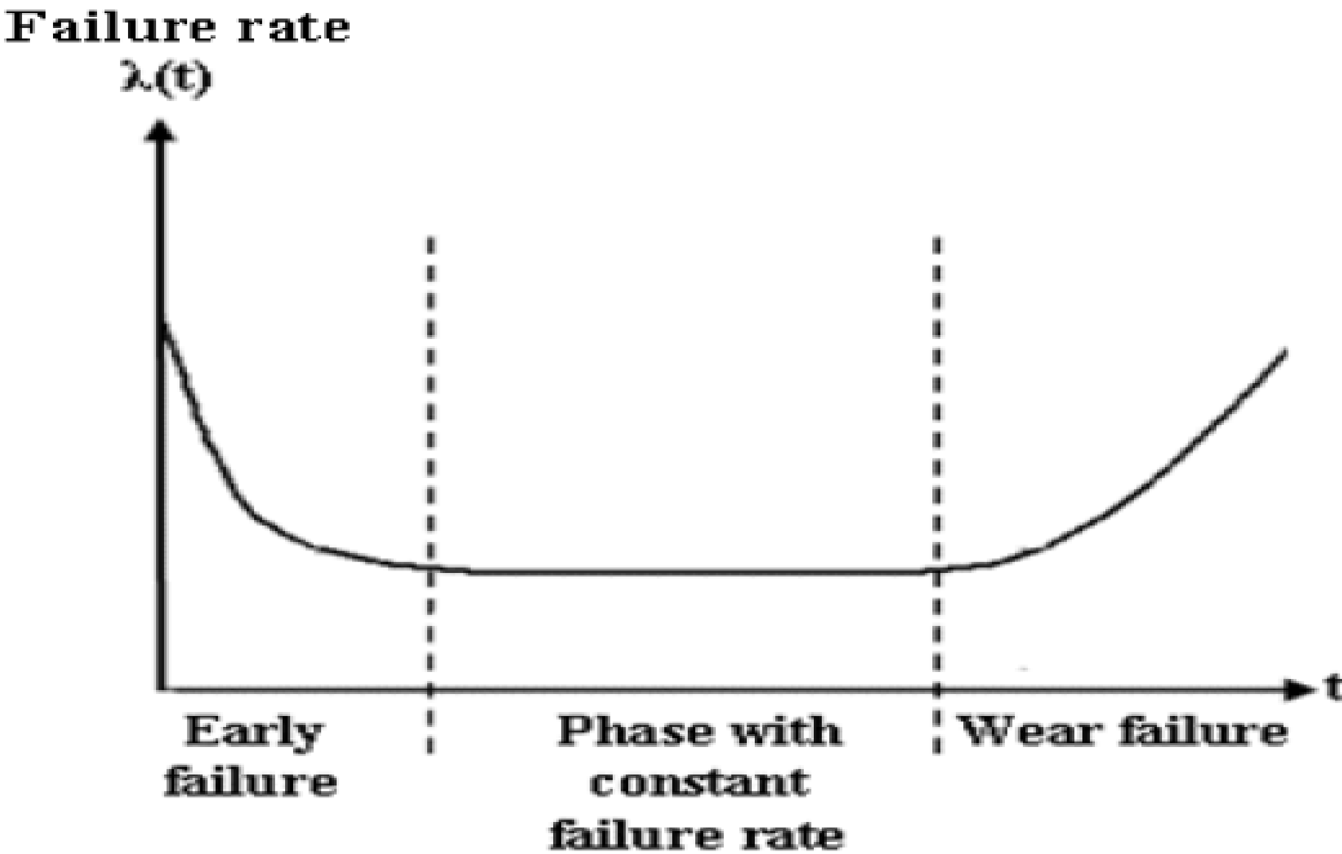
What is to be understood by MTBF?

The MTBF does not apply to an individual component, but is a statistical mean value for the average time between two failures during the normal working life. The higher the MTBF, the less often the component concerned fails and the more reliable it is.

Lifetime & MTBF Bathtub Curve

Source: SIEMENS

The reciprocal value of the MTBF that is a measure for the reliability of a component is the failure rate λ. Plotting of the statistical failure rate λ over time t gives the bathtub function (bathtub curve).



Falling below 50% of initial luminance is not a failure as the display is still working (with large reduced luminance)

Case Study : Lifetime

- **Task**

  Design
  "long lasting"
  display

- **Conditions**: Indoor, mostly static content, …
- **Solutions**:

Case Study for Lifetime : Airport Information Display

- 50”, HDTV resolution
- Static images
- Color required
- Operation 20h / 7d indoor
- Calculate operating cost for 10y
- Replacement cost workforce: 1,000 €

	LCD	PDP	Projection
Merits of technology			
Shortcomings			
Depth of display			

Case Study for Lifetime : Airport Information Display

- 50”, HDTV resolution
- Static images
- Color required
- Operation 20h / 7d indoor
- Calculate operating cost for 10y
- Replacement cost workforce: 1,000 €

	LCD	PDP	Projection
Price			
Useful life time			
# of replacements			
Cost (display + work)			
Total			

Summary Lifetime

- Lifetime is usually defined as half time luminance (or other parameters)
- Display is not “dead” after reaching lifetime, mostly luminance is reduced
- Caution: Lifetime specified for 25°C and ideal conditions (permanent ON)
- Different pixel ON time and grey level leads to Burn-In or Image Sticking
- Emissive displays change their RGB color by different lifetime of primaries (Differential ageing)
- What do you have taken into account for judging on useful lifetime in real world applications ?
- Noticeable Burn-In or Image sticking can be reduced by lowering display temperature, orbiting (panning), no low grey level background for LCDs, …

Overview

Some selected topics,
others can be also relevant!

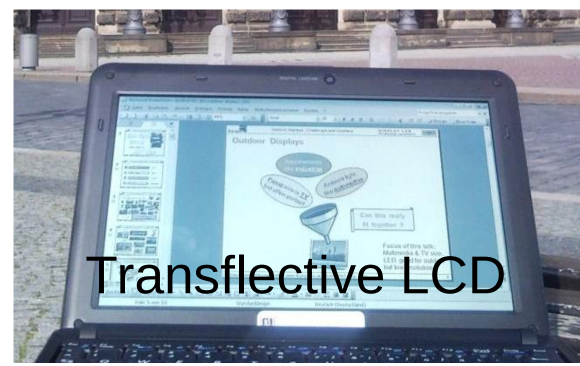
- Introduction
- Basic Parameters (Merits)
- Common Issues
- Display Technology Dependent Issues (Shortcomings)
- Summary

- Spatial domain: Uniformity
- Time domain:
  Life time, burn-in, …
- Ambient light
- Signal processing (see § TV)

Test patterns like § Basic Parameters,
mostly Full Screen Contrast Ratio

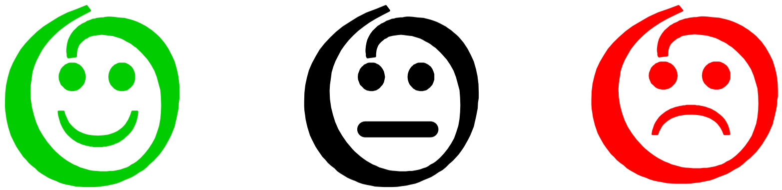
Examples For Display in Bright Light

E-paper



Reflections reduce image quality of all display technologies.

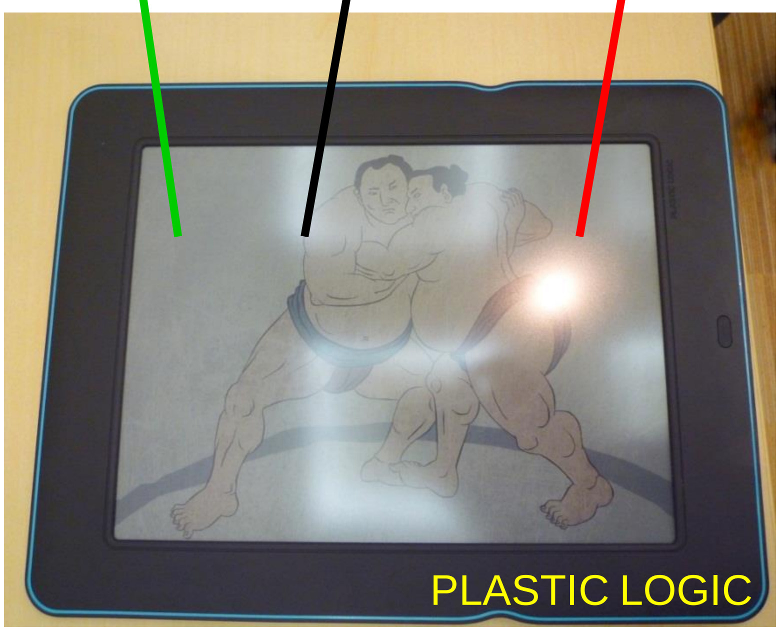
Reflections on Flat and Curved Displays



Diffuse ceiling

Neon lights

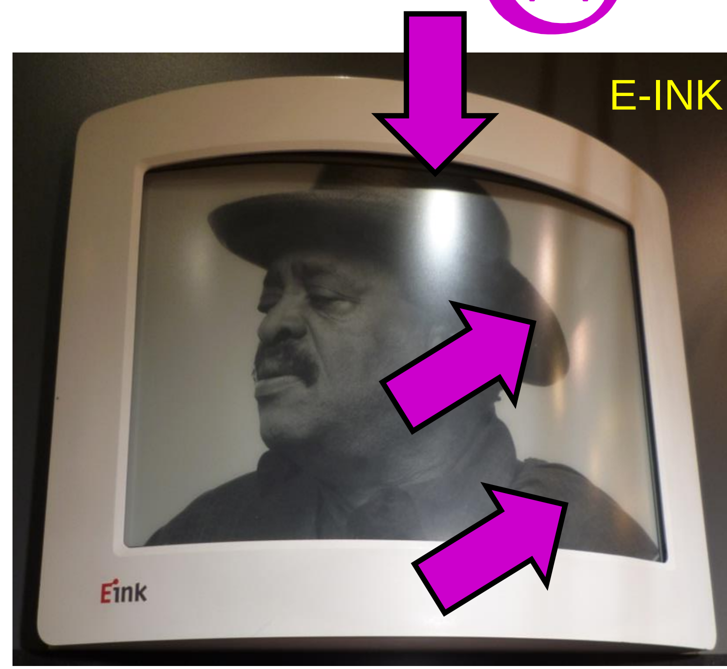
Spot lights



"Diffuse" illuminance from ceiling or sky is best for reflective displays

Curved Displays

… capture light from "everywhere!"

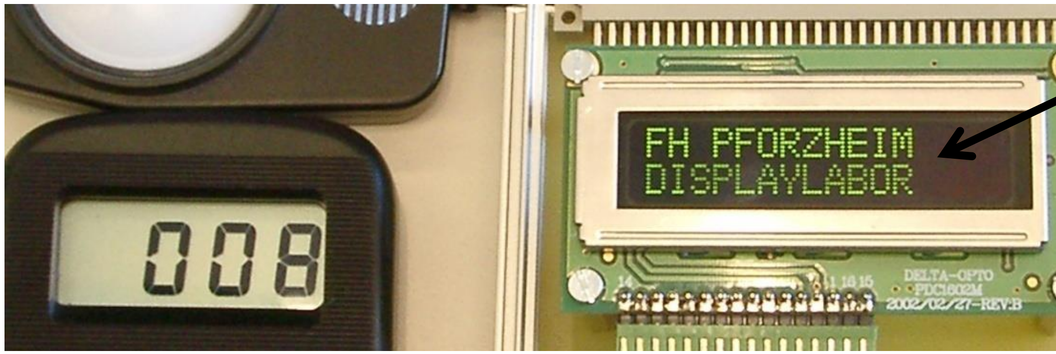


Displays vs. Ambient Illuminance

Reflective LCD **Emissive OLED**

Illuminance

800 lx

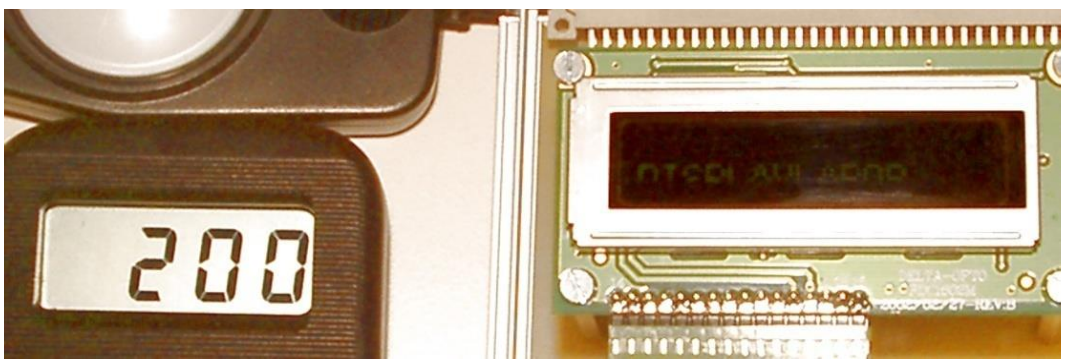


100 cd/m²
in darkroom

1 camera shot each

Luxmeter

20.000 lx



Display luminance is constant but eye (here: camera) adapts to ‘mean’ illuminance!

Reflective LCD is the right choice for illuminance meters (except for low light).

What should be the displays luminance at high ambient light ?

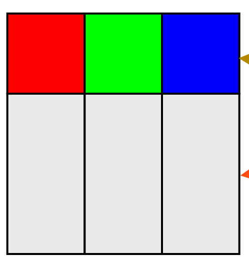
"Trimode" TN LCD by PIXEL QI

- **Trimode** = transmissive + transflective + reflective in one display
- **Benefit**: compromises power consumption and sunlight readability
- Best color in transmissive mode
- Monochrome (incl. grey levels) for reflective mode

Item	Specification
Dimensions	10.1" diagonal 222.72 x 125.28 mm active area
Display modes	Transmissive, transflective, reflective
Pixel count	1024 x 600 color 1024 x 3 x 600 black and white
Pixel Pitch	0.2175(h) x 0.2088 (v) mm
Pixel density	220 ppi
White-state reflectance	24%
Contrast ratio	>100:1
Field of view	±45°
Color gamut	45% NTSC
Refresh rate	25 – 60 Hz
Power consumption	0.4W – 0.8W, reflective (30Hz, 60Hz) 1.3W – 1.7W, transflective (30 – 60) 2.2W – 2.6W transmissive (30 – 60 Hz)
Colors	262,144
Brightness	150 nits

Transmissive

Reflective

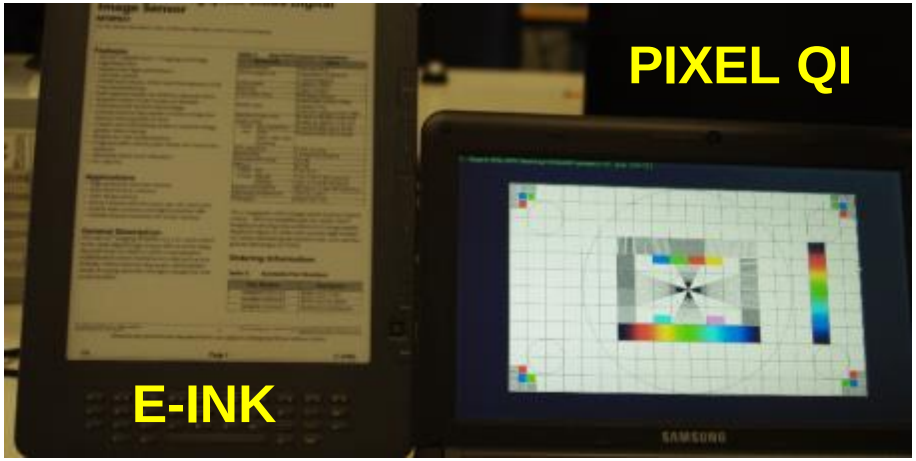


Trimode TN LCD by PIXEL QI vs. E-INK

E-INK : monochrome & no video, “no” power

PIXEL QI : monochrome (low power) or color (high power), video

Indoor	Outdoor



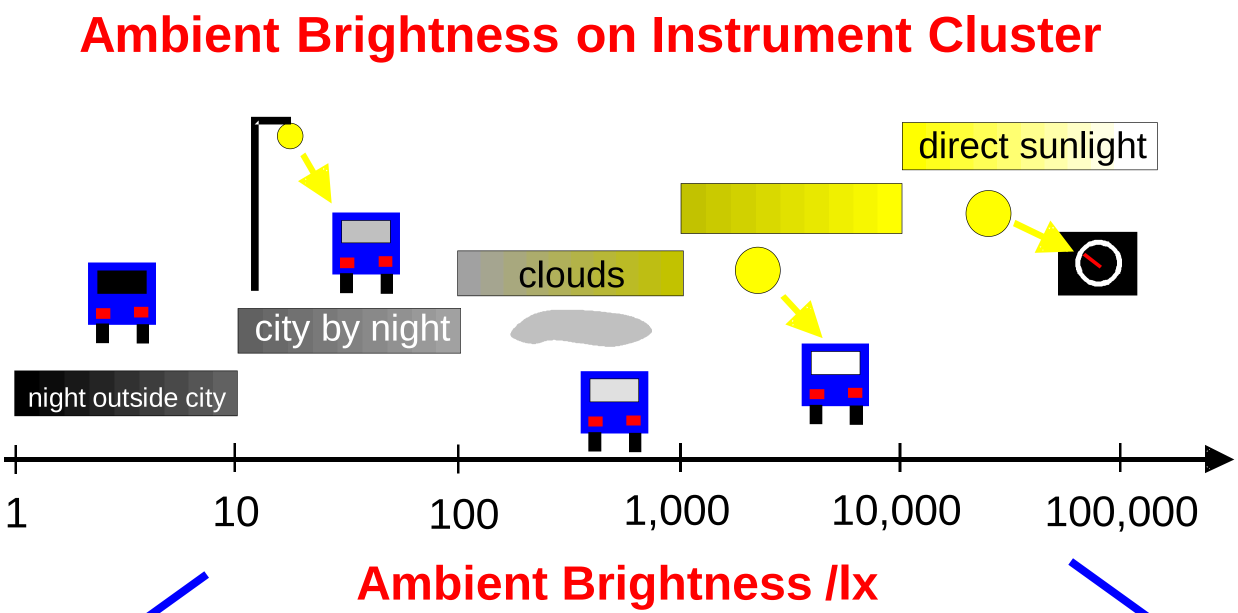
E-INK without frontlight but readable

PIXEL QI excellent & color (video) but high power (transmissive)

E-INK higher white reflectivity

PIXEL QI monochrome & low power (reflective)

Automotive Display Brightness

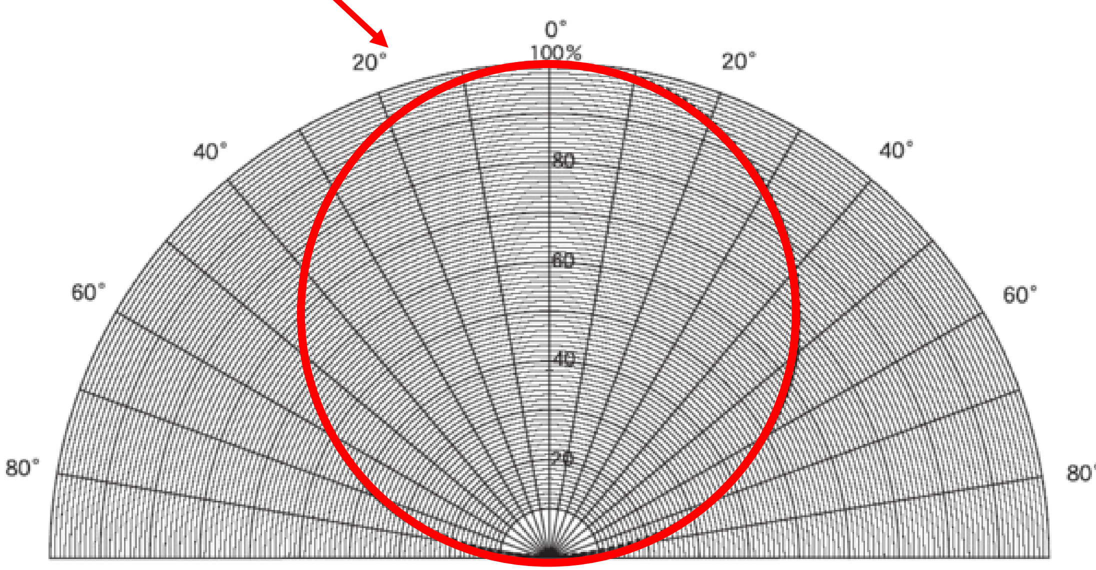


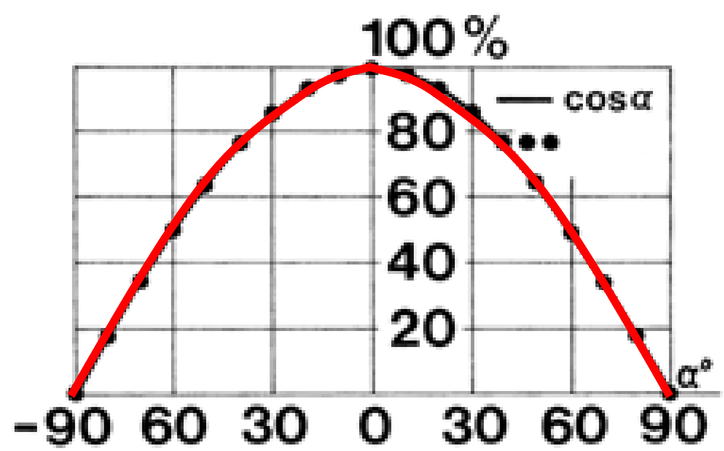
Parameter: Illuminance /lx

Meters starting at 30 € available.

Requirements:

- V(λ) corrected like luminance meters
- Cosine-shaped sensitivity over angle





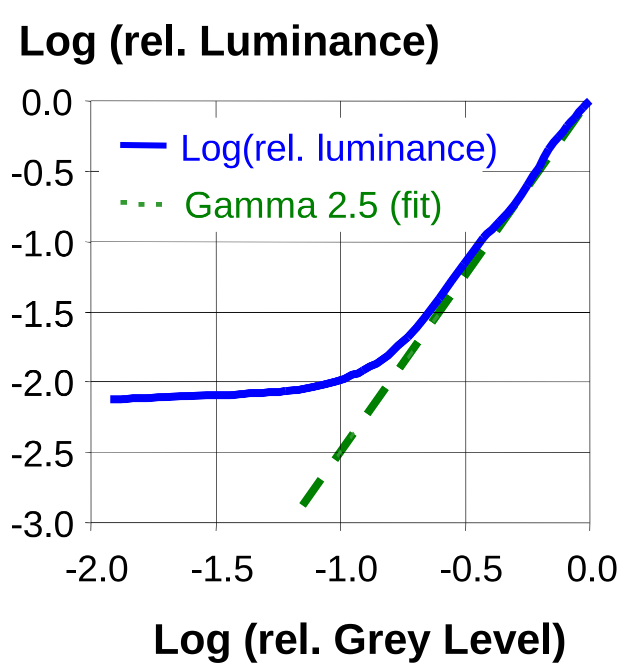
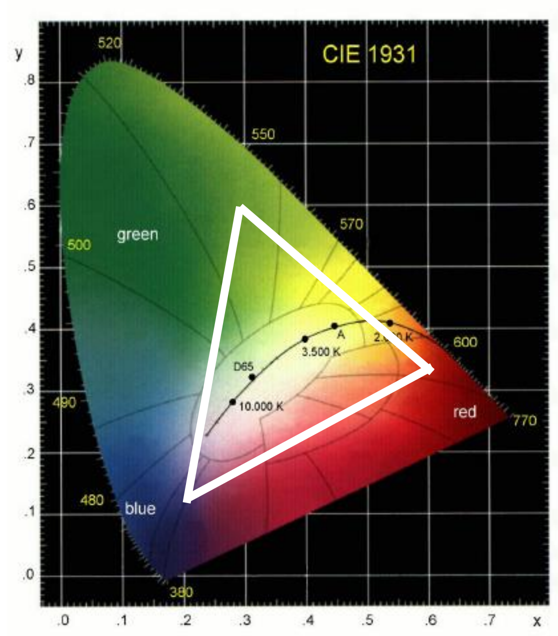
Incident angle /°

Capture light from any angle (half sphere)

Display Specs usually refer to Dark Room Conditions !

How degrade dark room values by ambient light ?

Dark room parameters

Contrast ratio	Grey Shades	Color Gamut
$C_R(0\,\mathrm{lx}) = \dfrac{L_{White}}{L_{Black}}$		

Consequences & Solutions for Readability

Readability reduced due to

- Eye adaptation to high illuminance
- Reflections from “bright” environment

Consequence:

- Reflected luminance adds to display luminance
- Reduction of readability (CR, grey scale, gamut)

Issue:

- Display specifications refer to dark room
- No formula to extrapolate to ambient light behavior

Solutions:

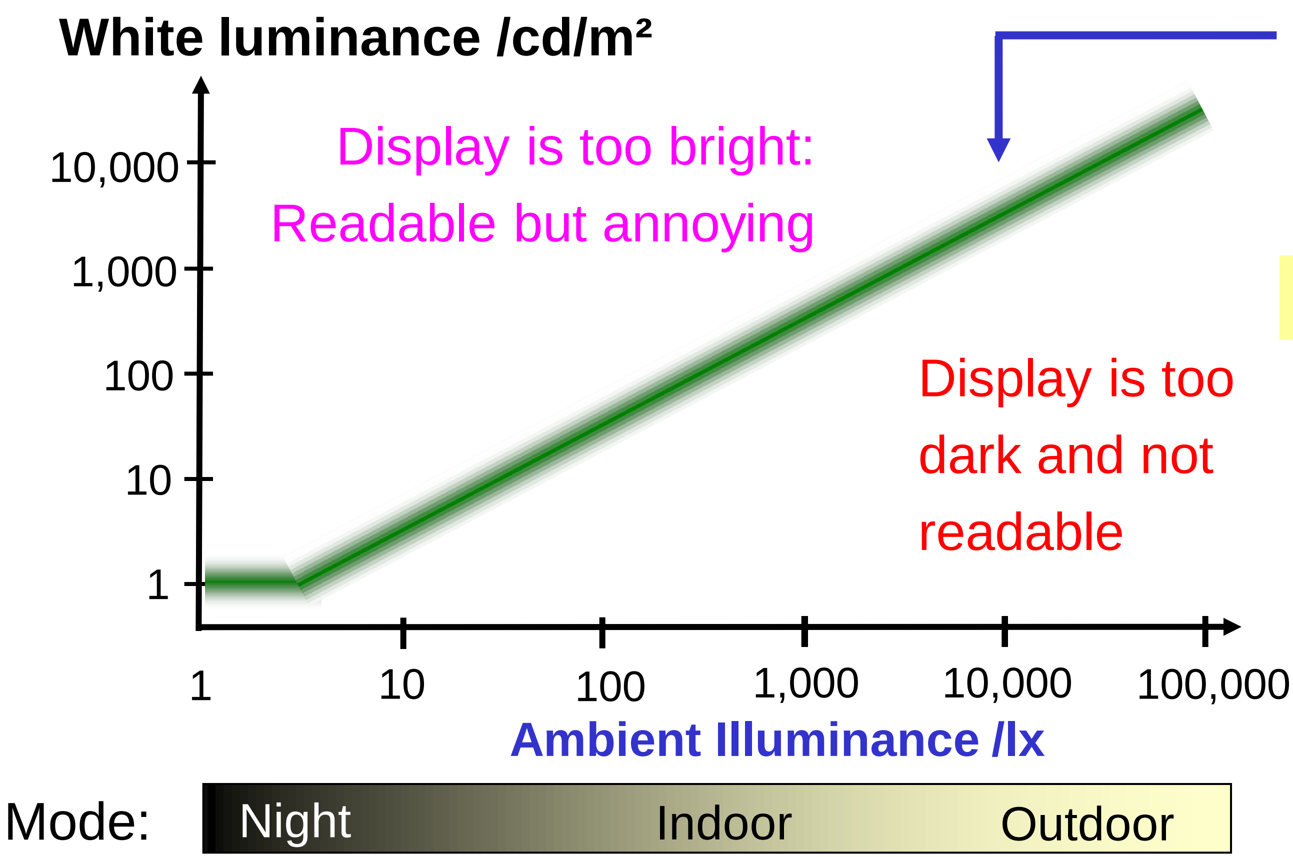
- Rise luminance (but T will thus rise and reducing lifetime)
- Reduce reflections (filter, optical bonding, location…)
- Measure ambient light characteristics of displays

Luminance & Eye Adaptation

Approach:

Display should have white luminance like white paper due to eye adaptation:

$$L^{Diffuse}_{Paper} = \frac{E}{\pi} \sim \frac{E}{3} \Rightarrow L_{Display} \geq \frac{E}{10}$$



Example:

$E = 10{,}000$ lx

$\rightarrow L^{Diffuse}_{Paper} = 3{,}333$ cd/m²

$\Rightarrow L_{Display} \geq 1{,}000$ cd/m²

Recommendations:

Negative mode @ night

Positive mode @ day

Readability for Bright Ambient Light

1. Eye adaptation

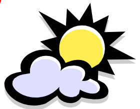
Display should have white luminance like white paper :

$$L^{Diffuse}_{Paper} = \frac{E}{\pi} \sim \frac{E}{3} \Rightarrow L_{Display} \geq \frac{E}{10}$$

Example: E = 10,000 lx ⇨ $L_{Display} \geq 1{,}000\ \mathrm{cd/m^2}$

2. Contrast ratio

$$C_R = \frac{L_{White}}{L_{Black}}$$



$\xrightarrow{\ }$ + ambient light

$$C_R = \frac{L_{White}(0\ \mathrm{lx}) + L_{Reflected}}{L_{Black}(0\ \mathrm{lx}) + L_{Reflected}} \approx \frac{L_{White}(0\ \mathrm{lx})}{L_{Reflected}} + 1$$

$L_{Reflected} > L_{Black}(0\ \mathrm{lx})$

$L_{Reflected\ (white)} = L_{Reflected\ (black)}$

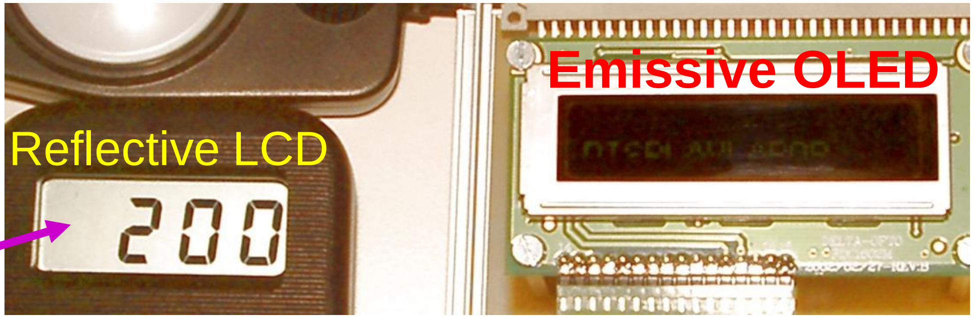
"No influence" of dark room contrast ratio !

1. + 2. must both be fulfilled !

Optimization: - Reduce illuminance E
- Increase display luminance
- Reduce reflections

Examples for C_R for Diffuse Reflectance of Illumination

- $r_{\text{System D}} = 0.05$; $r_{\text{Reflector}} = 0.3$
- E = 10,000 lx



100 cd/m² indoor

Emissive display with $L_{\text{White}} = 100$ cd/m² :

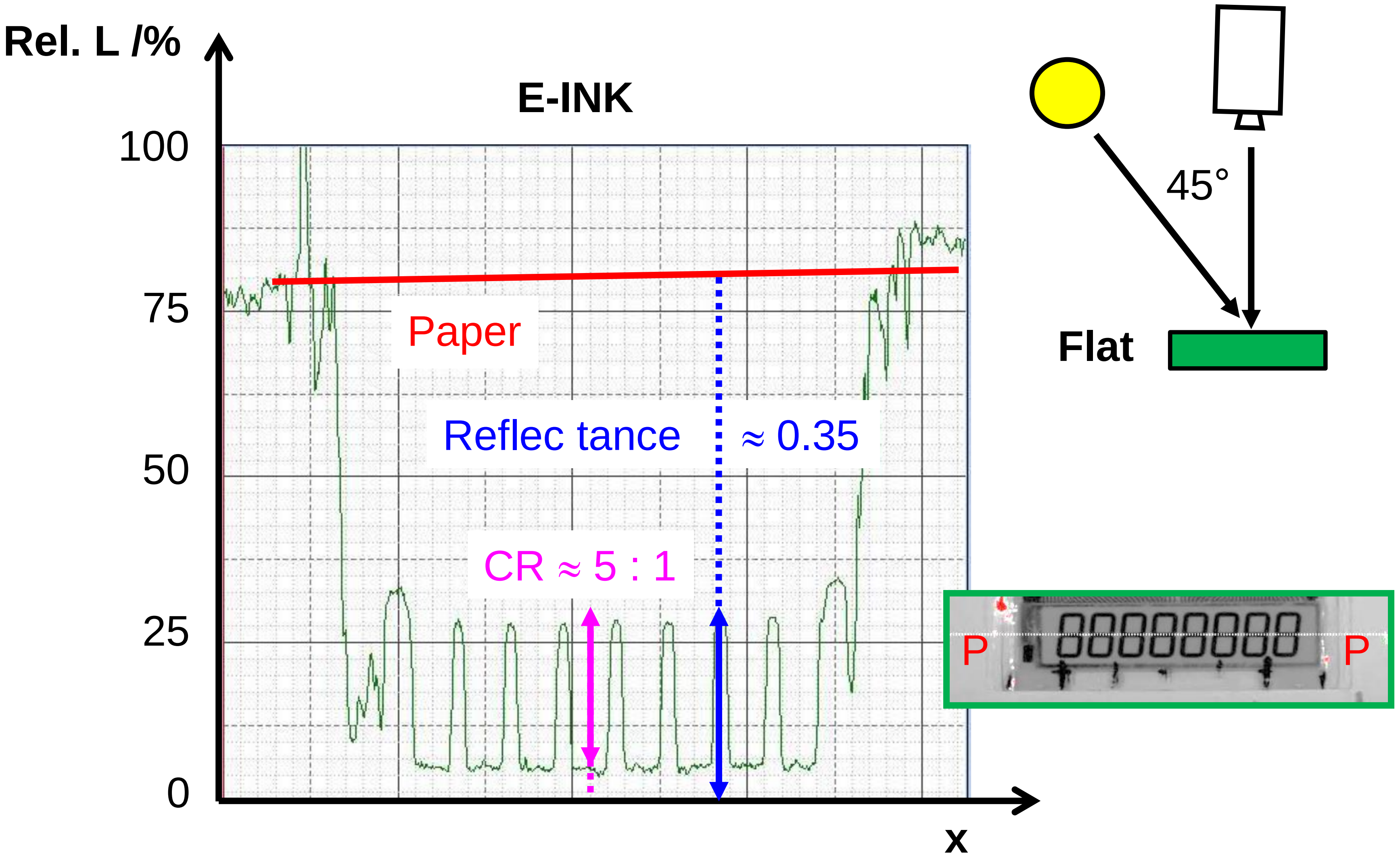
$$C_R^{\text{Emissive}} \approx \frac{\pi \; L_{\text{White}}(0\,\text{lx})}{E\, r_{\text{System D}}} (+1) = \frac{\pi \cdot 100}{10{,}000 \cdot 0.05} + 1 \approx 1.6:1$$

($C_R = 3.2 : 1$ for $L_{\text{White}} = 500$ cd/m²)

Reflective LCD :
$$C_R^{\text{Non-emissive}} \approx \frac{r_{\text{Reflector}}}{r_{\text{System D}}} = \frac{0.3}{0.05} = 6:1$$

Reflective displays are better readable in ambient light then emissive ones !

Diffuse Geometry: Reflective E - INK Display



Examples for Contrast Ratio Degradation

L_{White}	L_{Black}	C_R(0 lx)	C_R with $L_{Reflected}$ = 10 cd/m² *
500	1	500	510 / 11 = 46
100	1	100	110 / 11 = 10
500	5	100	510 / 15 = 34
100	5	20	110 / 15 = 7

* : $L_{Refl.}$ (W) = $L_{Refl.}$ (K)

Factor 5 for white luminance, L(K) = const. ➞ factor ~ 4.7 in C_R for ambient light

Factor 5 for black luminance, L(W) = const. ➞ factor ~1.4 in C_R for ambient light

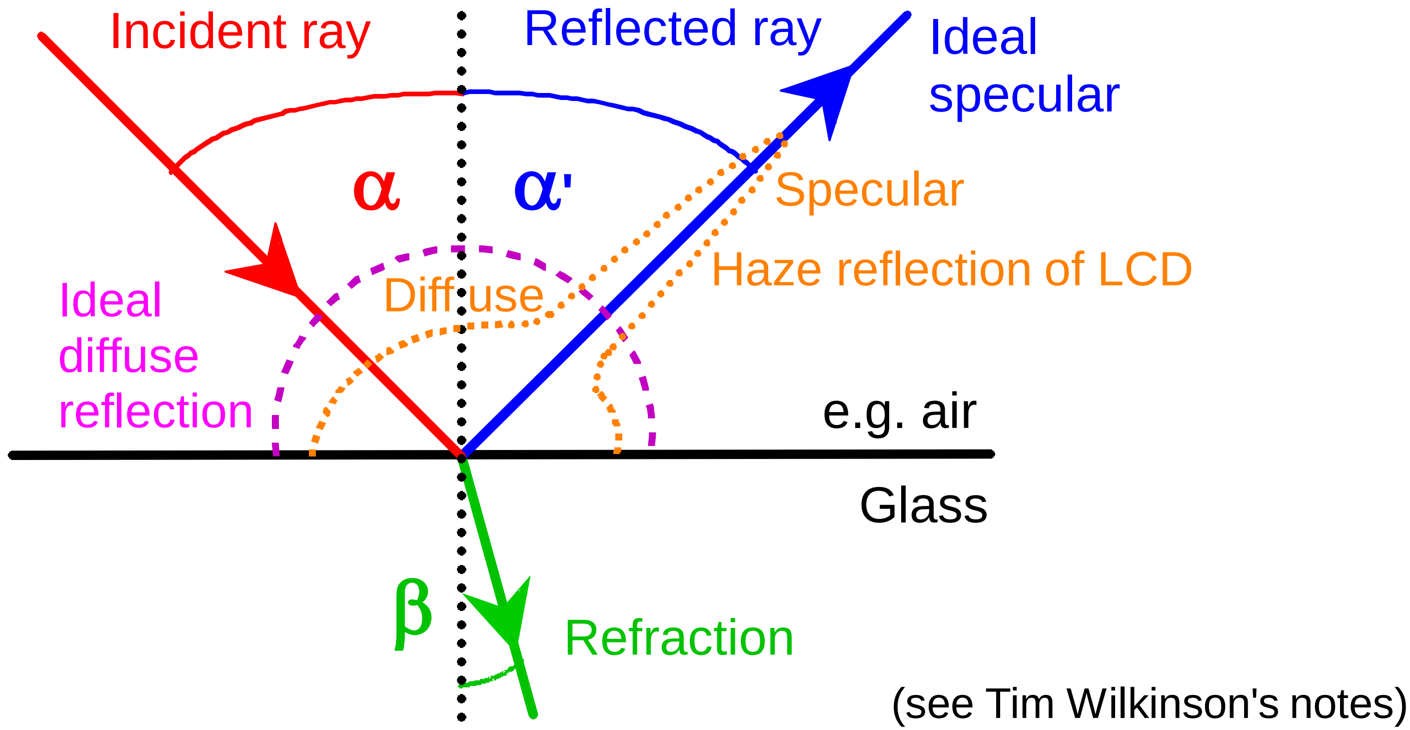
for L_{White} = 100 cd/m² and L_{White} = 500 cd/m²

Luminance of white has more influence on CR with ambient light than luminance of black and CR under dark room conditions !

Examples for Contrast Ratio & Ambient Light

	Display 1			Projection
Lighting conditions, geometry				
L_{white}				
L_{black}				
Contrast ratio				
Illuminance /lx				

Basics of Light Reflection



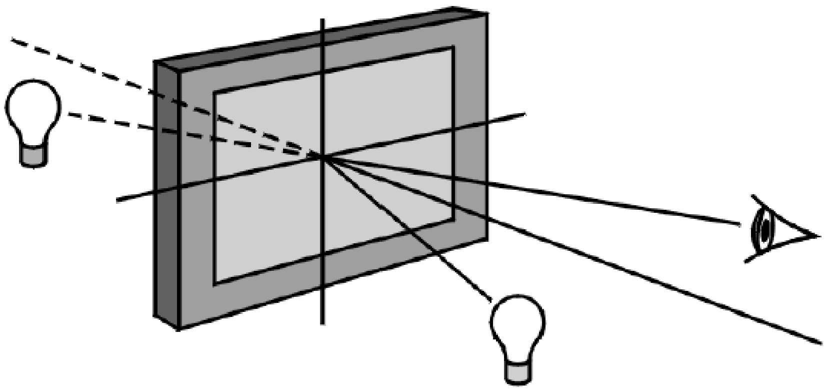
But things are not as easy as it seems !

Example: Glass has index of refraction of about 1.5. This sets, depending on the incident angle, the portion of refraction and reflection.

But e.g. a matte glass surface reflects light in all directions (diffuse) !

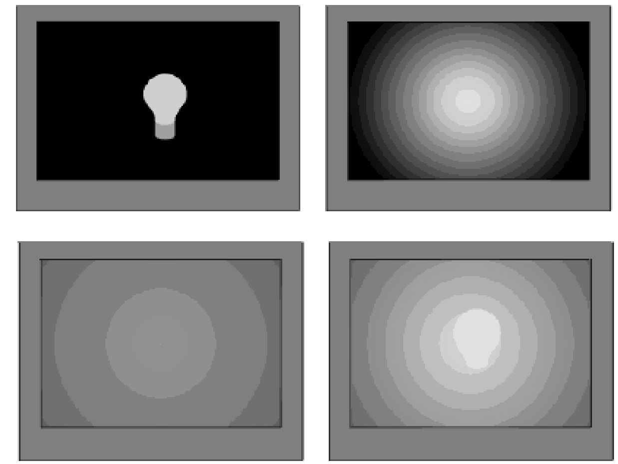
Fundamentals of Reflections for Displays

Components of reflections

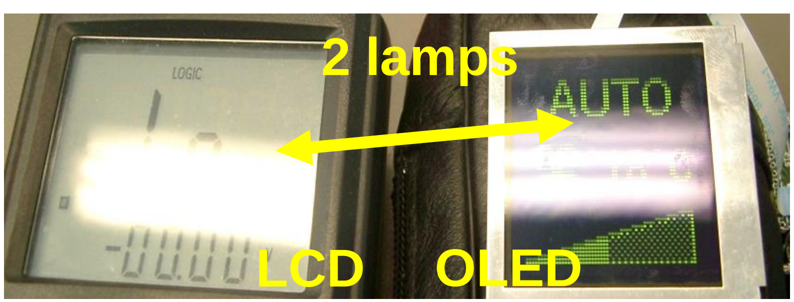


Source: E. Kelley, NIST

Specular Only *Haze Only*



Lambertian Only *All Three*



LCD (left) : specular & haze

OLED (right) : mainly specular

(diffuse with low intensity)

Luminance Generated by Reflections

$$L_{Reflected} = L_{Specular} + L_{Haze} + L_{Diffuse}$$

All values & parameters depend on
- Light source(s) (angle, spectrum, …)
- Observer angle, display orientation, …
- Display characteristics (surface, layers, …)

Component Characteristics

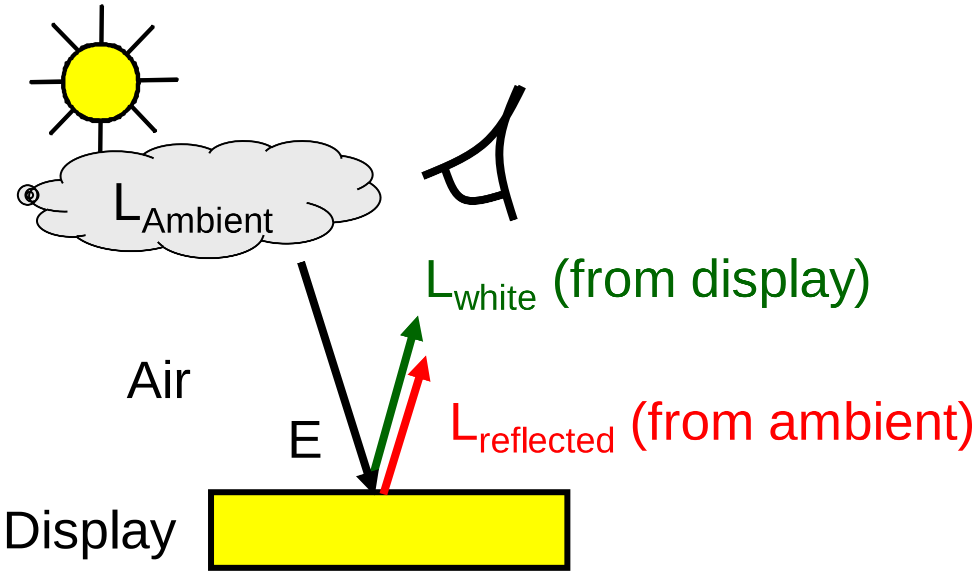
$L_{Reflected}$	Sum of all reflections, could be measured as BRDF (Bidirectional Reflectance Distribution Function, ISO 13406), usually not available from manufacturers
$L_{Specular}$	Directed (specular) reflection (incident angle = output angle): “mirror-like” glare-type displays
L_{Haze}	Experimental value similar to fog, occurs mainly for LCDs
$L_{Diffuse}$	Approximation as Lambertian light source: diffuse, matte, anti-glare

Best description by BRDF but not easy to obtain from measurements

Luminance Generated by Reflections

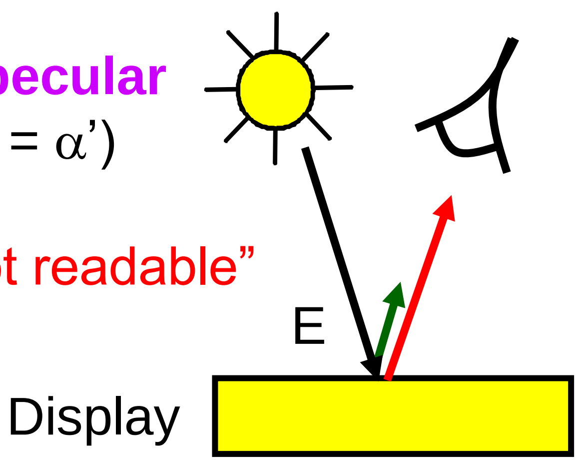
Reflected luminance depends on

- Geometry (angle)
- Reflection coefficient of display

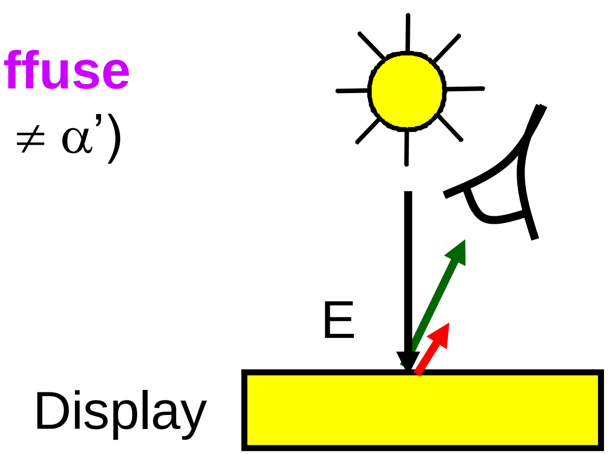


Specular
($\alpha = \alpha'$)

"not readable"



Diffuse
($\alpha \neq \alpha'$)



"readable"
mobile: turn
static: "shield"

Luminance Generated by Reflections Numerical Examples

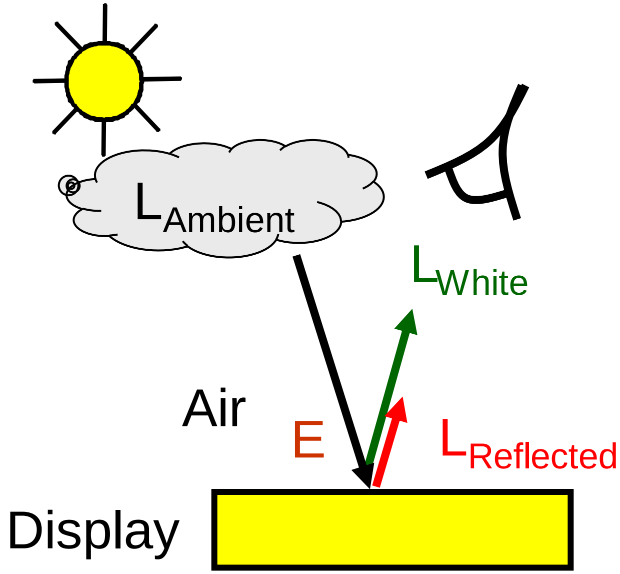
Formula: $$CR \approx \frac{L_{White}}{L_{Reflected}} + 1$$

Values: - L_{White} = x cd/m² (display showing white)

- $L_{Ambient}$ = 5,000 cd/m² (illuminance E ≈ 30,000 lx)

Parameters (here):

- Perpendicular incidence
- Reflection coefficient r
- $L_{Reflected} = r \cdot L_{Ambient}$

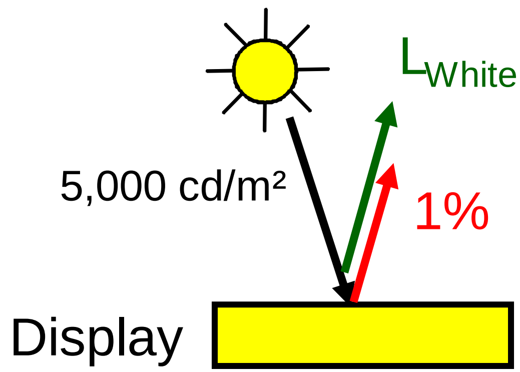


Recommendations for High Contrast Ratio

Display luminance

- 1,000 or 300 cd/m²
- 1% reflectivity (low!)

⇨ luminance rises CR

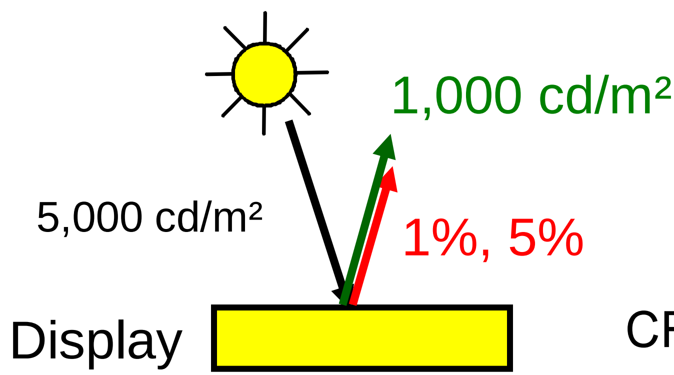


$$CR \approx \frac{1{,}000}{0.01 \cdot 5{,}000} + 1 = 21$$

$$CR \approx \frac{300}{0.01 \cdot 5{,}000} + 1 = 7$$

Display reflectivity

- 1% or 5% reflectivity
- 1,000 cd/m²
- ⇨ reflectivity decreases CR



$$CR \approx \frac{1{,}000}{0.01 \cdot 5{,}000} + 1 = 21$$

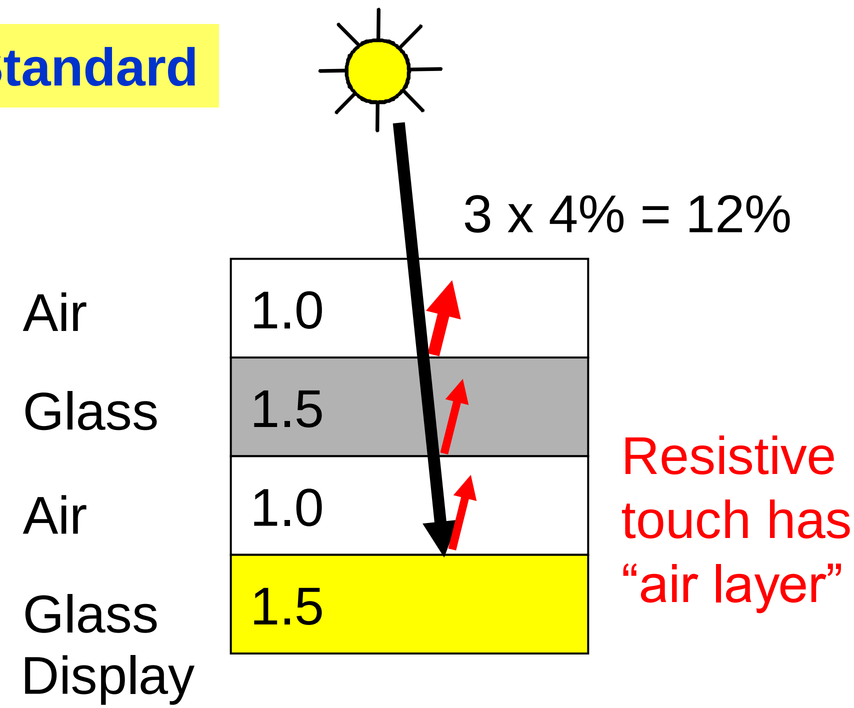
$$CR \approx \frac{1{,}000}{0.05 \cdot 5{,}000} + 1 = 5$$

Reflection Reduction : Optical Bonding

L_{White} = 1,000 cd/m²
$L_{Ambient}$ = 5,000 cd/m²

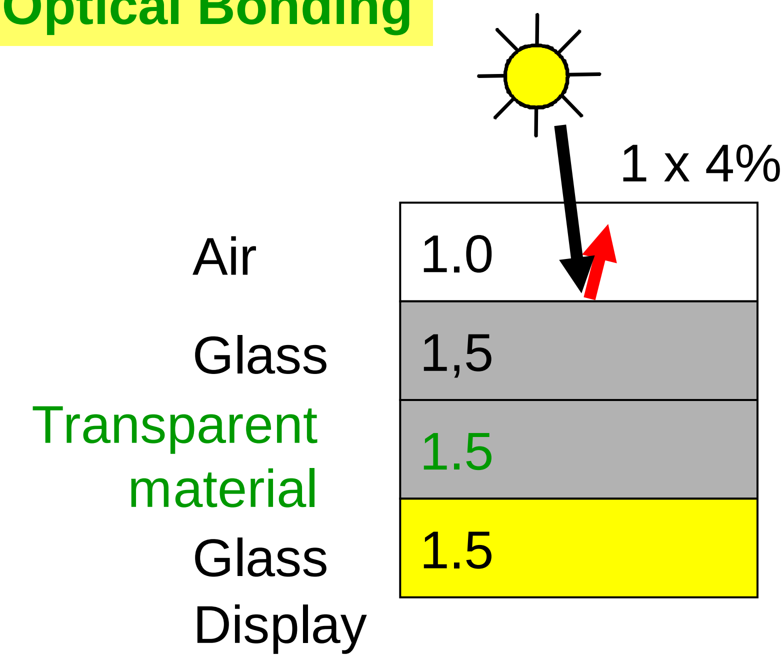
Protection glass or PCAP touch screen in front of display

Standard



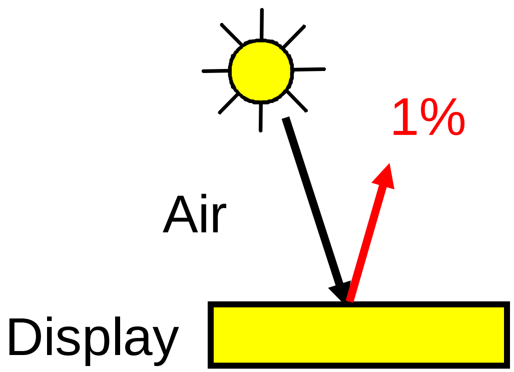
$$CR(12\%) \approx \frac{1{,}000}{600} + 1 \approx \boxed{2.5}$$

Optical Bonding



$$CR(4\%) \approx \frac{1{,}000}{200} + 1 \approx \boxed{5}$$

Summary for Reflection Reduction Methods



$$CR \approx \frac{1{,}000}{0.01 \cdot 5{,}000} + 1 = 21$$

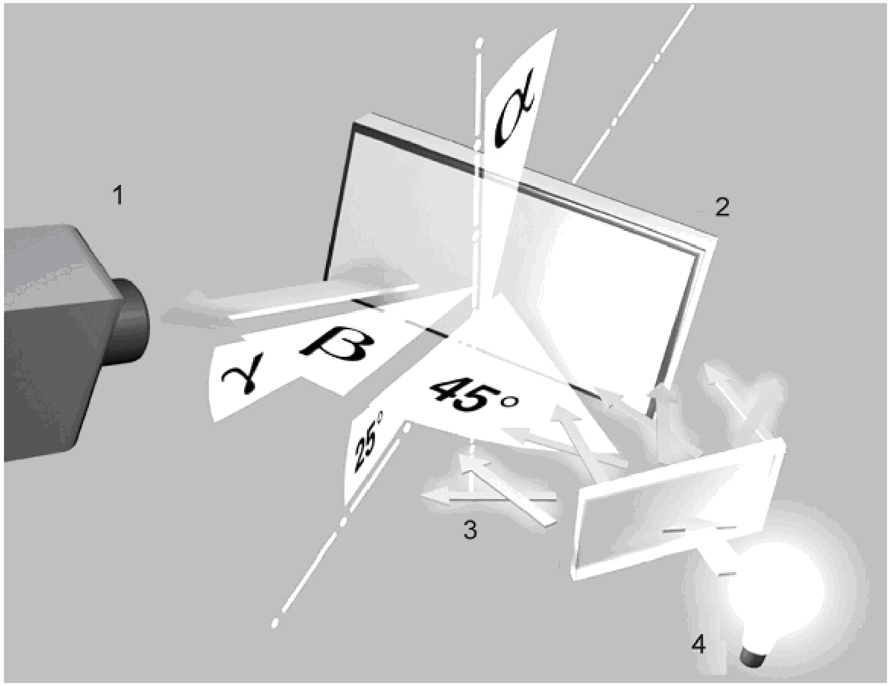
$$CR \approx \frac{300}{0.01 \cdot 5{,}000} + 1 = 7$$

Grey level and color can be calculated as well

- 1% reflection is required for good outdoor performance
- High white luminance of the display is required
- However most references use perpendicular incidence. Oblique conditions lead to higher reflectivity !
- For touch and/or cover glass use optical bonding
- Resistive touch not good for outdoor

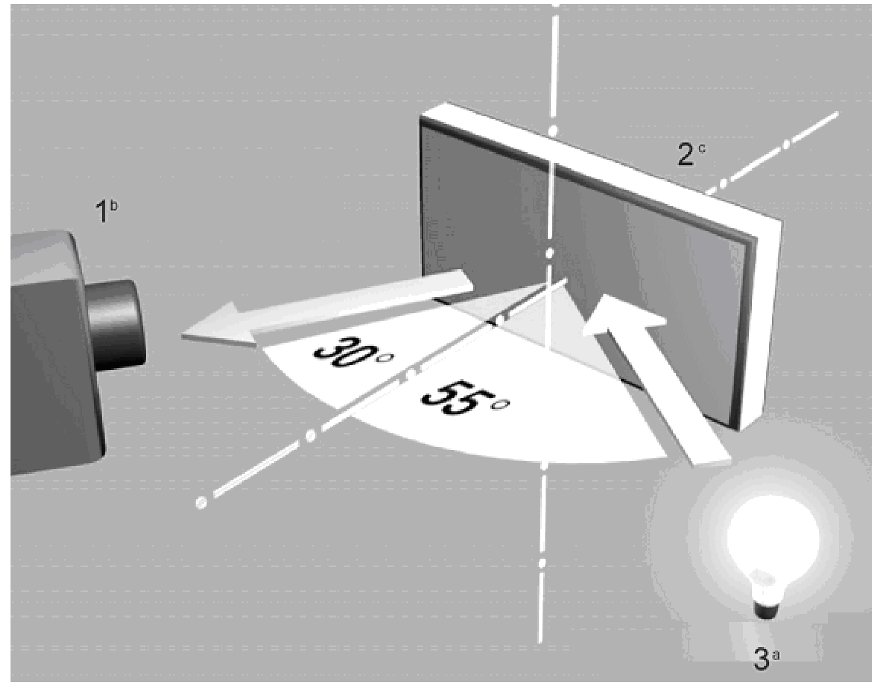
ISO 15008 for Automotive Evaluation : Geometric Set - Up

Daylight Simulation



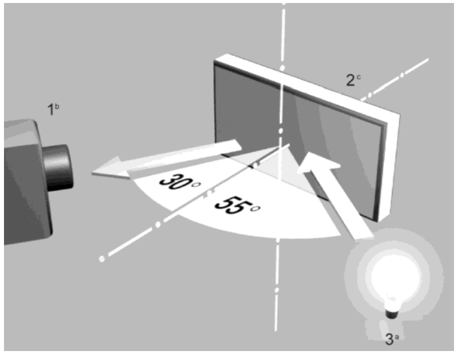
- Angles acc. geometry of driver
- Large diffuser close to display
- Diffuse light with 3,000 lx at display

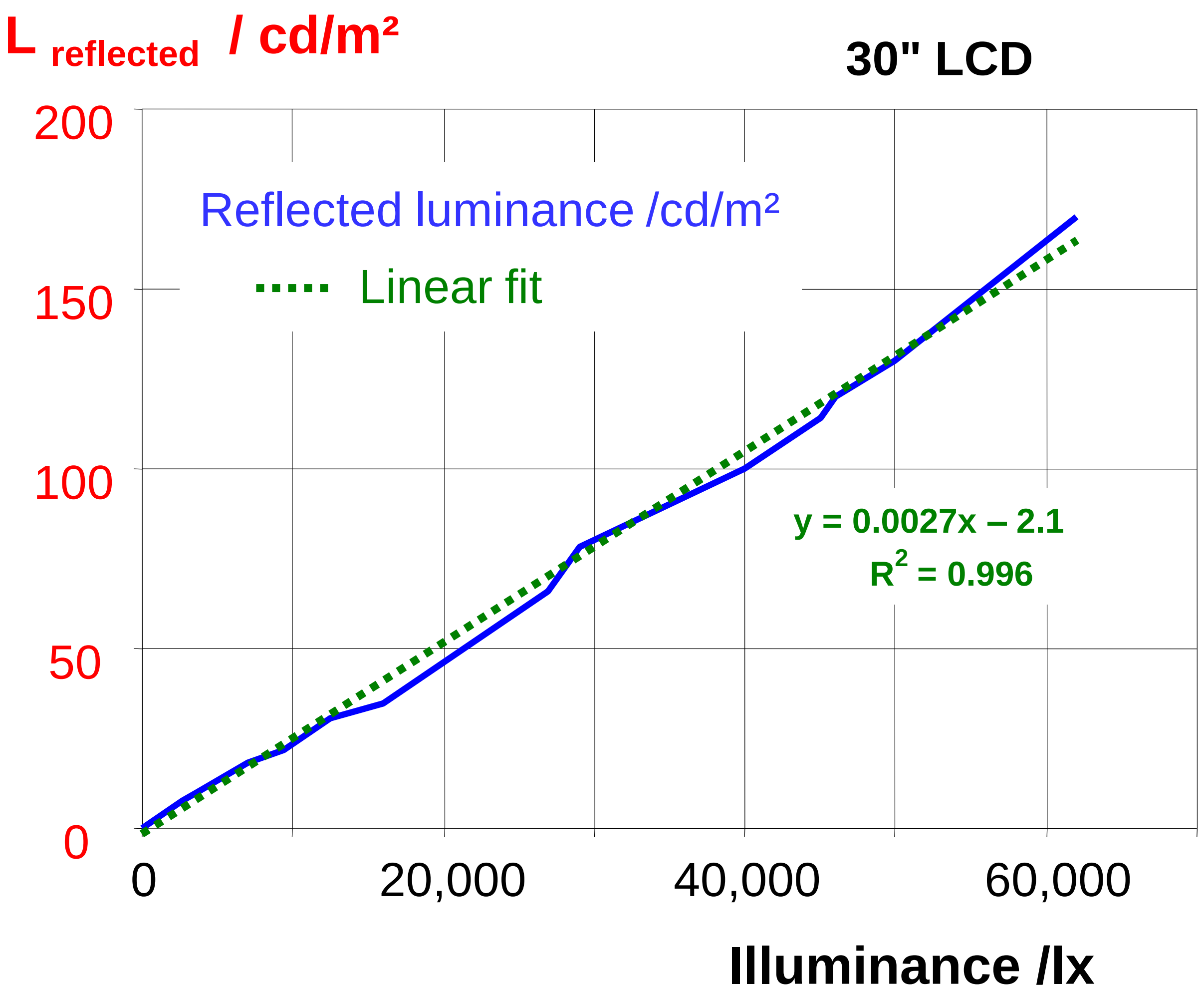
Sunlight Simulation



- Measuring diffuse and haze reflections for sunlight
- Distant small diffuser close to lamp
- Light with 45,000 lx at display

ISO 15008 Sunlight Simulation (I)





$$C_R \approx \frac{\pi L_{white}(0\,lx)}{r\,E}$$

Here:

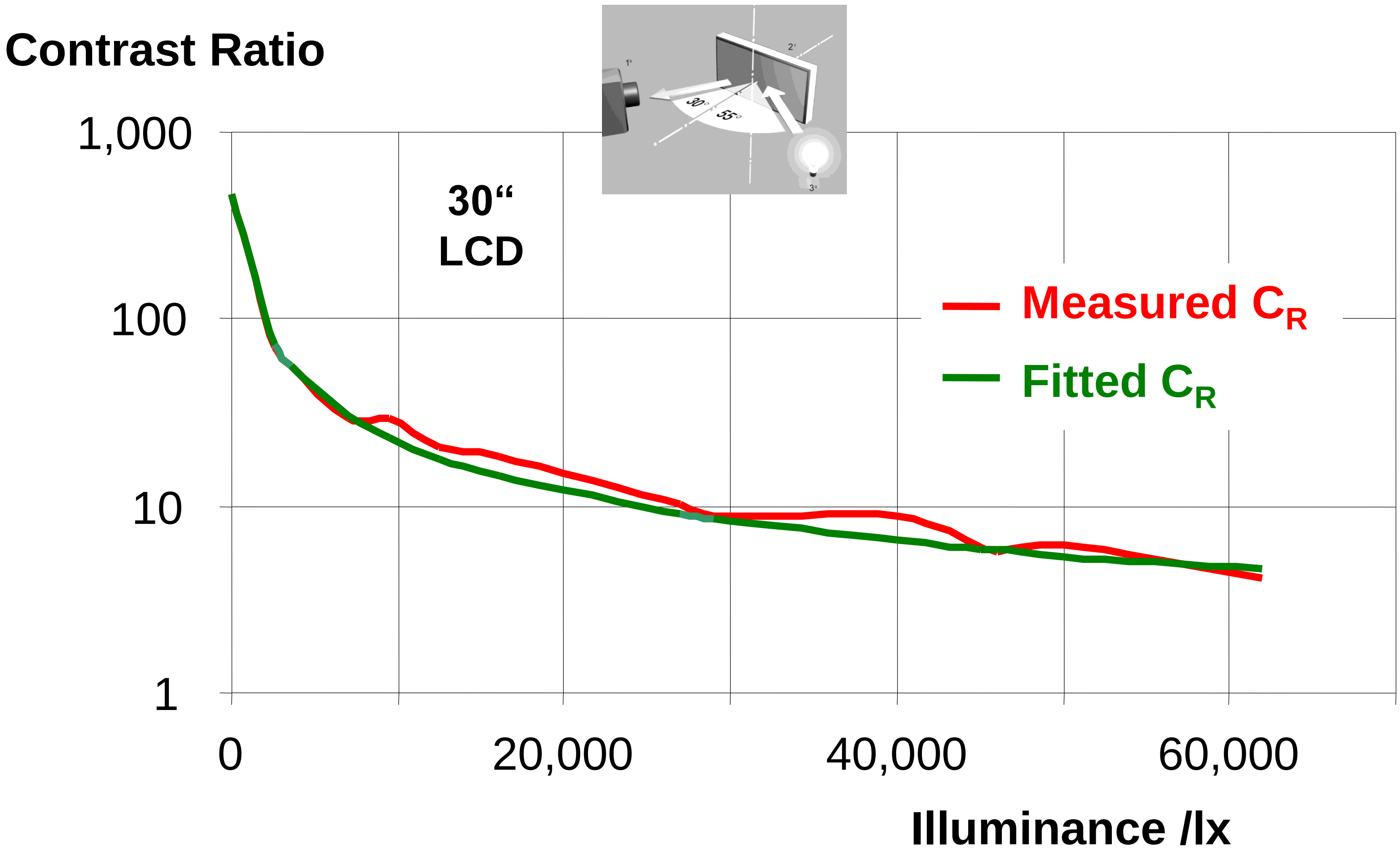
$L_{reflected} = 0.0027\,E$

$\rightarrow\ r = 0.0085$

($\approx$ 1 %)

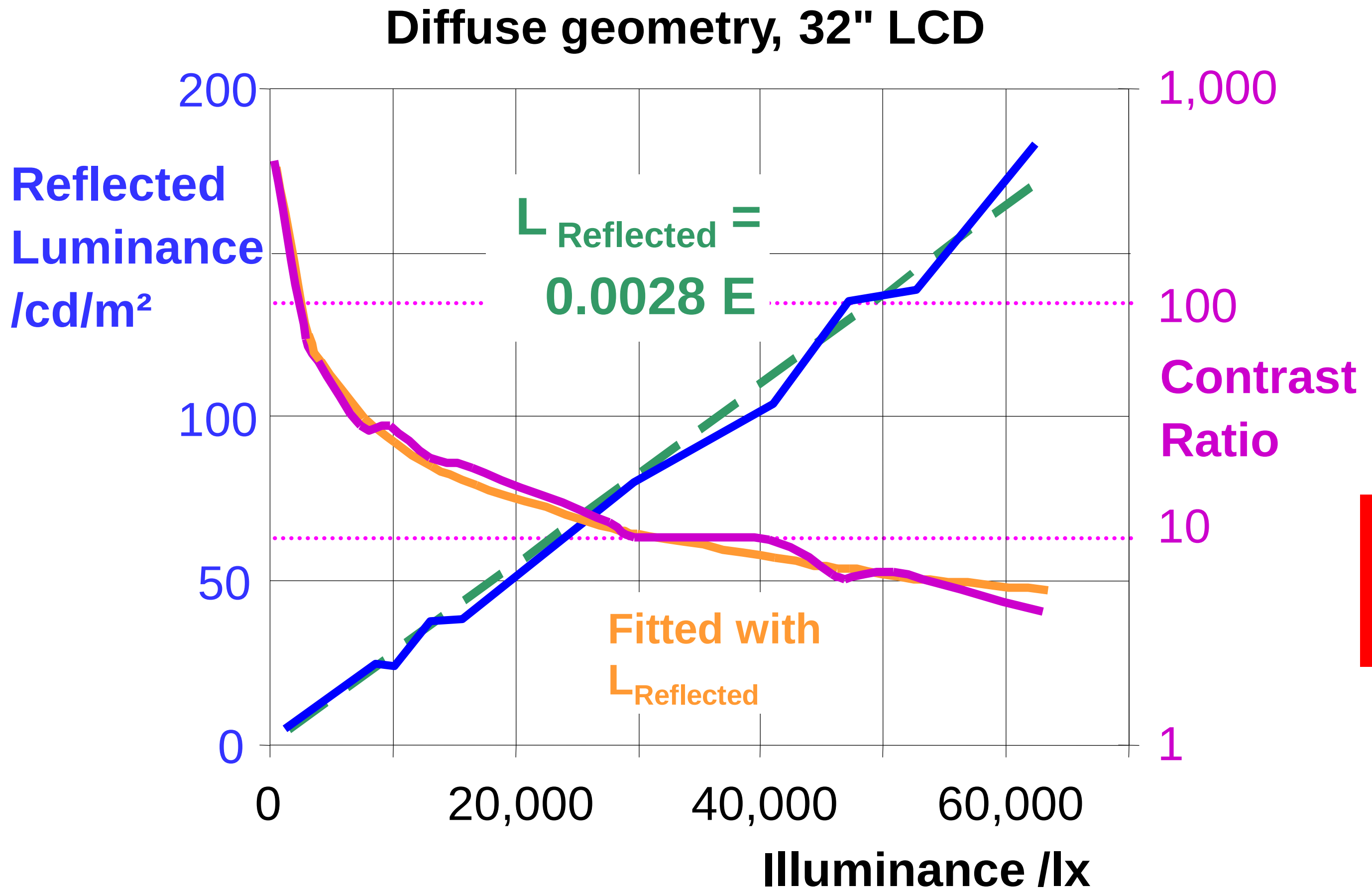
$L_{reflected}$ is proportional to illuminance E → extra-polation to other values

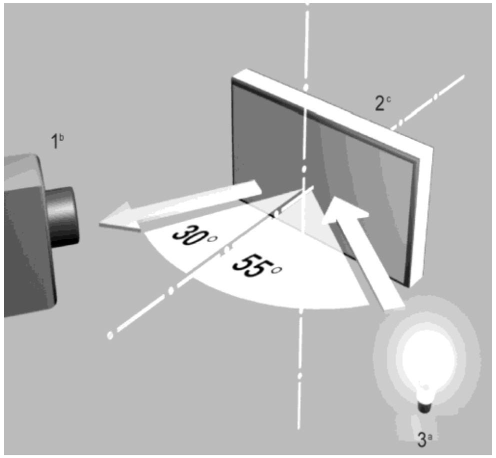
ISO 15008 Sunlight Simulation (II)



Full screen white / black Contrast Ratio was measured and fitted (s.a.): 1/E

ISO 15008 Sunlight Simulation





Results only valid for this set-up !

- **Such measurements are just for comparison**
- **Evaluation in application environment is necessary !**

ISO 15008 for Automotive Evaluation

4.3.1 Minimum contrast

The minimum contrast ratio (higher to lower luminance) between symbol and background shall be

— 5:1 for night conditions,

— 3:1 for day conditions, and

— 2:1 for sunlight conditions.

These figures seem to be relatively low,
but are difficult to achieve in day- or sunlight !

Precautions for High Ambient Light Measurements

Enormous heat can be generated by lamps - display can be damaged!

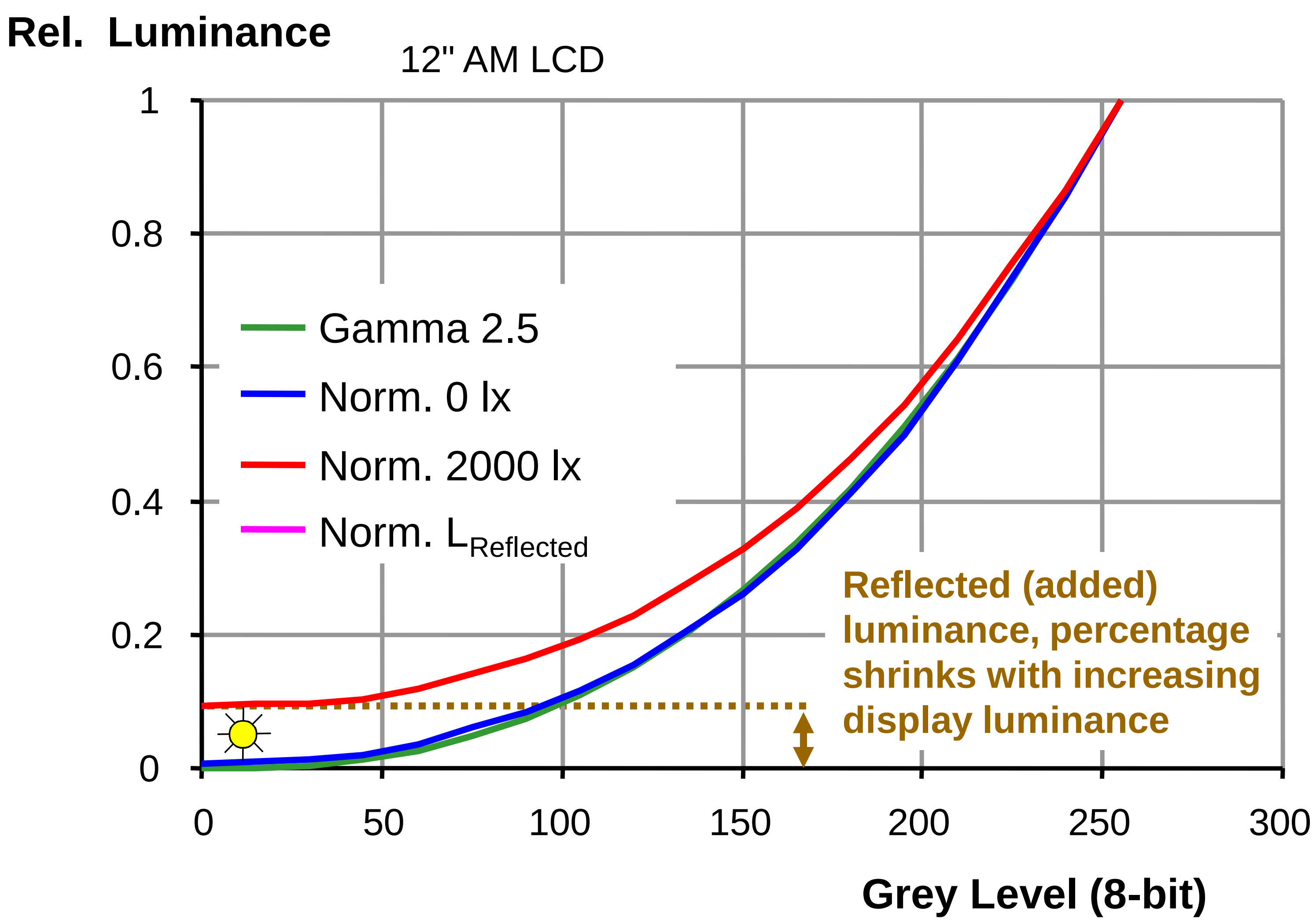
Use IR-blocker or LED lamps and measure temperature at the surface of the display, ventilators are strongly recommended.

LCDs are critical due to polarizer and clearing temperature T_{cl} , other displays can be also sensitive.

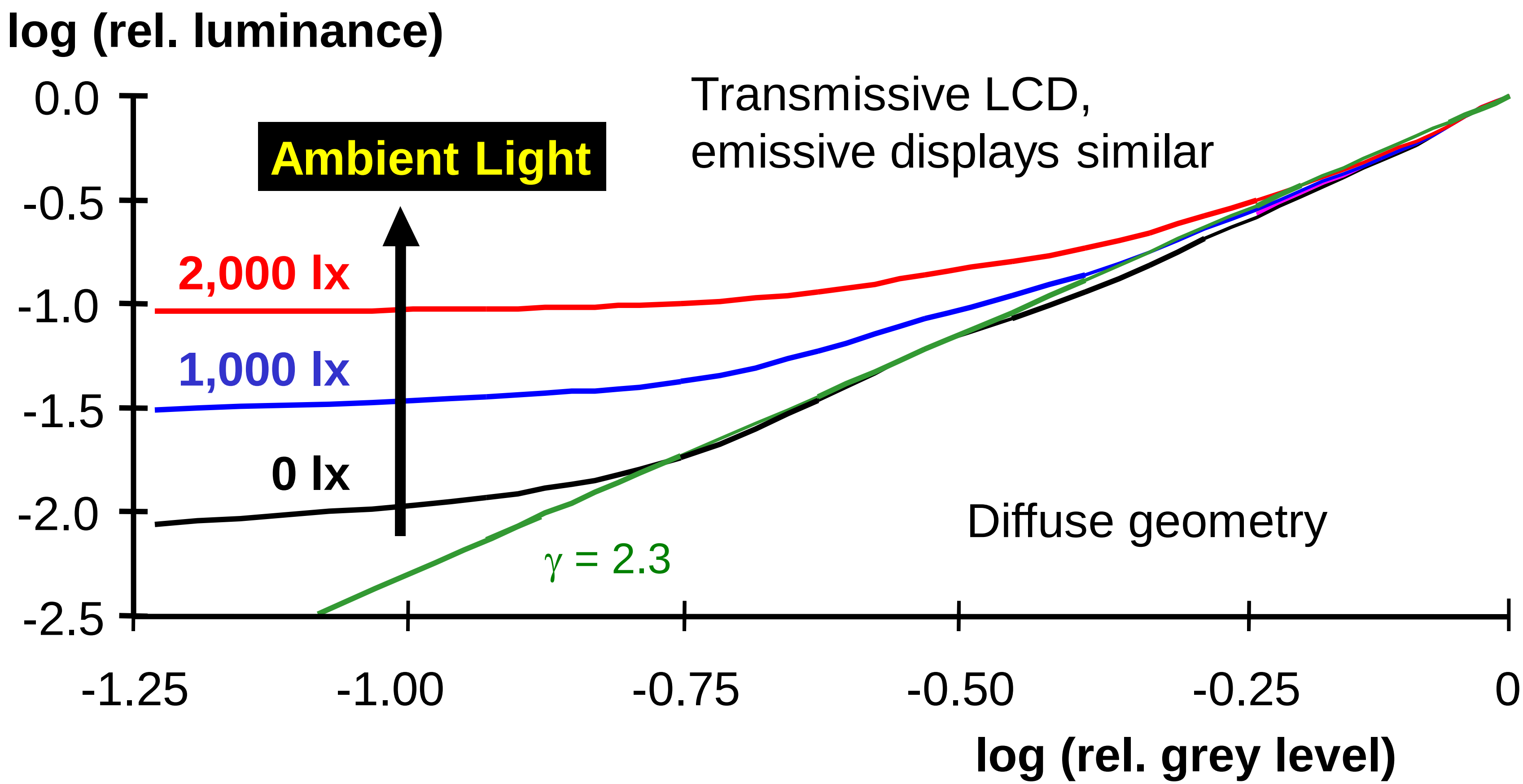
1,000 W light source applied for 30s

White areas of LCD are above T_{cl}

Grey Shades under Diffuse Ambient Light



Ambient Light & Grey Scale



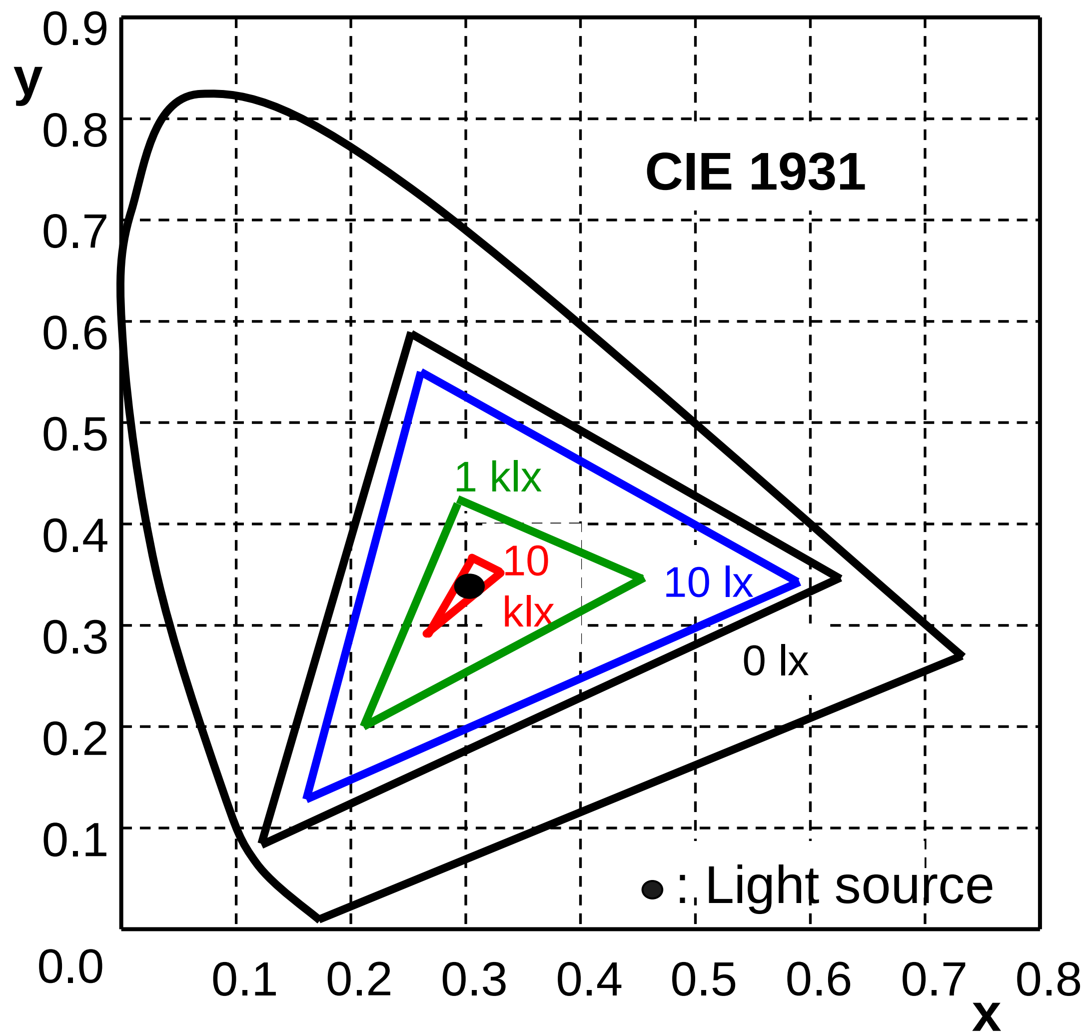
- **Ambient light reduces the number of grey shades (JND)**
- **Do not provide 'information' via low grey levels !**

Ambient Light & Color

- **Reflections on display reduce color gamut**

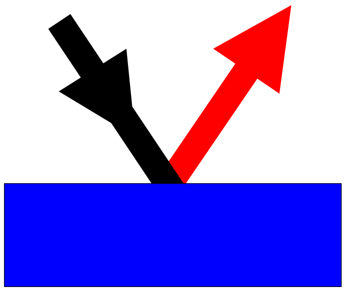
- Color co-ordinates (of the primaries) were shifted towards the co-ordinates of the light source

- Numerical exercise:
  Calculate color shift using Tristimulus and 10 cd/m², … 1,000 cd/m² white reflected luminance



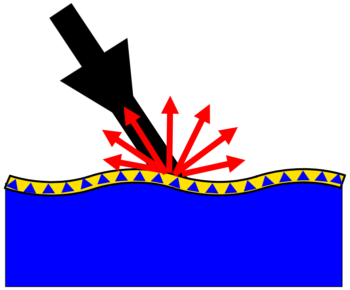
Reflection Reduction Methods (I)

- **Normal**



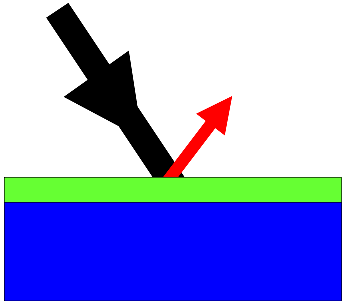
~ 5% reflection for perpendicular incidence

- **Anti-Glare**



Specular → diffuse

- **Anti-Reflex**



Specular reduced

Reflection Reduction Methods (II)

‚Original without anything‘

Anti-Glare

(specular → diffuse)

Anti-Reflex

(specular reduced)

Anti-Glare + Anti-Reflex

(‘best’ + most expensive)

Reflection Reduction Methods (III)

AR

AG

Notch - Filter

Reflection Reduction Methods (IV)

Display Placement:

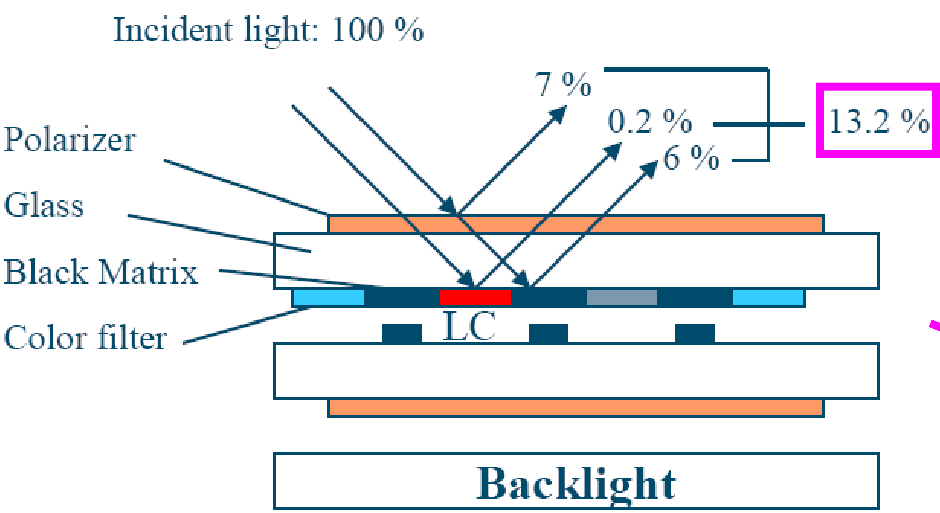
- **Mobile displays**
  Mostly not critical as “turned by user” to reduce most bright specular reflections but certain luminance is required due to eye adaptation

- **Display installations** like airport, e-signage
  - Display cannot be oriented to reduce bright reflections as observer – display geometry cannot be changed
  - Light reflections can be reduced by louvers etc.

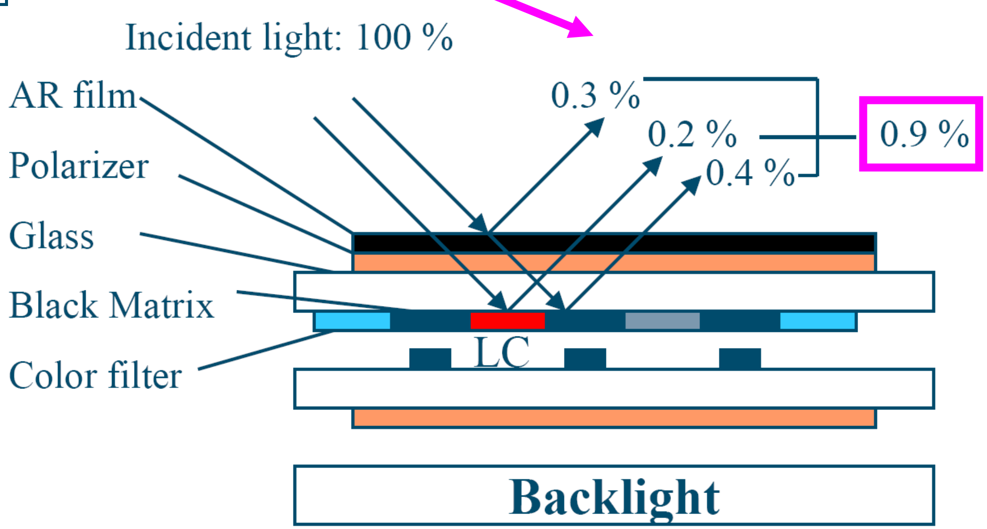
Source: EIZO

Ambient light enables only LED and reflective displays for outdoors

AM LCDs: Ambient Light & Reflections



Anti-Reflective coating on polarizer and replacing Cr black matrix with CrO_2/Cr



Ambient Light Reflections vs Grey Level & Visibility

Reflections are 'enhanced' on dark areas and 'invisible' for 'bright' areas'

Same display, geometry, illumination etc.

Case Study : Ambient Light

- **Task**
  Design "readable" display

- **Conditions**: Ambient light, display location, "light from everywhere", …
- **Solutions**:

Summary & Questions

- Ambient light measurements are difficult to perform
- Illuminance measurements are standardisized but usefulness to real world is limited. However displays can be compared by standards procedures.
- Ambient light calculations can easily be done for projection (diffuse screen)
- Ambient light degrades all dark room parameters
- Why is illuminance for specular relative low ?
- Types of reflections, parameters, … ?
- Why is the reflected luminance proportional to the illuminance ? Are there limits ?
- Which display has a better performance in bright light :
  - Low max. luminance and superb AR + AG
  - High max. luminance but standard reflection reduction ?
- LCD of E-Signage at elevator ‘sparkles’. What is that and reason why ?

Overview

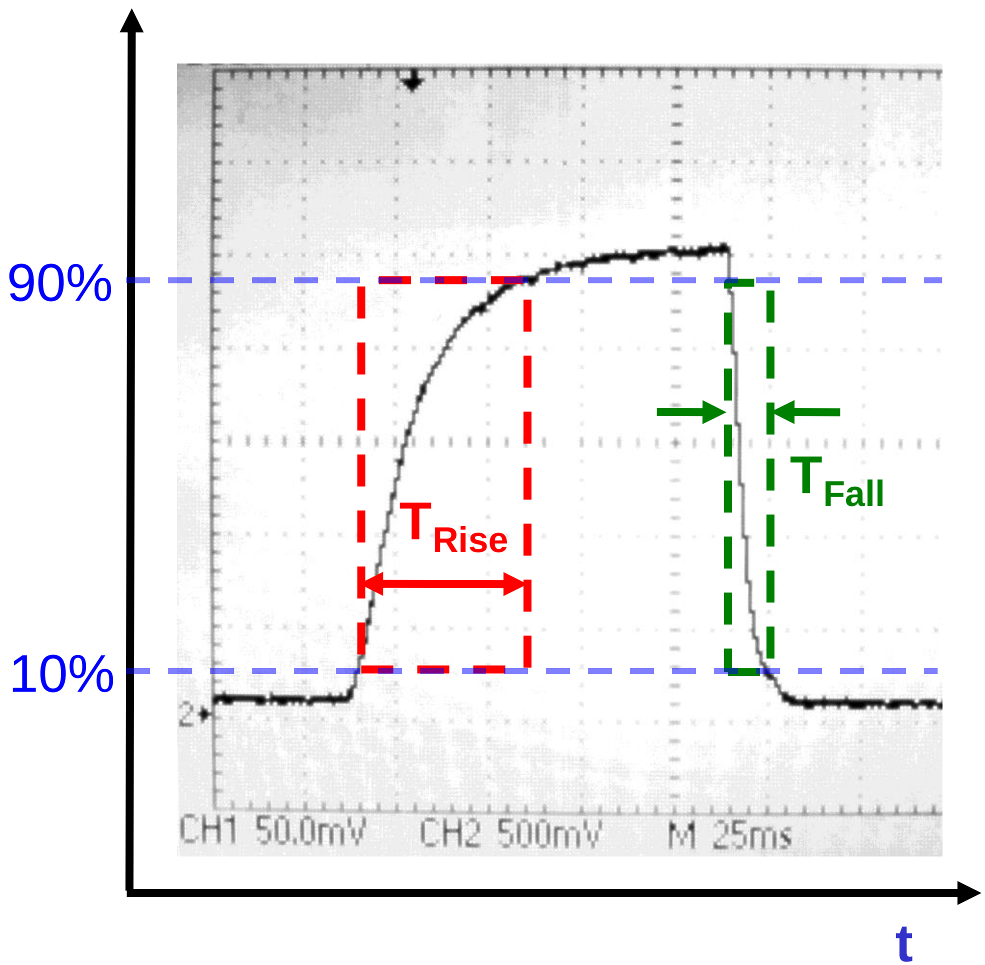
Some selected topics,
others - including for other display technologies - can be also relevant!

- Introduction
- Basic Parameters (Merits)
- Common Issues
- Display Technology Dependent Issues (Shortcomings)
- Summary

- LCD: Response time, viewing angle
- PDP: Loading, false contour

Response, Rise and Fall Time (Switching Time, Speed)

Def: $T_{Response} = T_{Rise} + T_{fall}$



„Response time“ is also often used for rise or fall time.

The “standard” definition for rise 10% - 90% and 90% - 10% for fall is used.

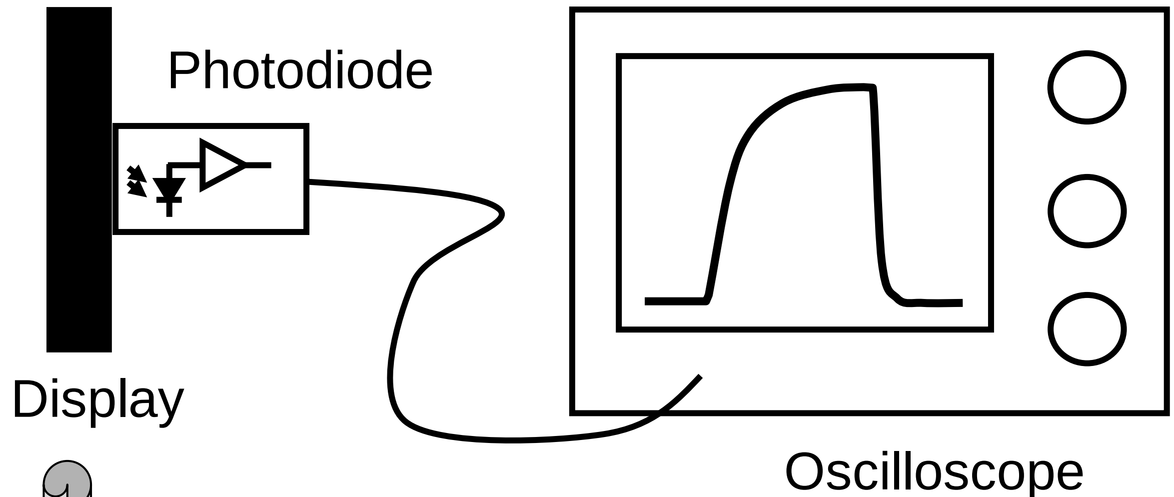
However for LCDs, raise and fall time might not be the same. Furthermore, the rise and fall time depend on the “jump” from initial to final grey level (s.b.). This is called G2G response time.

Switching Time Measurements

Test pattern:

Switch black ↔ white,

grey 1 ↔ grey 2, …



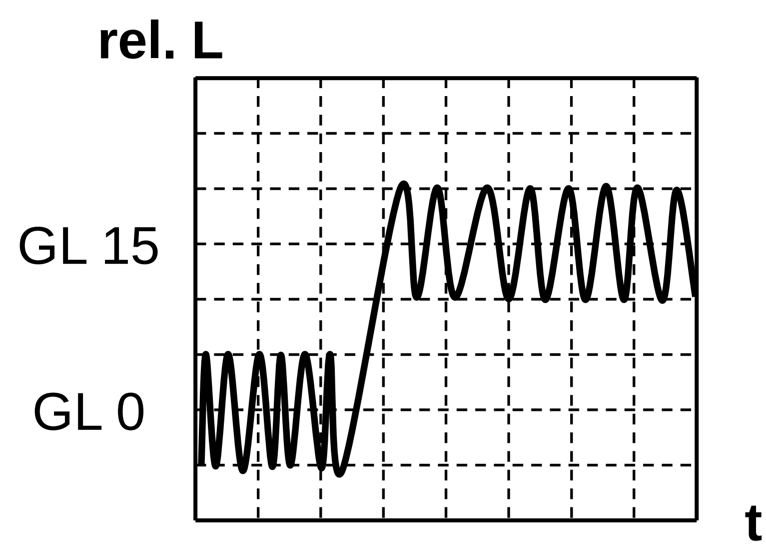
Measure front surface temperature for LCDs as $T_{Response} = T_{Tesponse}(T)$

Issue:

Noisy signal at low grey levels

→ 10% ↔ 90% difficult to extract

→ filter with moving average, …



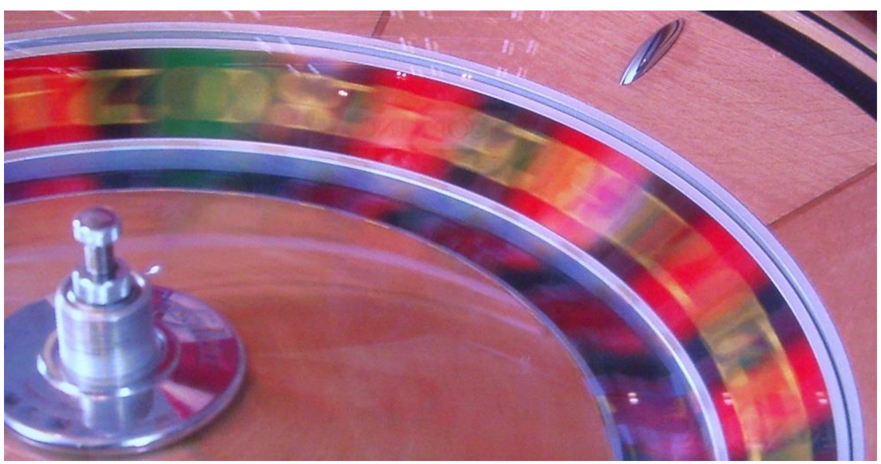
LCDs : Response Time Effects

Temperature dependent !

$\boxed{Ta=25℃,}$ f_v =60Hz,VCC=3.3V

Item	Symbol	Condition	Min.	Typ.	Max.	Unit	Remarks
Response Time	Rise(Ton)	$\phi=0°, \theta=0$	-	15	-	ms	Note 4
	Fall(Toff)		-	10	-		

Only K→W (rising) and W→K (falling) is given, values are different !



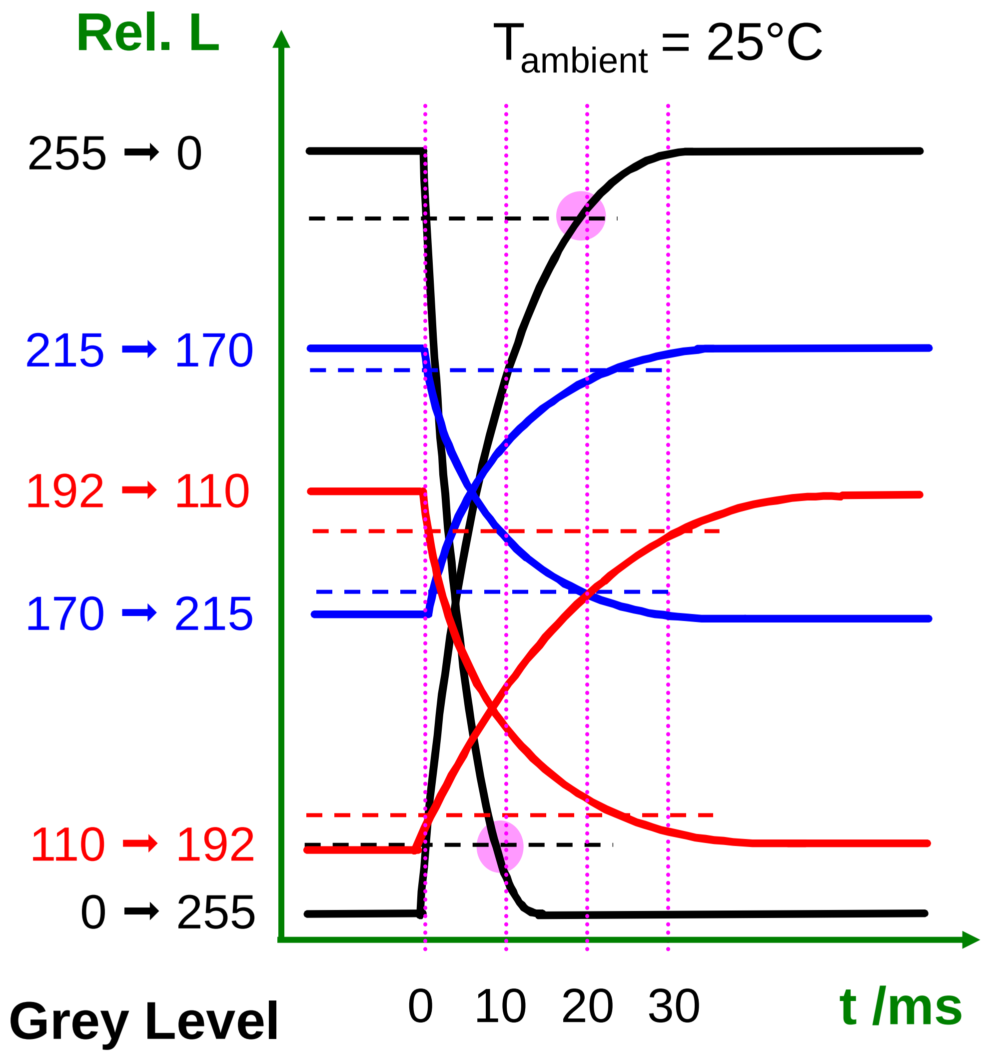
Pixel per frame

‚Visible‘ response time

Scroll direction

No ‚visible‘ response time

LCDs : Response Time Effects

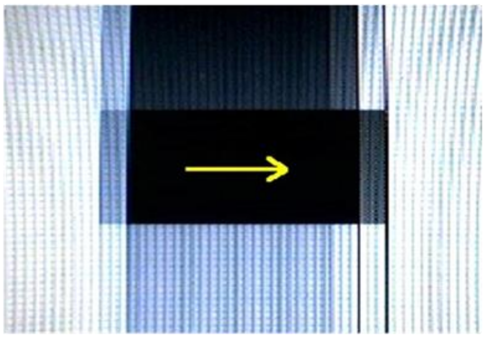


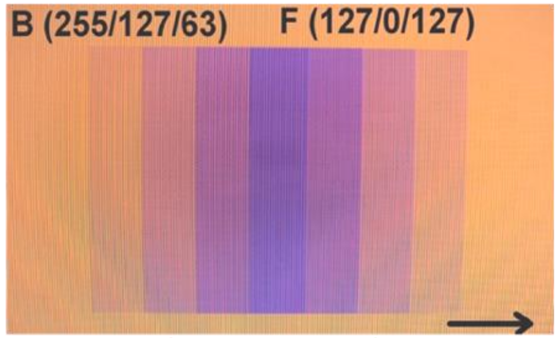
Grey level transition	T_{Rise} /ms	T_{Fall} /ms
0 ↔ 255	20	9
110 ↔ 192	32	24
170 ↔ 215	23	19

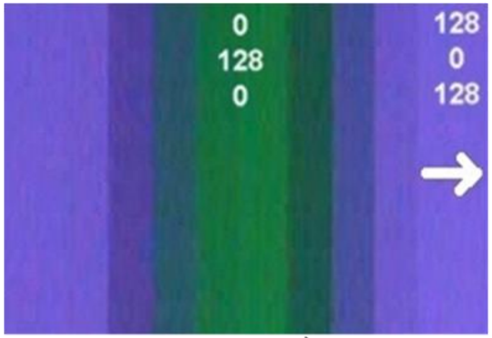
- T > frame time (16.7 ms)
- T_{Rise} > T_{Fall}
- T = T(grey 1 ➞ grey 2)

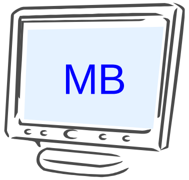
Grey level & color shifts !

Moving Picture Response Time (MPRT) : Visual Assessment







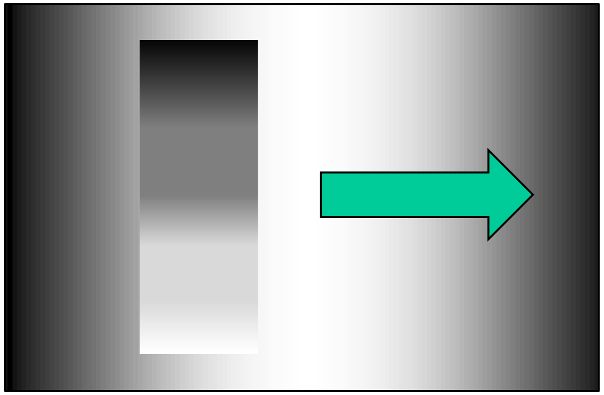


Fall time

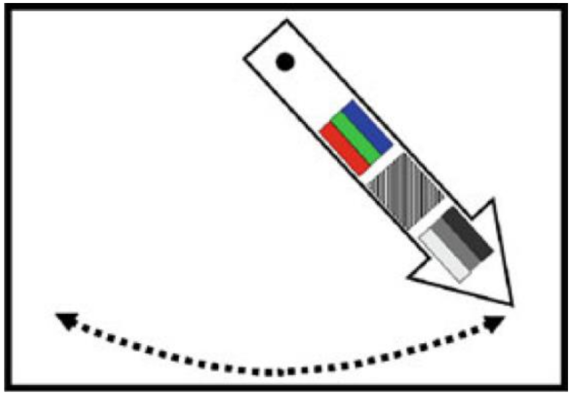
Rise time

'Dark'

Bar with 9 GLs



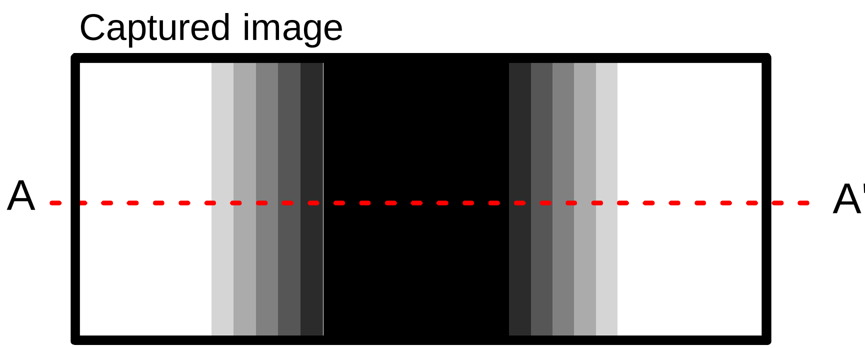
Moving Pendulum

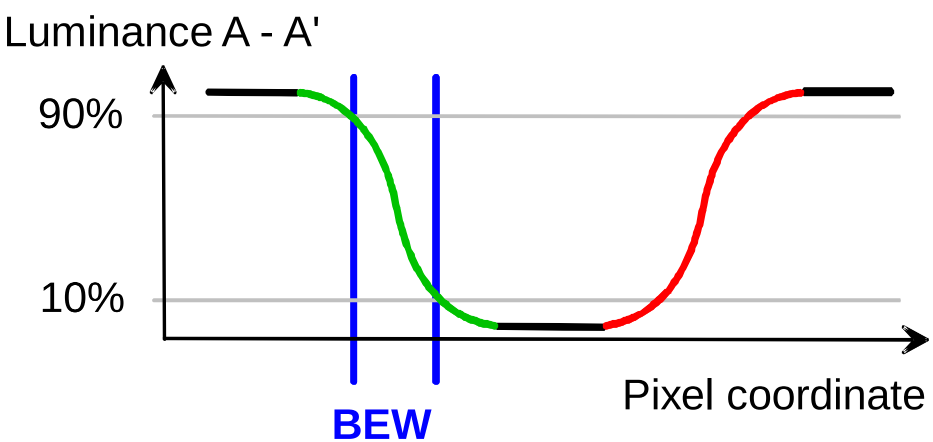


Use also
PFU DL
ANDROID
Motion Blur
App

Moving Picture Response Time (MPRT)

Blur (or Brightness) Edge Width





Measurement setup:

Camera and screen (one moving, one fixed)

VESA

- GL 0, 6, 18, 36, 63 and 100% (equidistant in lightness)
- Measure GL_i to GL_j for all $i \neq j$
- 10% to 90% Blur-edge width b_{ij} (in units of pixels)
- Extended BEW $w_{ij} = b_{ij} / 0.8$
- MPRT (seconds) with
  N: number of $i \neq j$ transitions, here 30
  u: speed (pixels per frame time)

$$\boxed{\mathrm{MPRT} = \frac{1}{u\,N} \sum_{i \neq j} w_{ij}}$$

LCD TV : MPRT ≈ 25 ms ≈ 2.5 T_R

Visual inspection of Response Time

… with PIXPERAN by Wilfried Welti

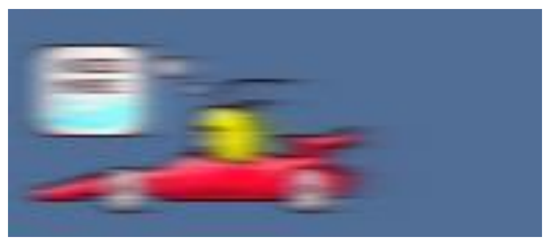
Motion blur by hold-type display

Original

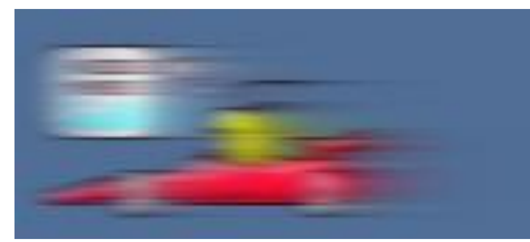
$T_{rise} = T_{fall} = 2$ ms

$T_{rise} = T_{fall} = 5$ ms

$T_{rise} = T_{fall} = 10$ ms



$T_{rise} = T_{fall} = 20$ ms

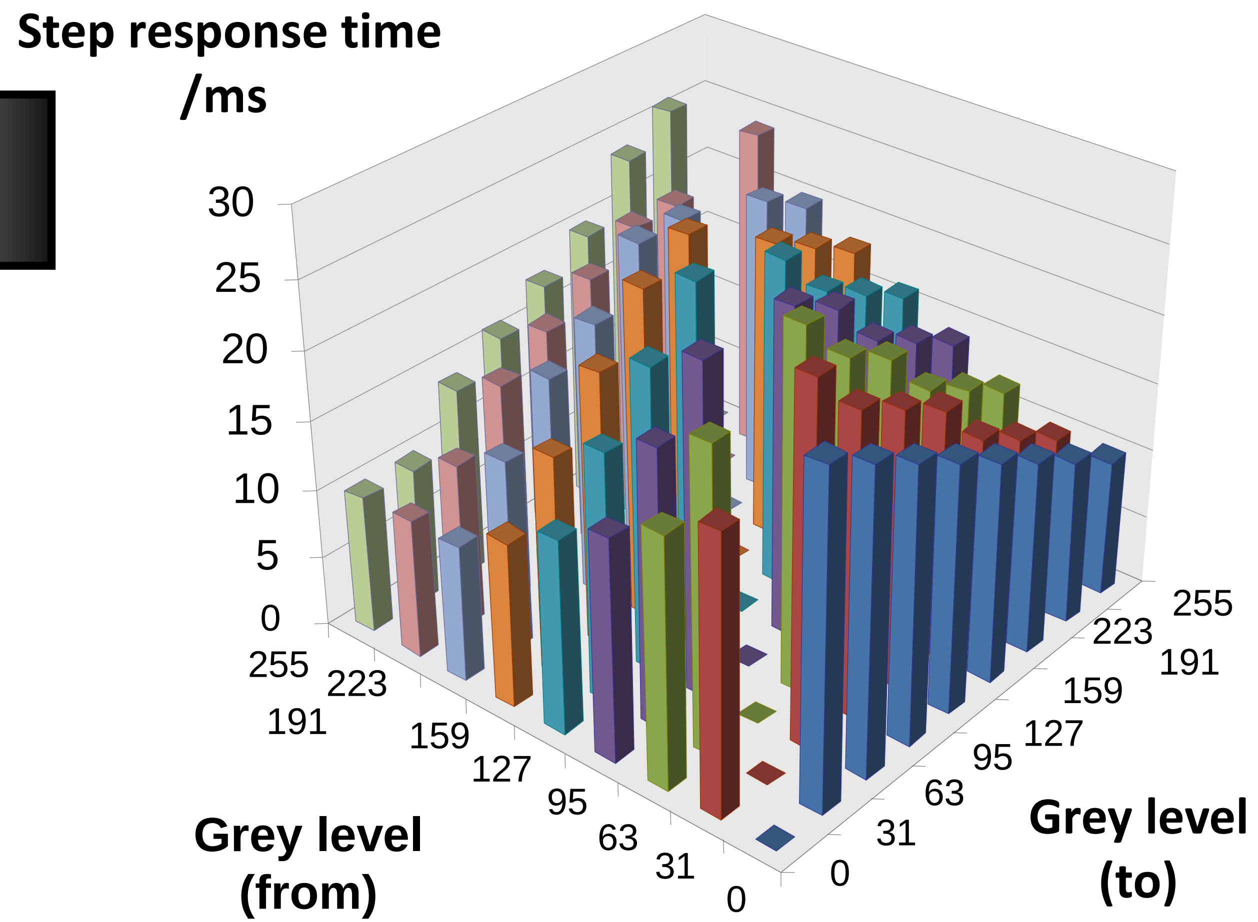


$T_{rise} = T_{fall} = 50$ ms

Improvement by blinking backlight or Black Frame Insertion (see AM Driving)

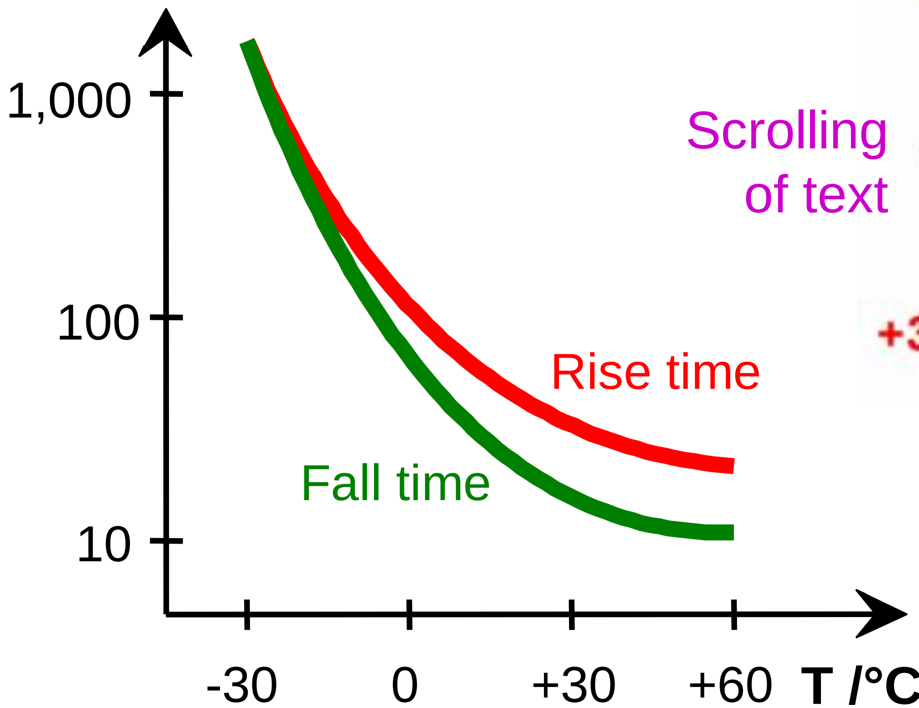
Measurement of Grey – To – Grey LCD Response Time

Grey shade dependent !



Temperature Dependency of LCD Response Time

Response Time /ms



What does RT (25°C) mean?
- LC has 25°C **or**
- Air temperature is 25°C
  (“hot” backlight → LC 50°C)

Typical requirement:
- Text, graphics < 50 ms
- Video, touch < 16 ms

Watch out in spec!

Summary & Questions

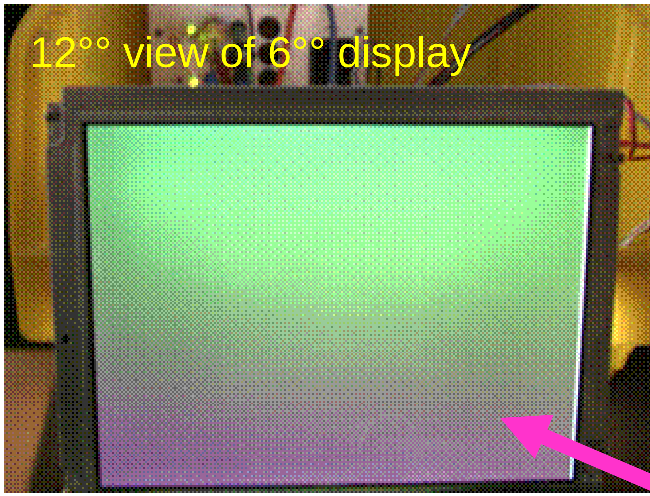
- Response time is mostly given for K → W and W → K.
  This is especially for LCDs misleading – why ?
- Response time of LCDs depend on … .
- What are the reasons for motion blur and how can that reduced ?
  Search in internet.
- (Test your LCD monitor for flicker.)

Overview

Some selected topics, others - including for other display technologies - can be also relevant!

- Introduction
- Basic Parameters (Merits)
- Common Issues
- Display Technology Dependent Issues (Shortcomings)
  - LCD: Response time, viewing angle
  - PDP: Loading, false contour
- Summary

LCDs Viewing Angle Examples



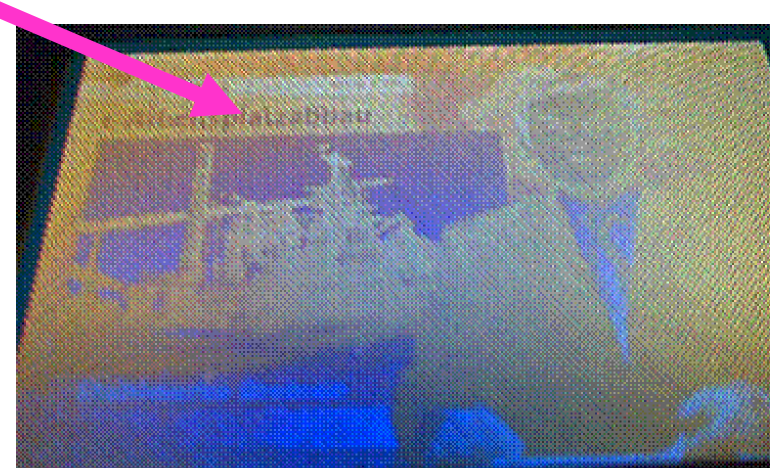
OLED

Color inversion !

← perpendicular

Moiré

6°° →



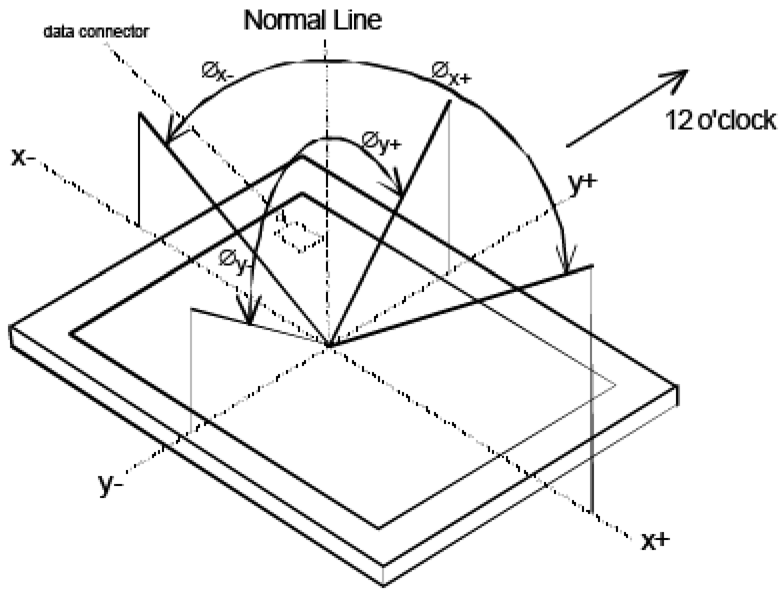
Example from LCD – Specification / Data Sheet

Threshold definition

Parameter		Symbol	Condition	Min.	Typ.	Max.	Unit
Viewing Angle	Horizontal	Øx+	CR>10, Øy = ±0°	-	60	-	deg.
		Øx-	CR>10, Øy = ±0°	-	60	-	deg.
	Vertical	Øy+	CR>10, Øx = ±0°	-	45	-	deg.
		Øy-	CR>10, Øx = ±0°	-	50	-	deg.

Viewing angle is a threshold definition:

- The maximum CR is about 500:1
- "Viewing angle" is provided for 10:1
- CR do not represent grey scale and color degradations !

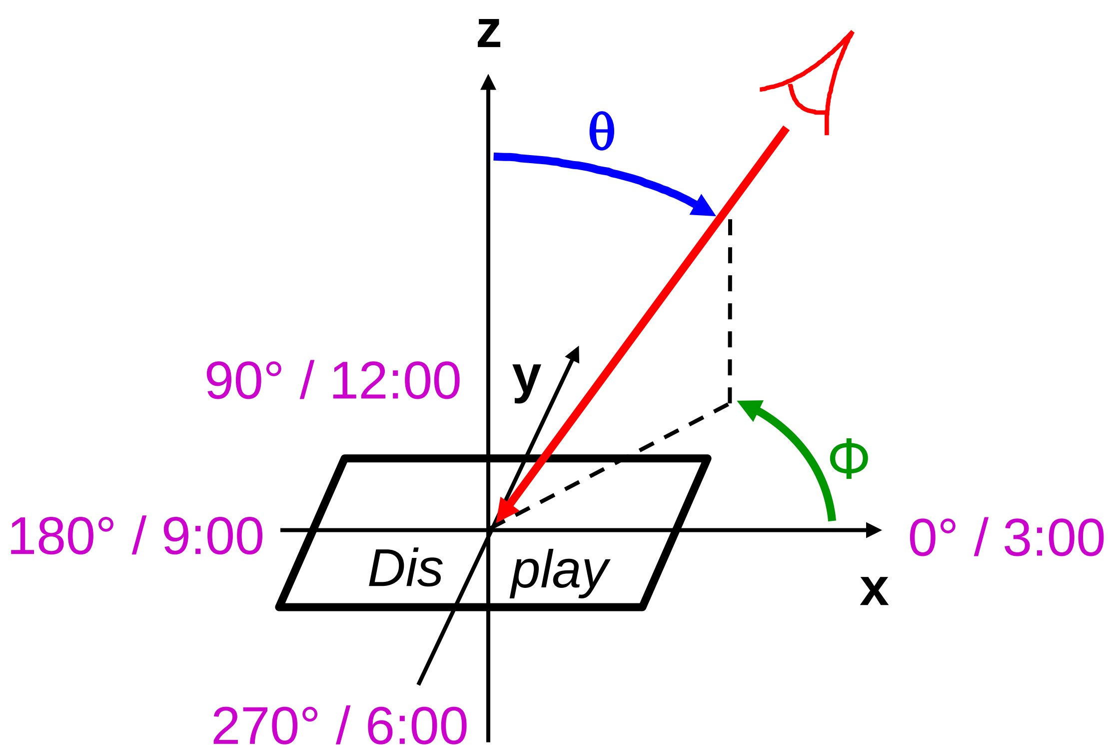


Definition of Viewing Angle

Acc. IEC 61747 :

- θ : from z - axis
- ϕ: xy - plane

2D und 3D measurements

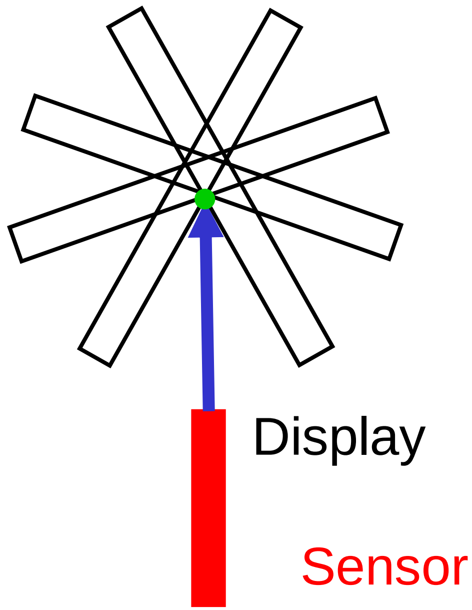


Definition:

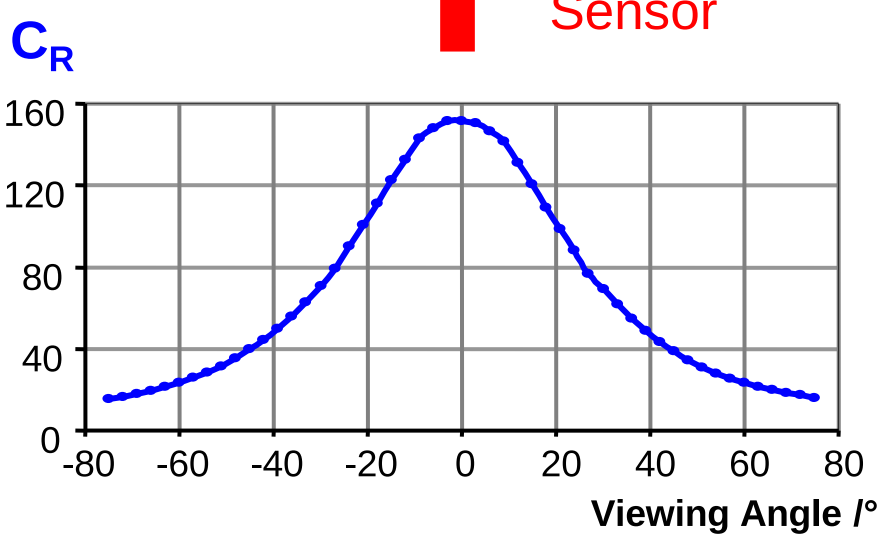
- Φ = 6:00 (6 o'clock, 6OK) : calculator, watch, smartphone, bus, …
- Φ = 12:00 : Laptop, automotive CID, vending machines, ...

Viewing Angle Measurement Set-ups

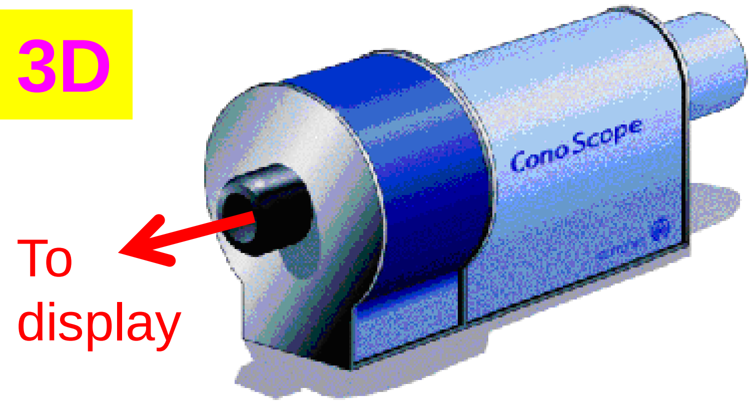
2D



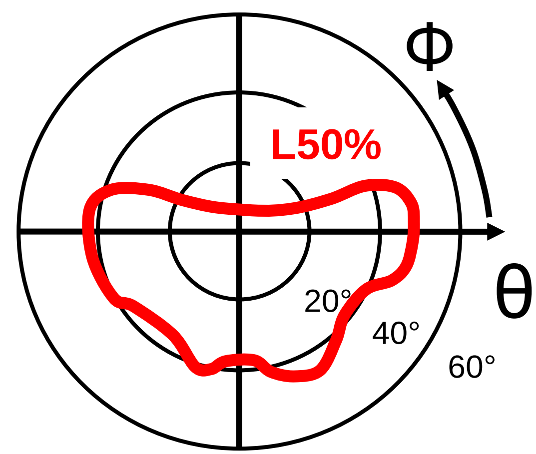
Only horizontal and vertical line charts



3D



Better but costly: all viewing angle as iso plot (iso = lines of constant L or CR, …)

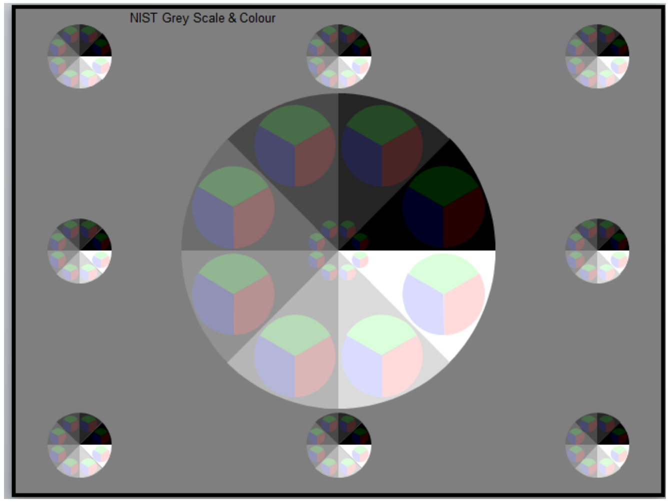


Viewing Angle Overview

- **Methods for measuring and chart**
  - 2D
  - 3D

- **Measurements** (full screen, patterns see § Basic Parameters)
  - Luminance
  - Contrast ratio
  - Grey scale
  - Color

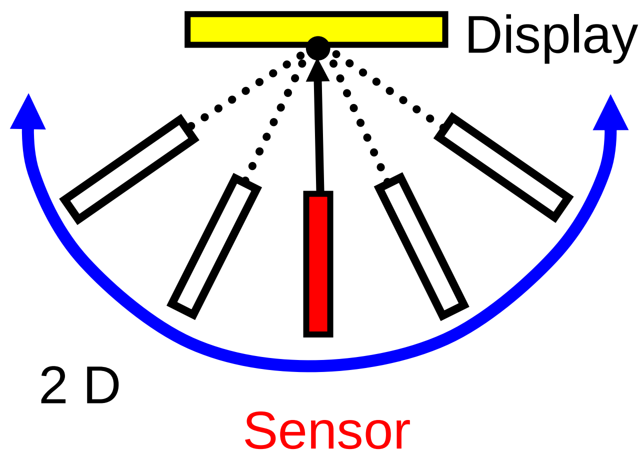
- **Visual inspection:**

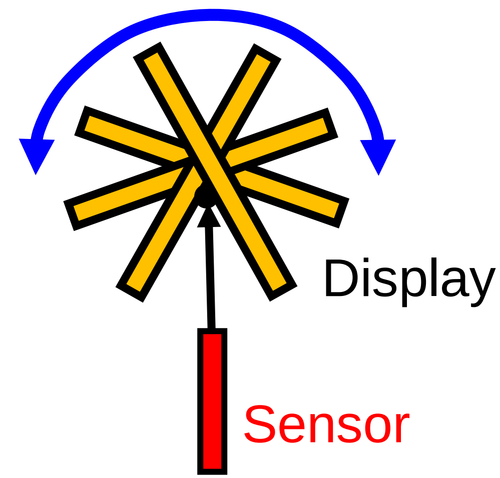


Viewing Angle Measurement Set-ups: Gonioscopic

2D

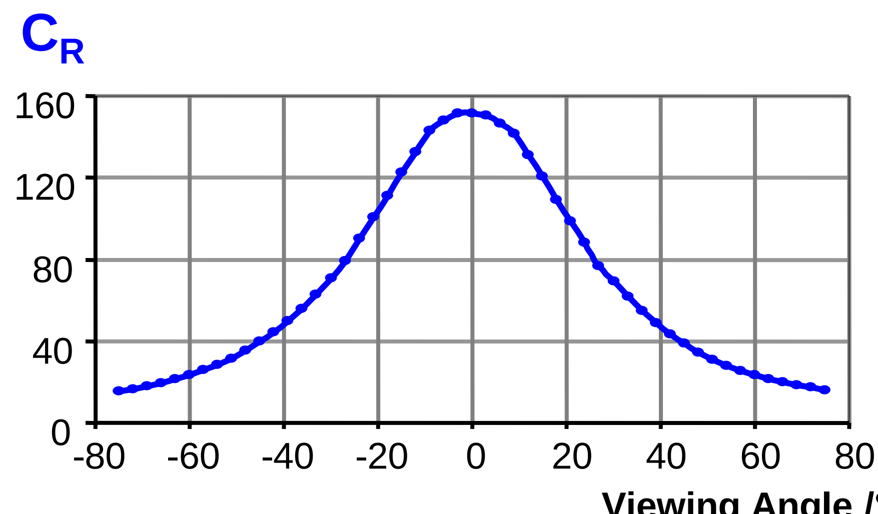
Lab training



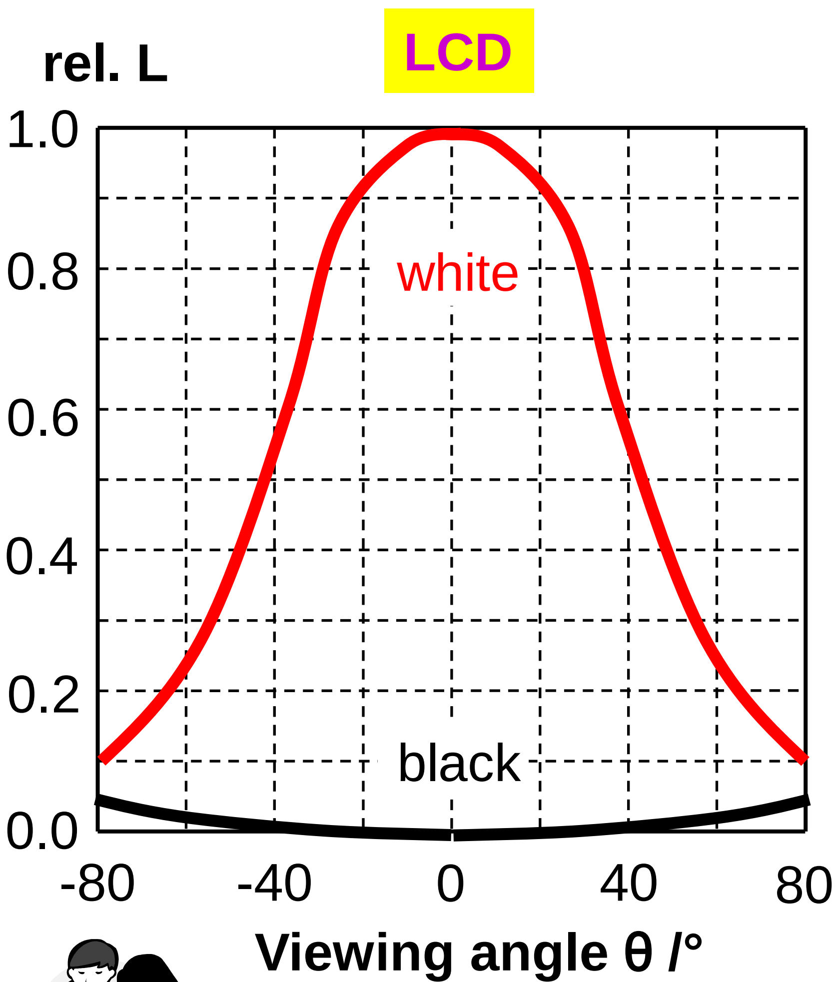


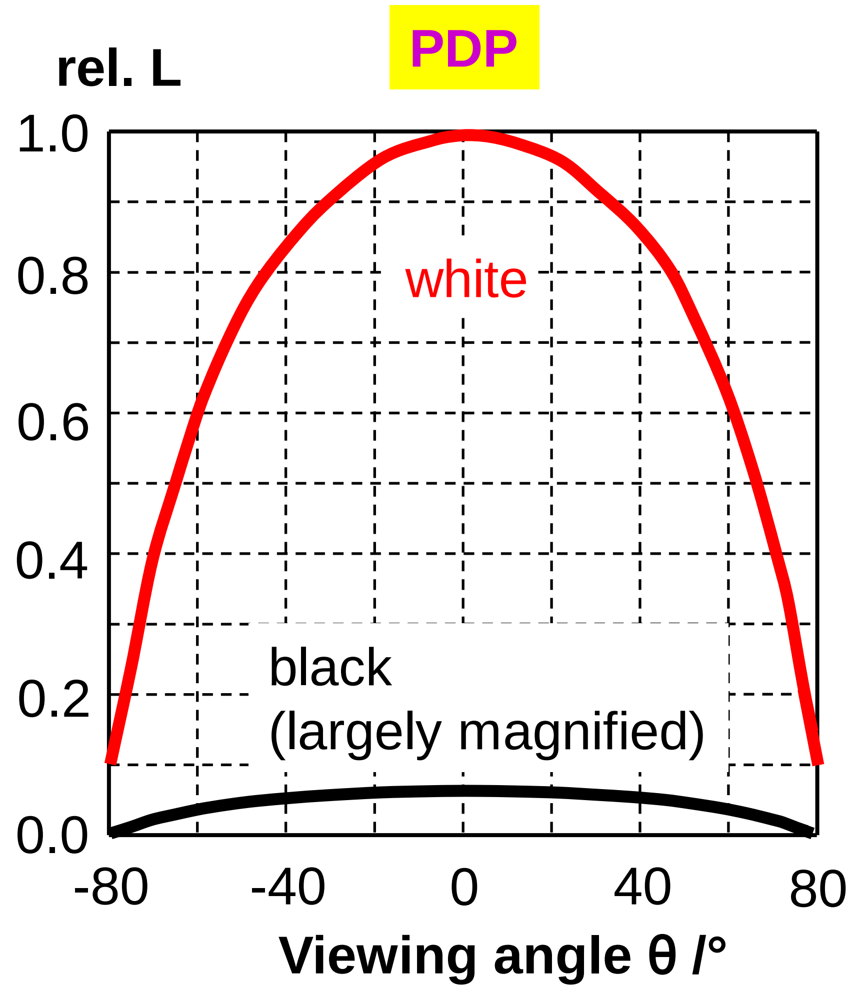
Recommended for large displays

Typical result:
Horizontal and vertical line charts



2D Luminance Dependency of Horizontal Viewing Angle

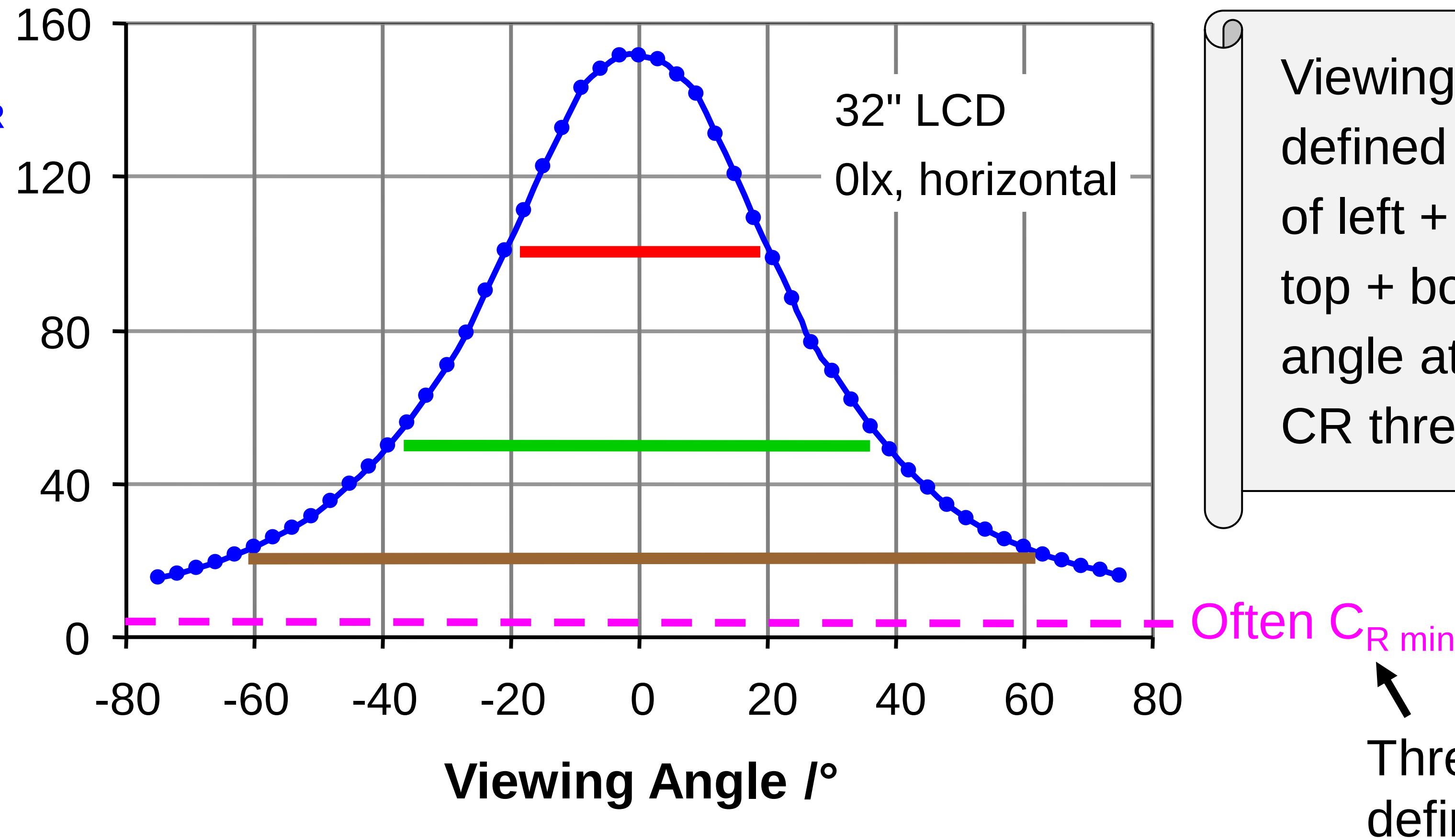




Lab training

Lambertian emitter with some geometric blocking (barrier ribs)

2D Contrast Ratio Dependency from Viewing Angle of LCD

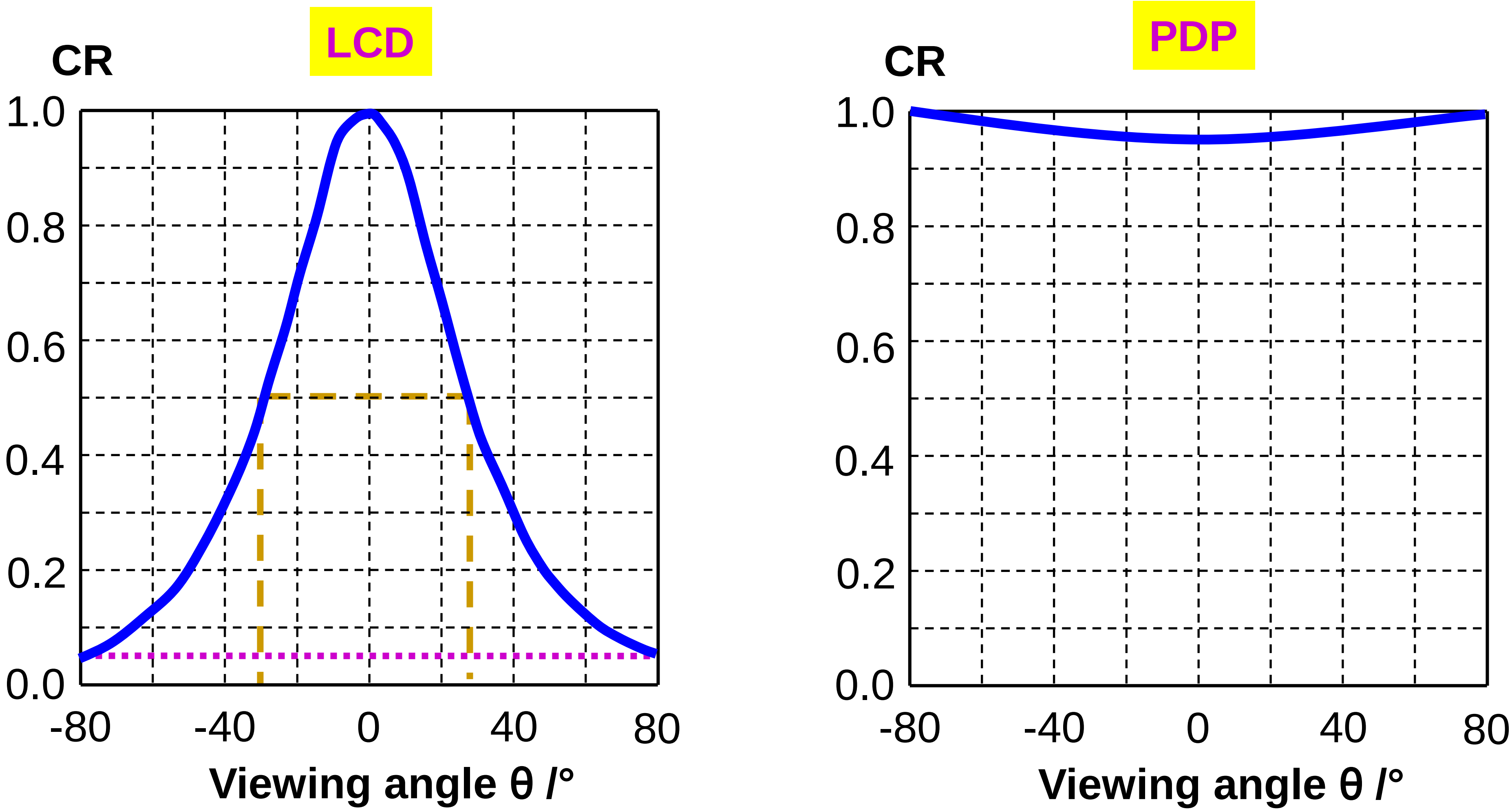


Viewing angle is defined as sum of left + right or top + bottom angle at given CR threshold.

Specify viewing angle only with the minimum contrast ratio (or better color difference ΔE)

here : 40° @ C_R > 100 : 1 ; 70° @ C_R > 50 : 1 ; 125° @ C_R > 20 : 1 ; ??° @ C_R > 5 : 1

2D Contrast Ratio Dependency of Horizontal Viewing Angle

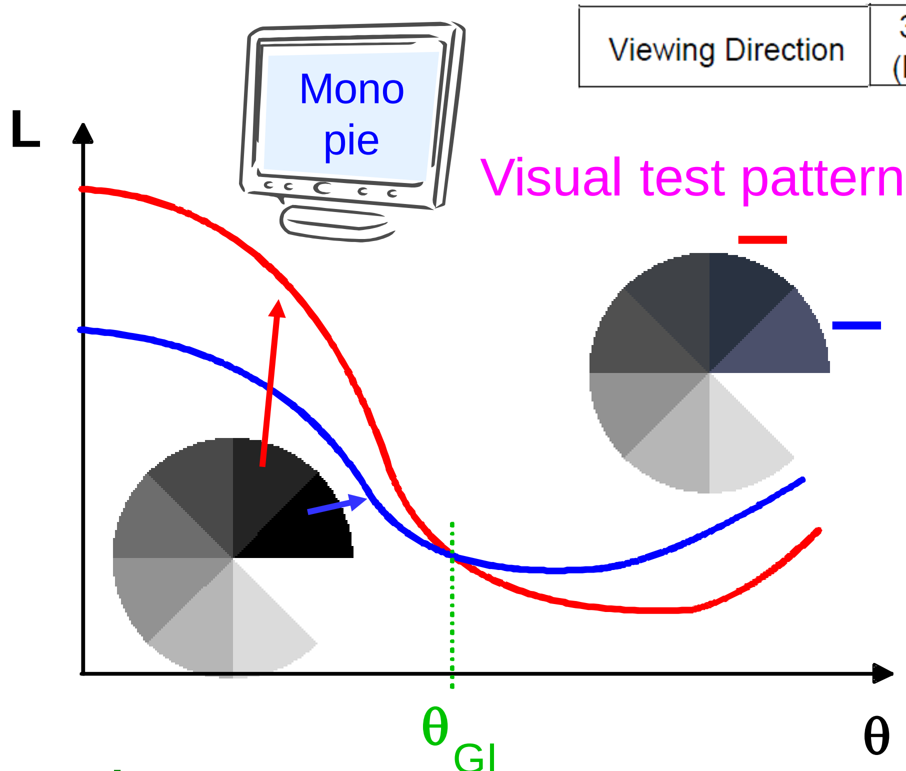


PDP shows “no dependency” as luminance for black and white has the same angular characteristic

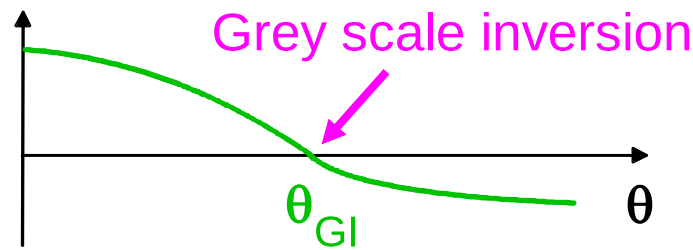
2D Grey Scale Inversion

16:9 in portrait mode

Viewing Direction	3 O'clock (No inversion of gray level scale and less change in brightness)



$\Delta L = L_{dark\ grey} - L_{black}$



Remarks

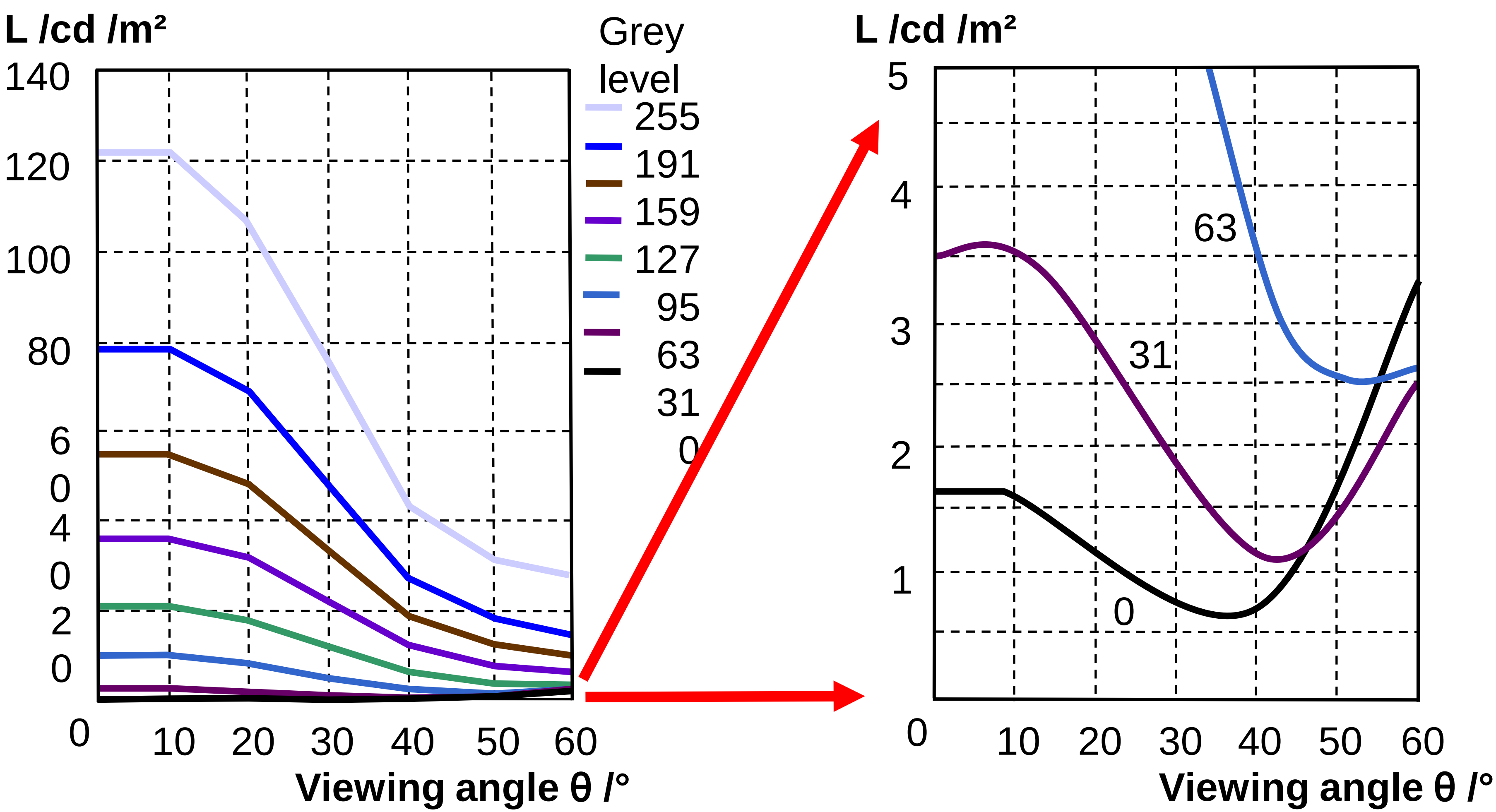
- If the sign doesn't change and luminance levels only merge, the image quality is horrible, but grey scale inversion doesn't 'occur' in meaning of standard (norm)

- Contrast inversion is the extreme case of grey scale inversion, when maximum and minimum luminance levels change

2D Grey Scale Dependency

AMLCD 12", horizontal

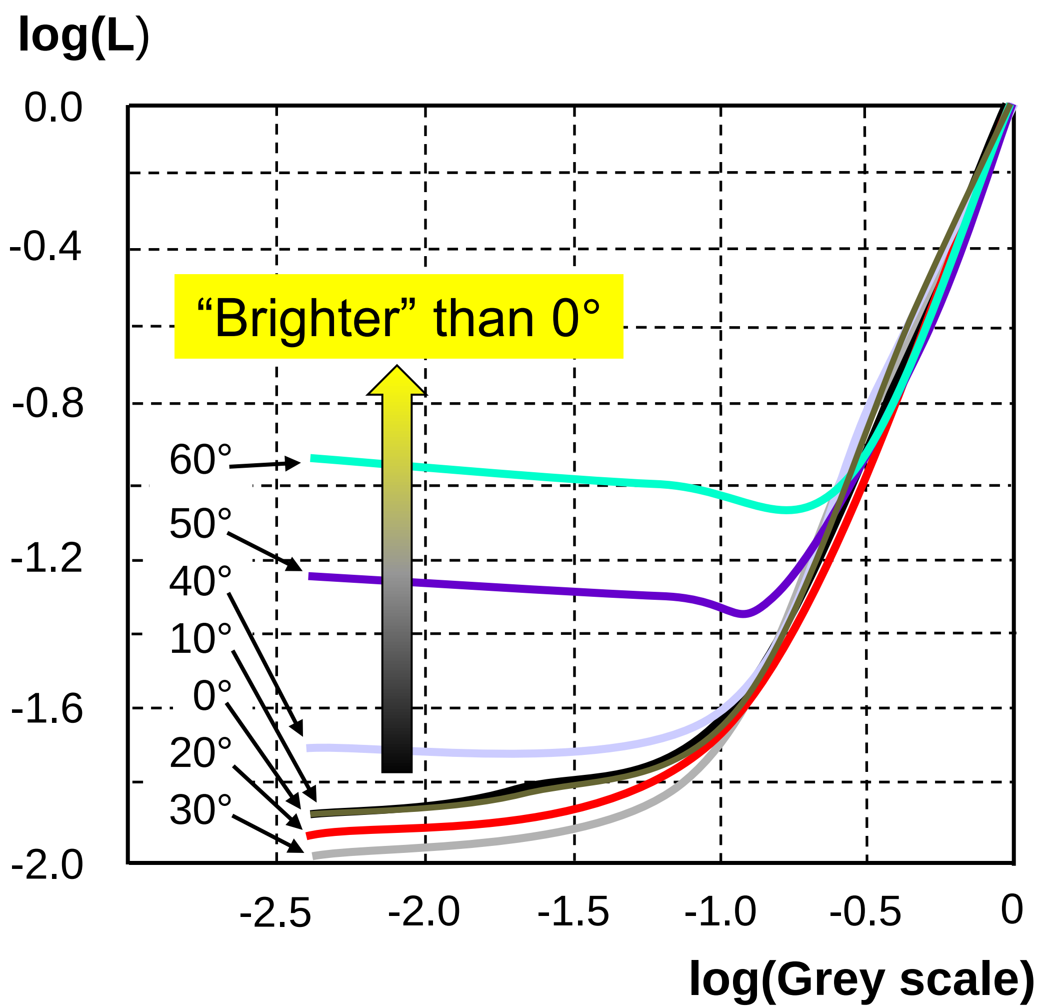
Luminance (GS) vs. Viewing Angle



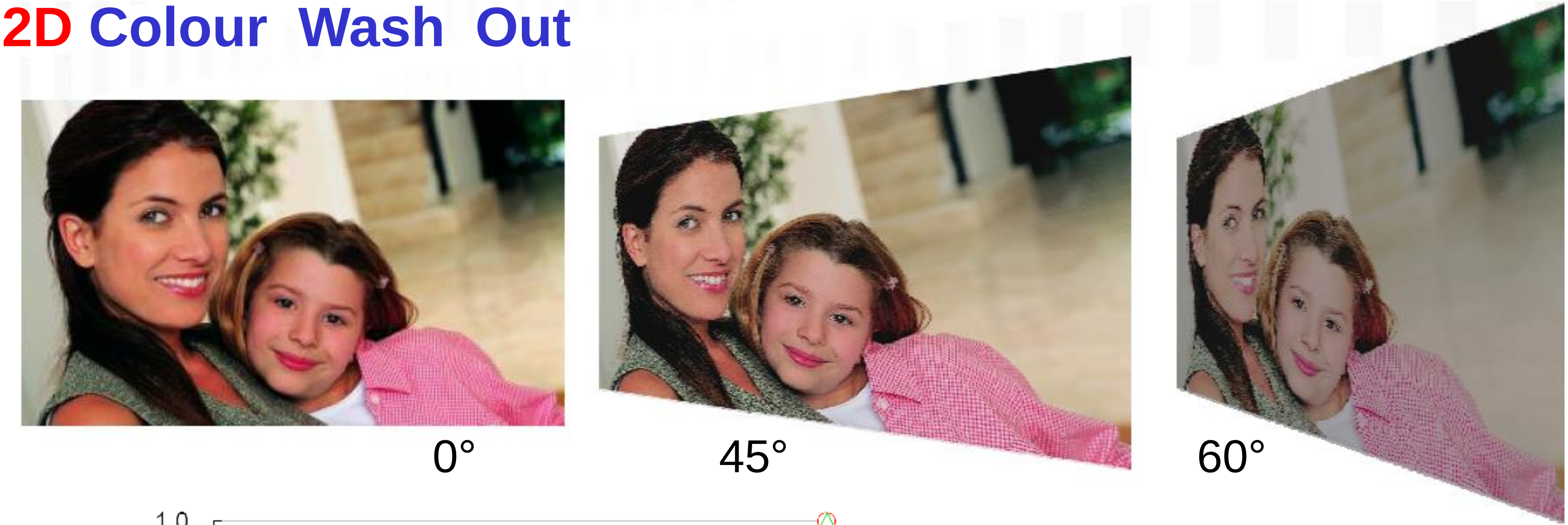
2D Grey Scale Dependency

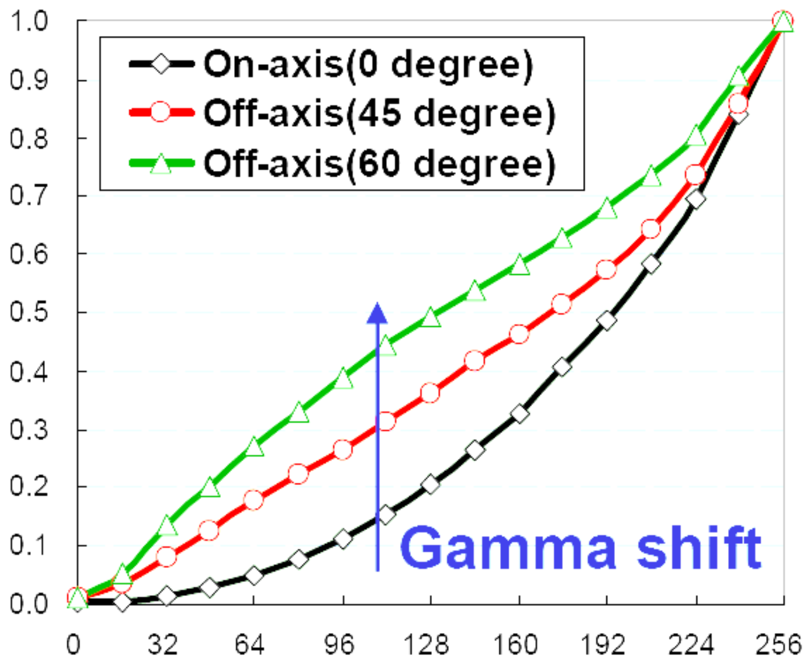
Gamma (GL) vs. Viewing Angle

AMLCD 12", horizontal



2D Colour Wash Out

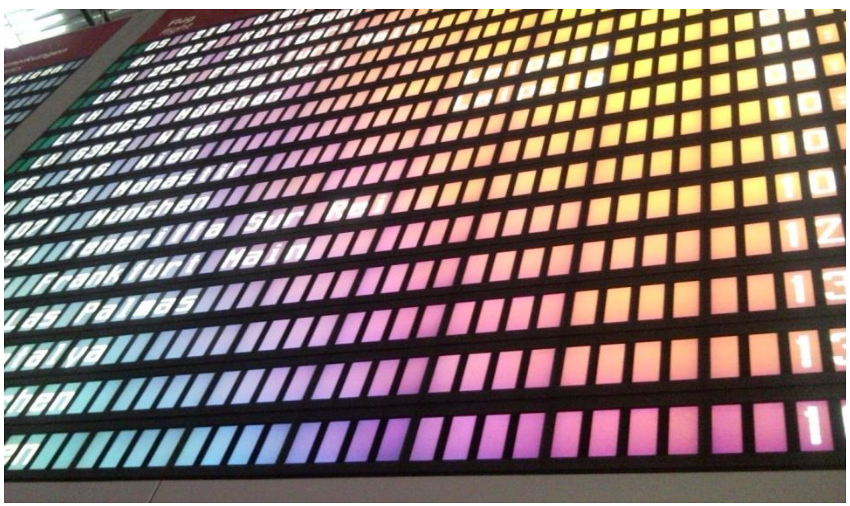




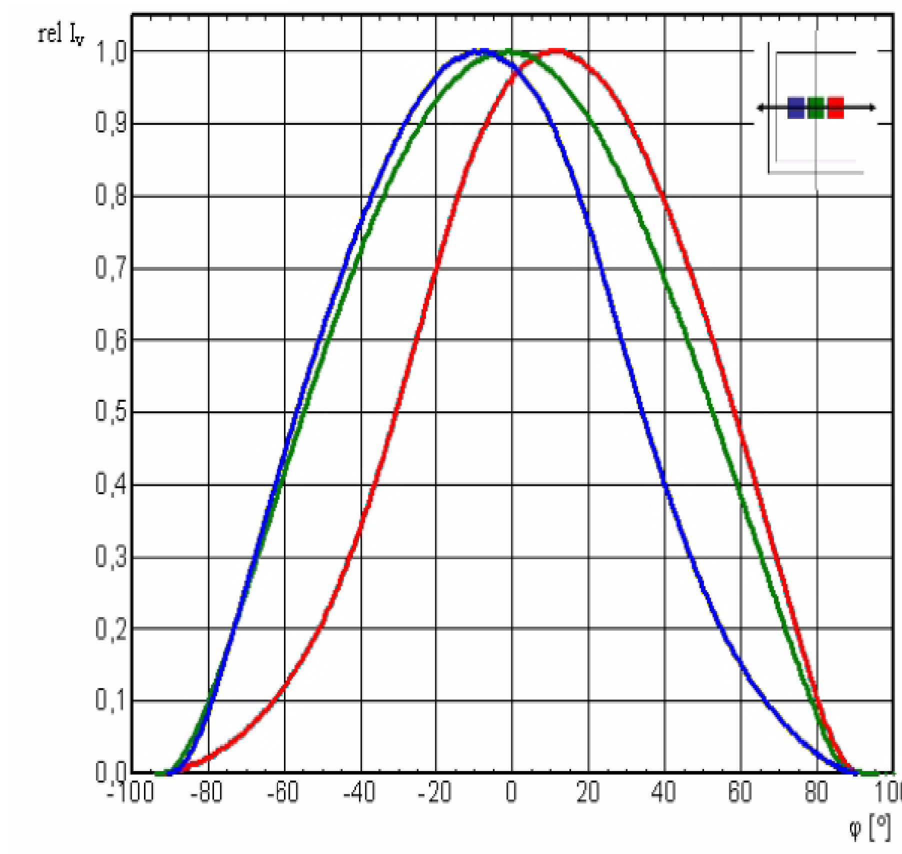
Electro-optical curve changes with viewing angle!

2D Colour Change with Viewing Angle

LCD



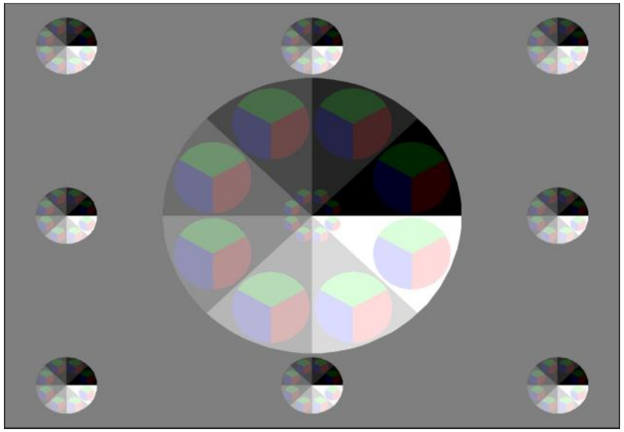
LED



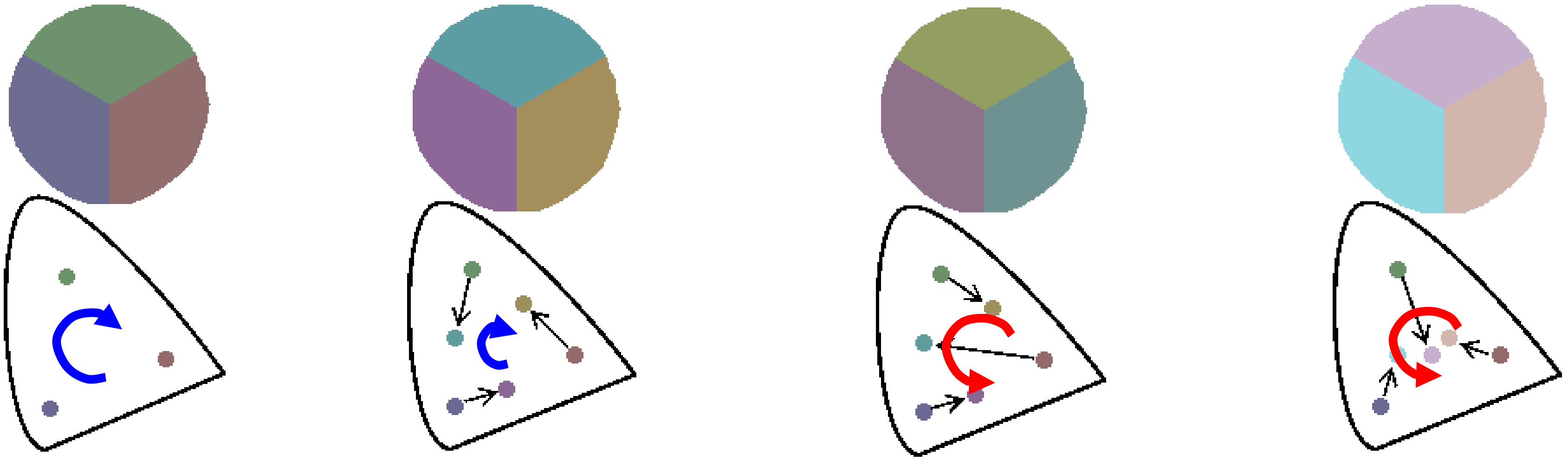
2D Color Inversion of LCDs

Measurement procedure similar to grey scale inversion

NIST test pattern



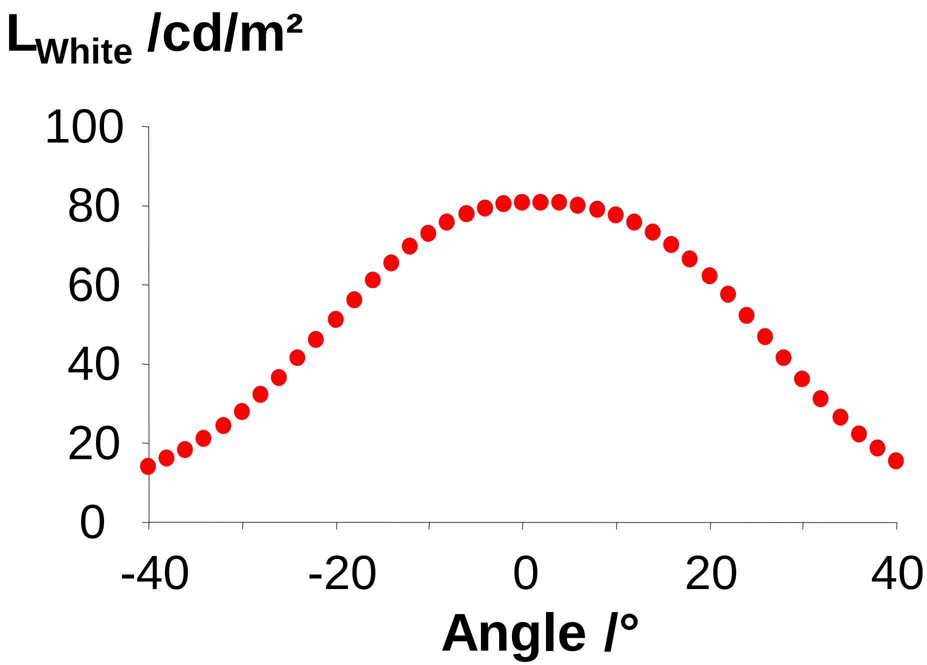
Example

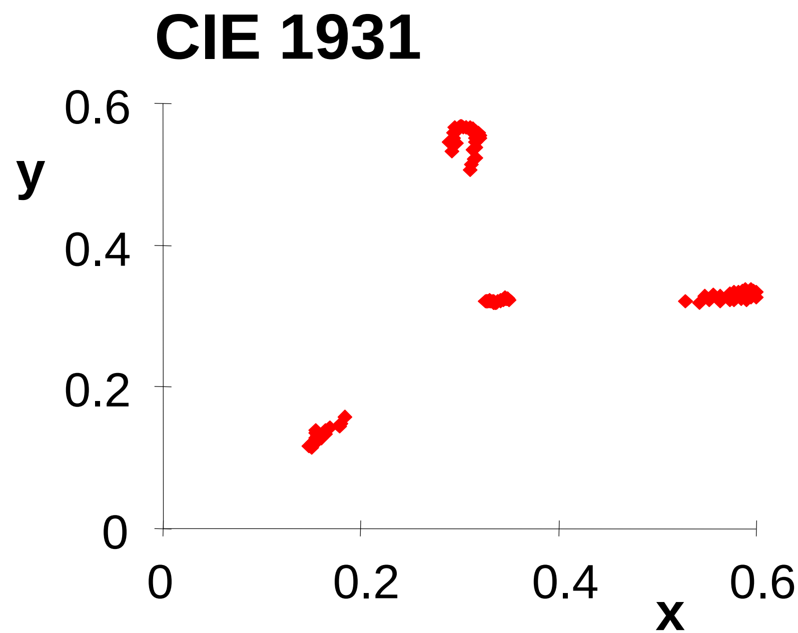


Original Color inversion : No yes yes

2D Angular Measurements: Luminance & Color

0 lx **10.4" LCD Horizontal Scan**

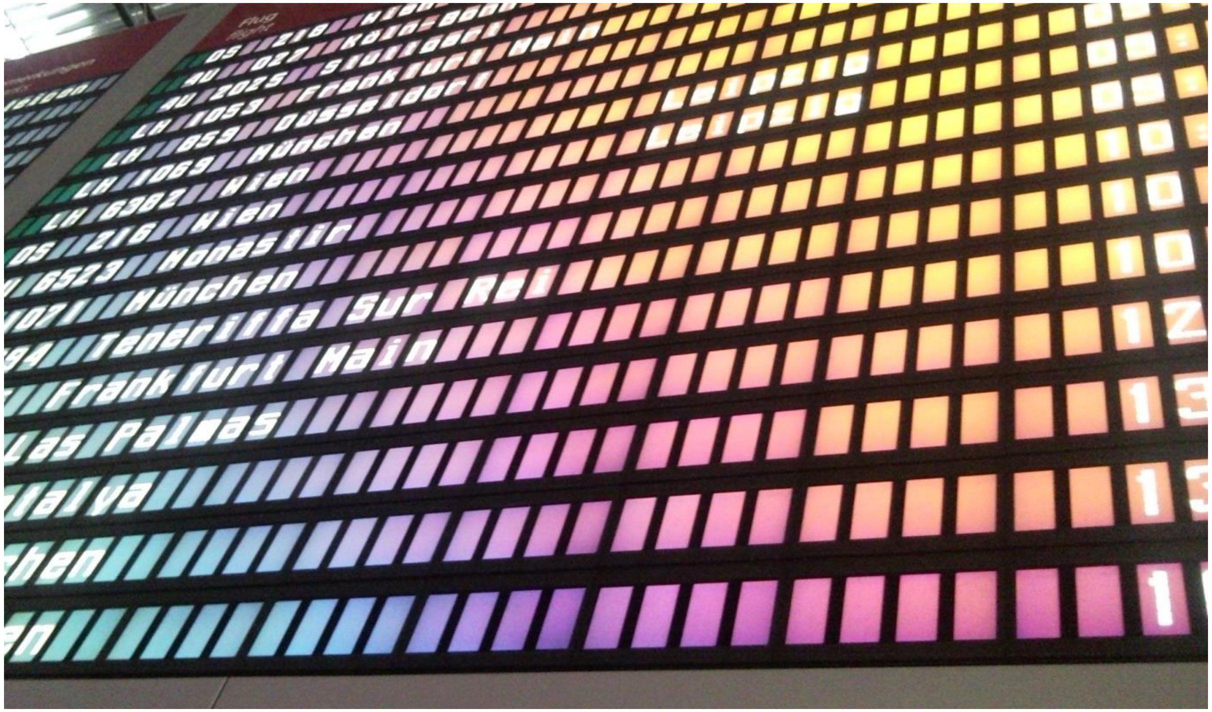




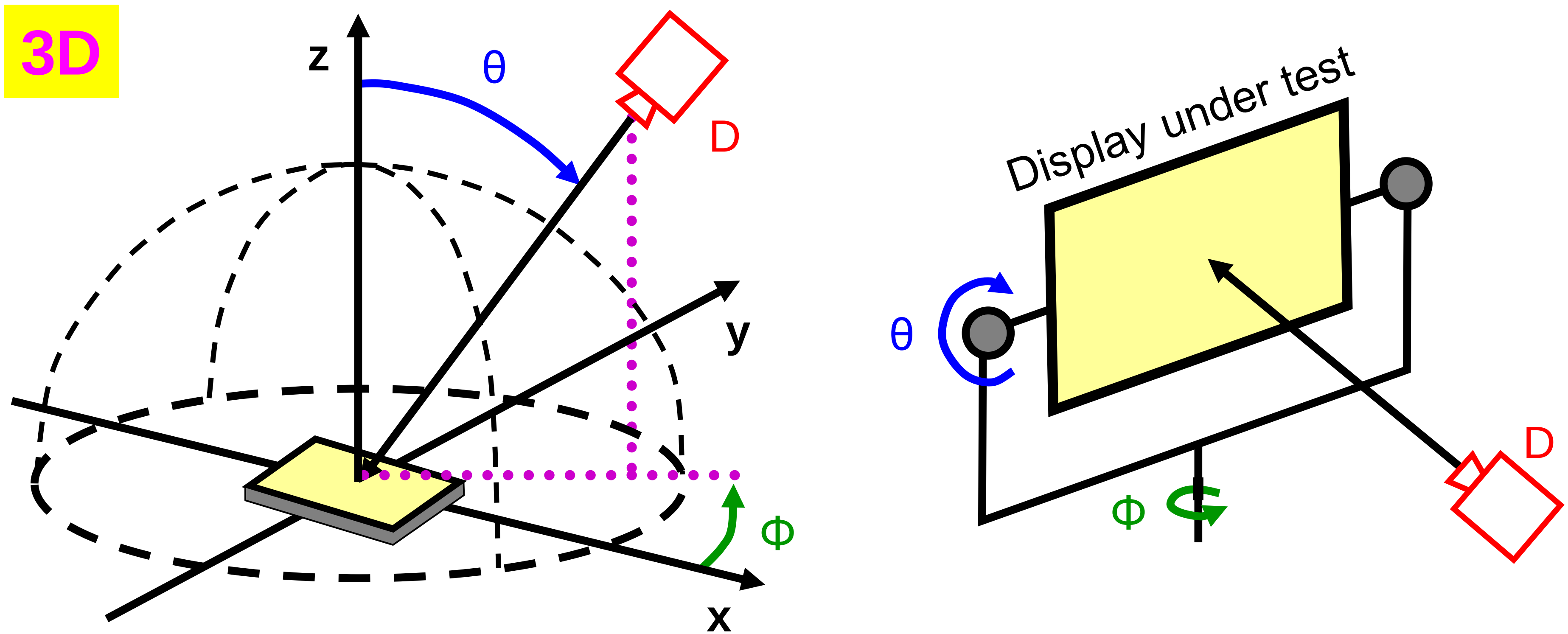

Lab training

LCD color co-ordinates depend on viewing angle.

Colour Change with Viewing Angle



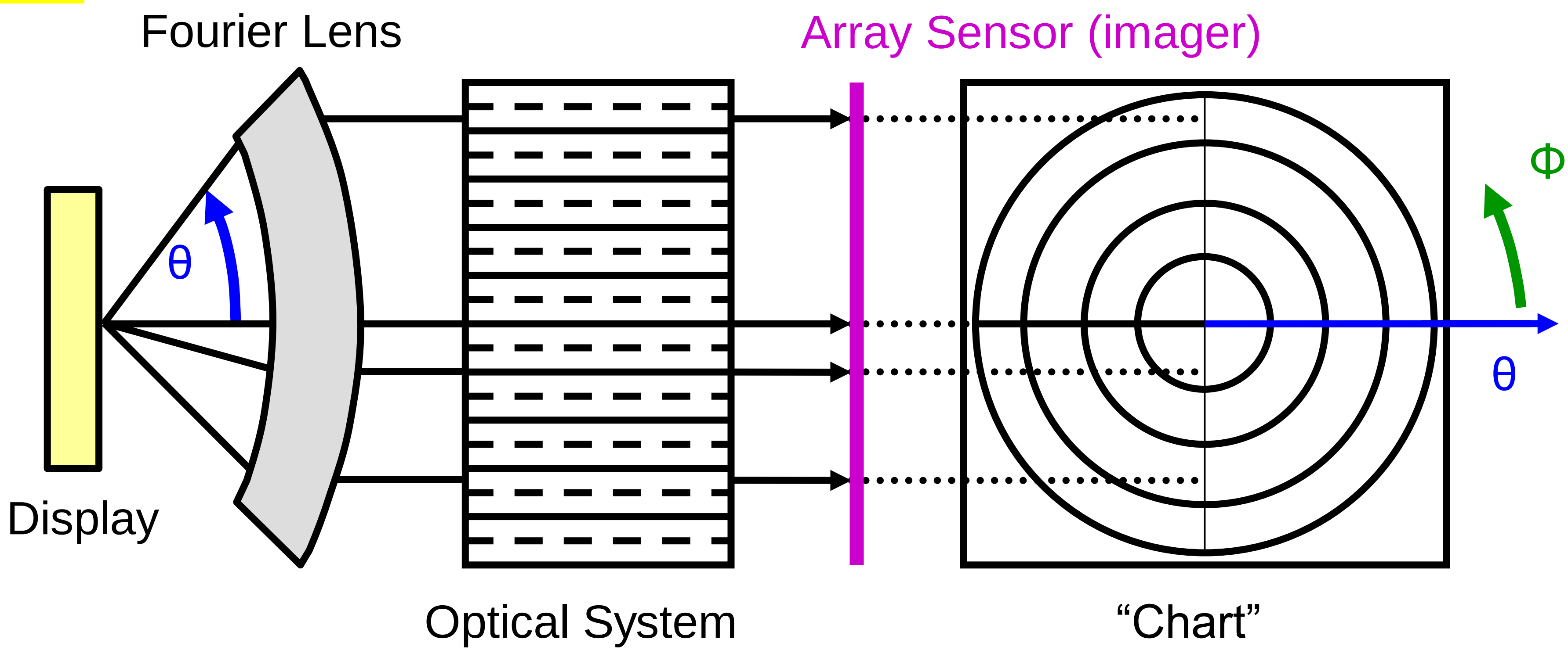
Viewing Angle Measurement Set-ups: Gonioscopic



- 3D plots (see conoscopic)
- Needs long time
- Expensive mechanical set-up for large displays

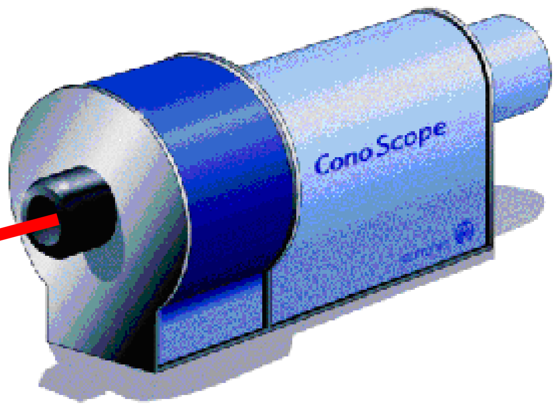
Viewing Angle Measurement Set-ups: Conoscopic

3D



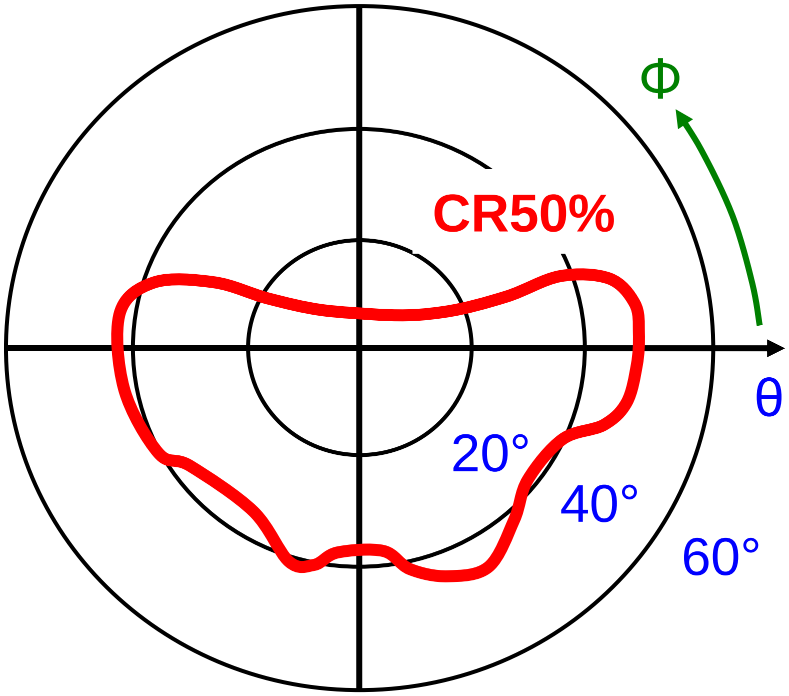
Viewing Angle Measurement Set-ups: Conoscopic

3D



To display

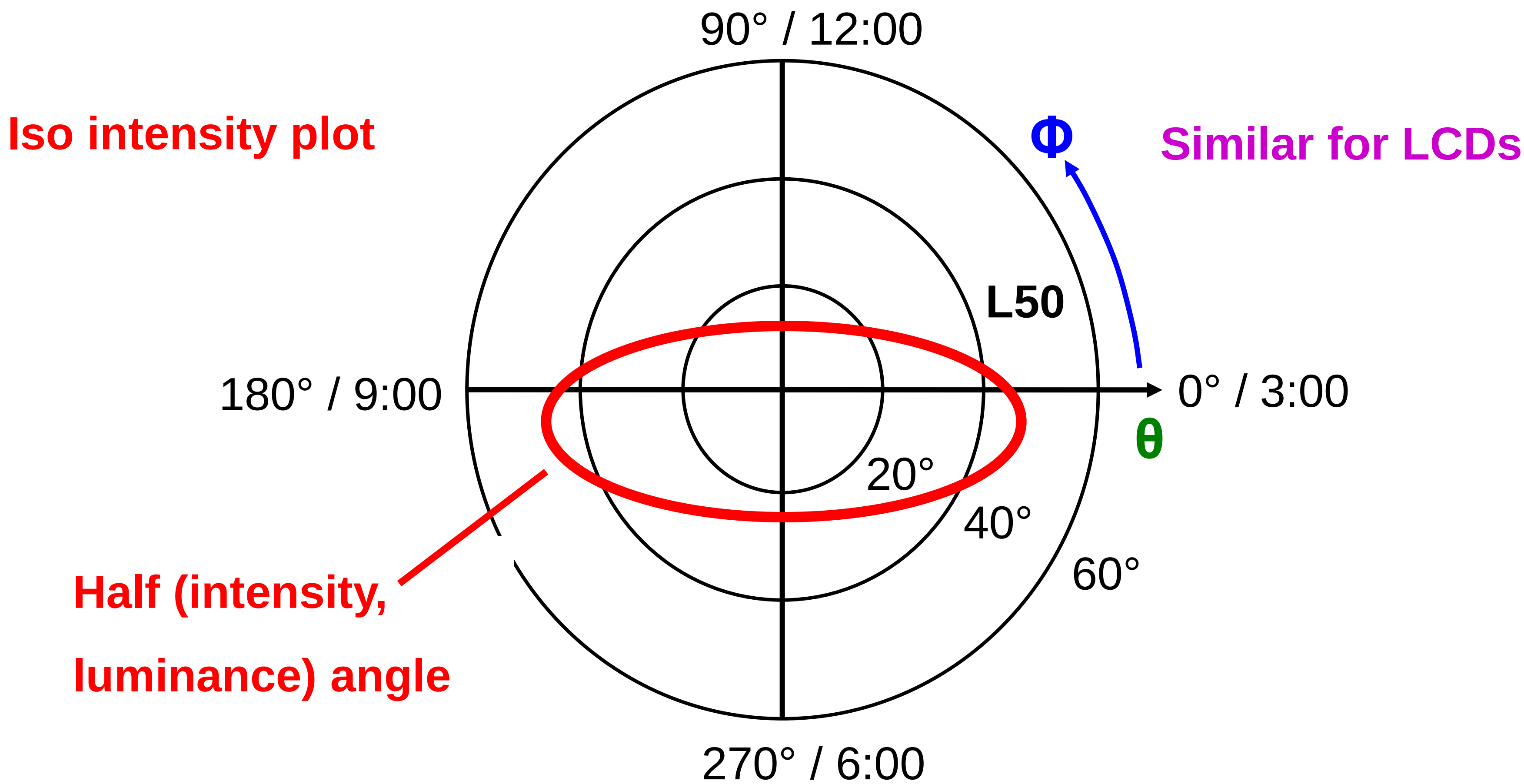
- All viewing angles are captured in one shot
- Iso-plots (iso = lines of constant L or CR, …)



See MG OS presentation

3D Angular Emission of LED Luminance

"Oval" characteristic "good" for LED walls as vertical observer positions differ mostly not largely compared to horizontal positions.



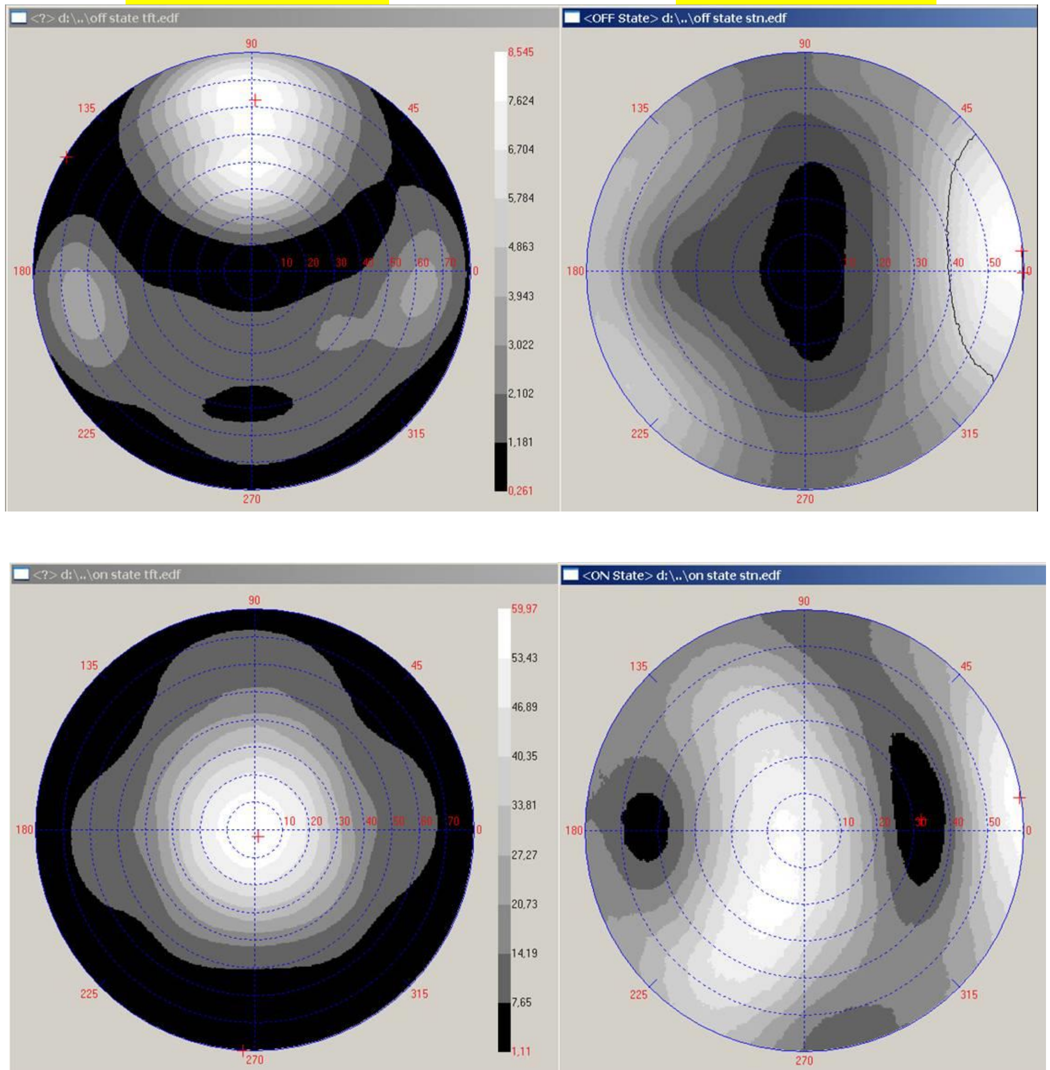
3D Iso - Luminance Plots

AM LCD

PM LCD

Black

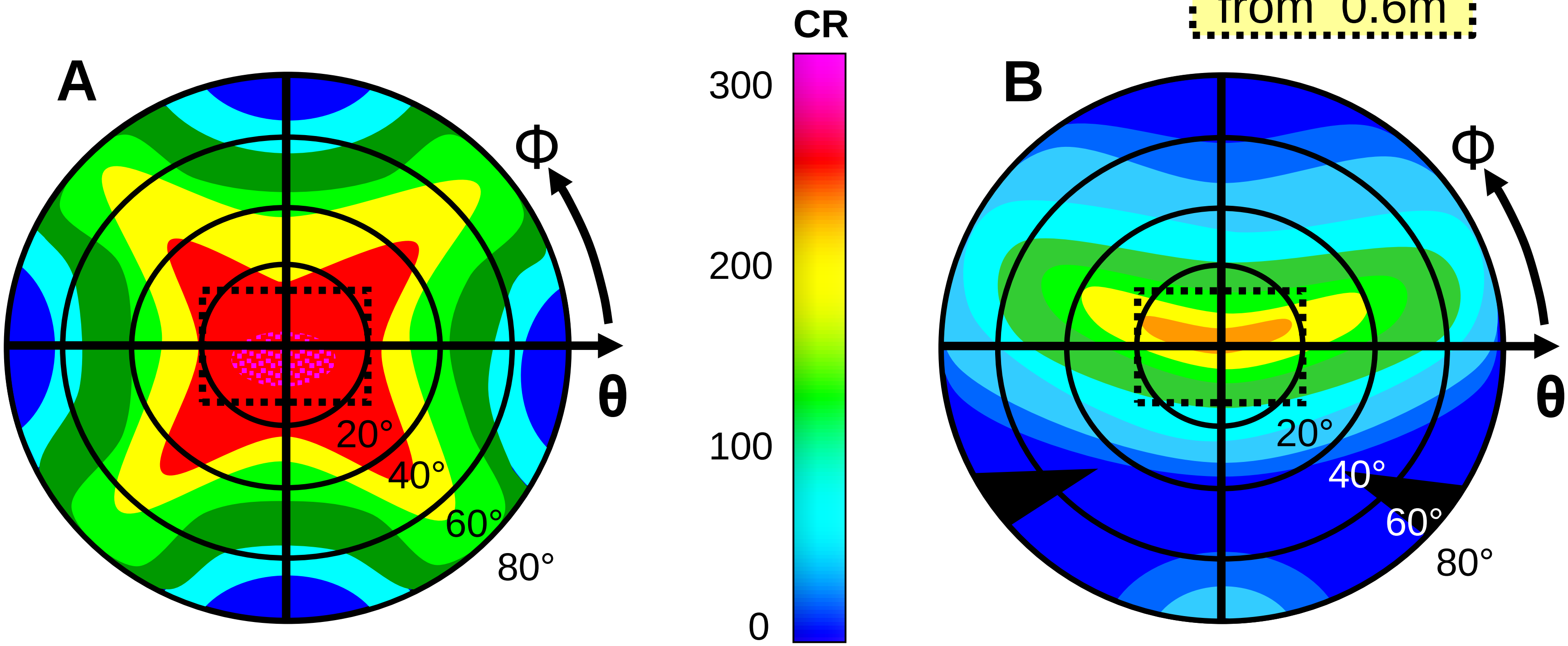
White



Measurements by Westar for DisplaySearch Report on TV Performance, N. Bardsley

3D Iso - Contrast Plots of AMLCDs

17” seen from 0.6m

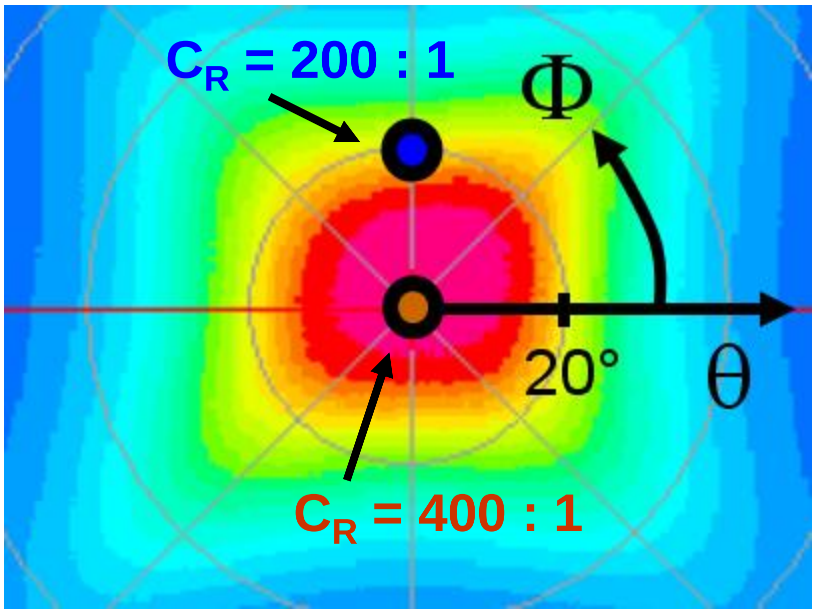


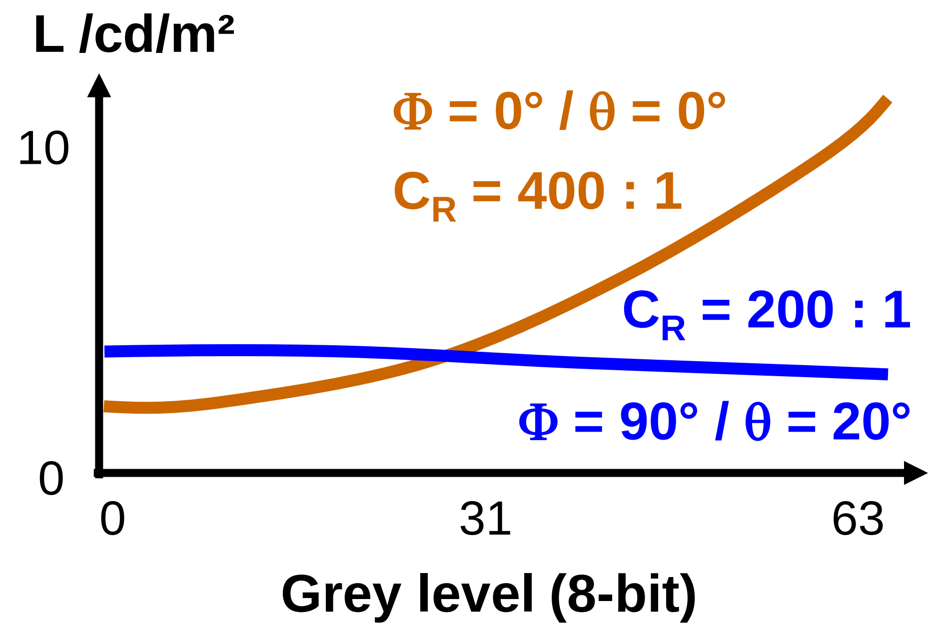
Display A is better because of

- Larger area with nearly constant contrast ratio for perpendicular incidence
- Larger maximum contrast ratio

In both cases a 6:00 observer position with $\theta \approx 15°$ is recommended

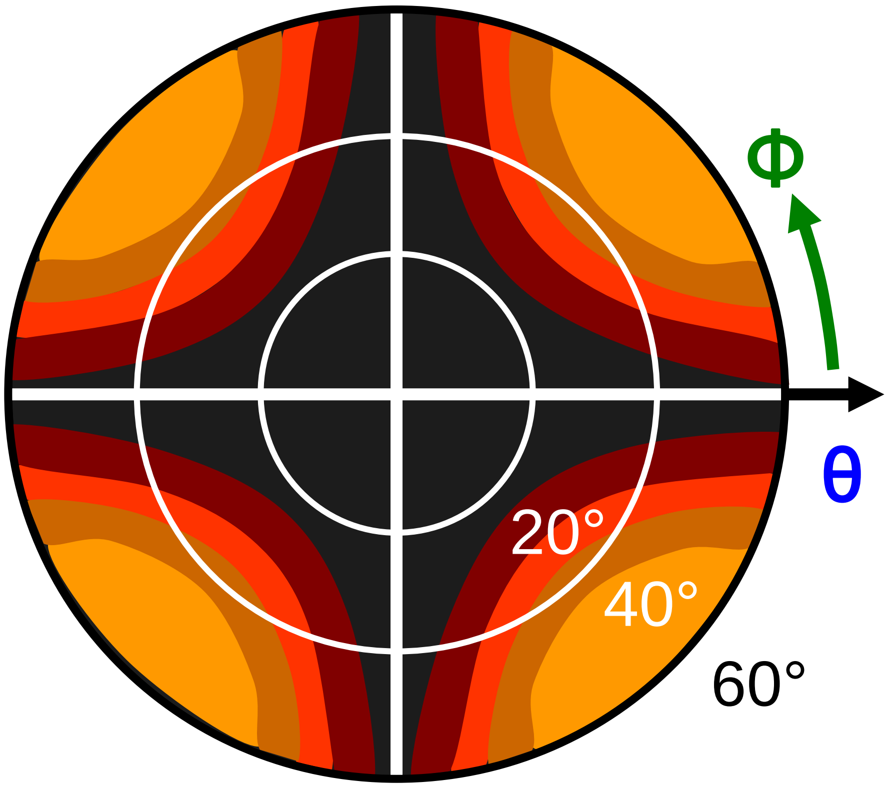
3D Contrast Ratio vs. Grey Scale Performance





Contrast Ratio values are misleading here because a reduction of 'only' 2 (400 → 200) occurs but the grey level reproduction is completely vanished or inverted (flat curve, blue) compared to perpendicular incidence (OK, brown) → no grey shades visible for 20° off !

3D Color Dependency from Viewing Angle of LCDs

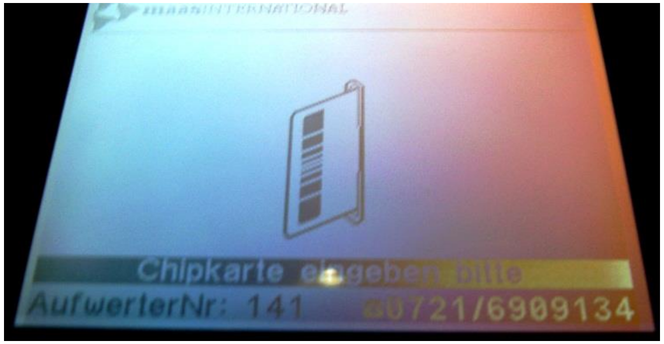


Measured color representation, black was shown on the screen !

12:00

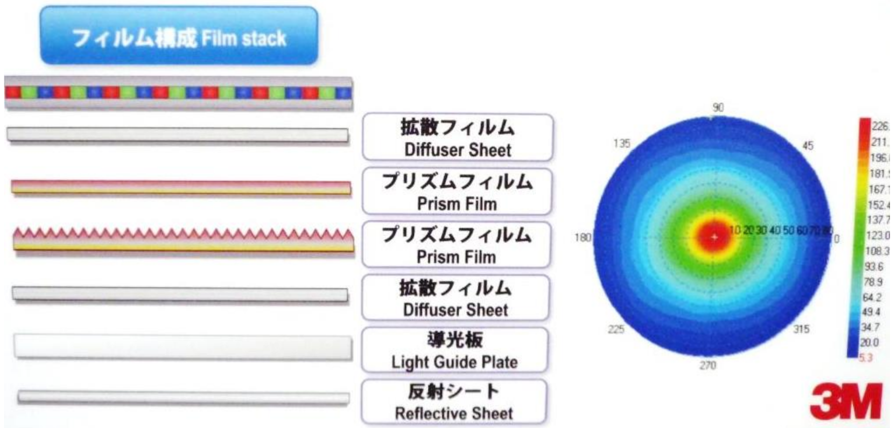
Contrast and color inversion !

6:00

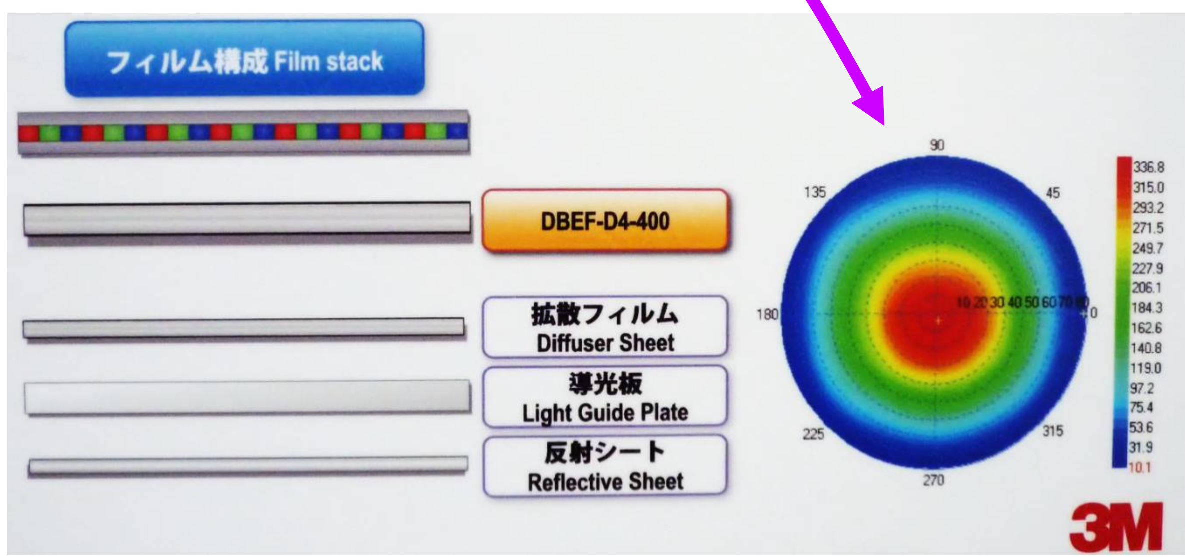


Playing with Viewing Angle

… for increasing viewing angle of LCDs

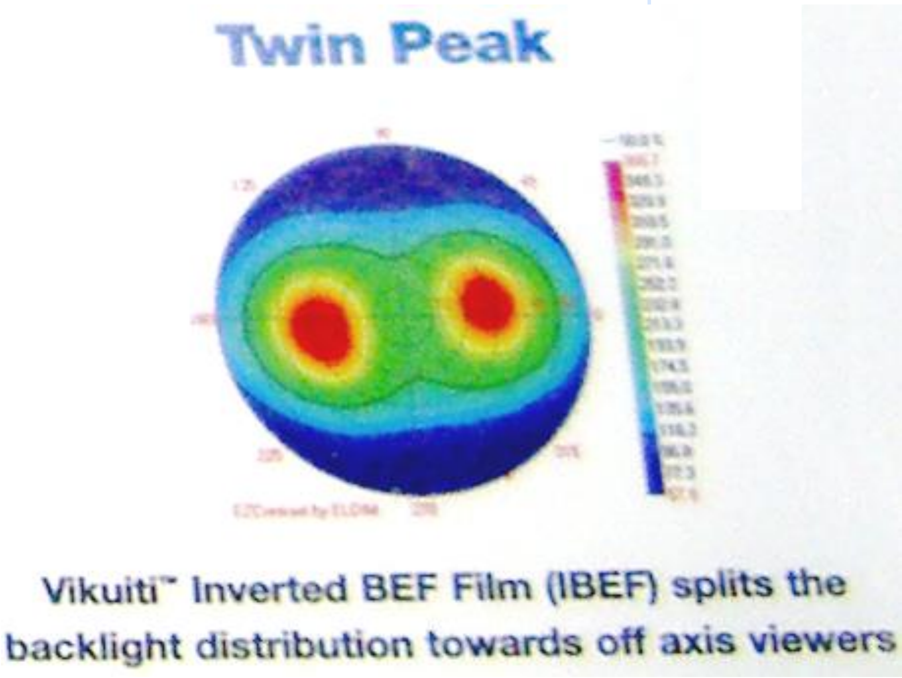


increasing viewing angle by optimized foil



Playing with Viewing Angle

… for special applications like CID



Other filters limit viewing angel like for ATMs privacy.

Dual View LCD

- 2 different images for 2 viewers
- Application e.g. center information display (CID)

  driver: navigation, co-driver: video; introduced as Split View by MERCEDES

Some thesis by Pforzheim ET students were made on this topic helping to implement this technology with high quality.

Case Study : Viewing Angle

- **Task**
  Design "valuable" display

- **Conditions**: Indoor, "brand" colors, "TV display", …
- **Solutions**:

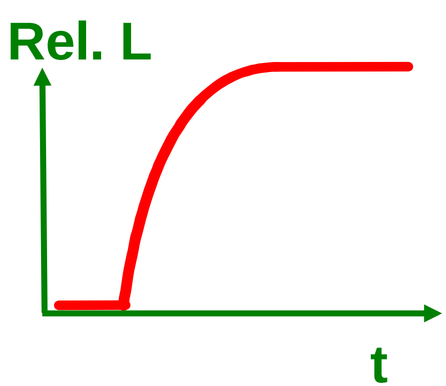
Summary & Questions

- Viewing angle degradation affect all display technologies, however the largest effects occur for LCDs
- Viewing angle values are threshold ones which are often defined by panel producer.
- ‘Inversion free’ (grey level, color) seems to be great but grey levels and colors can merge closely so that performance is strongly degraded
- 2D scans (horizontal or vertical) are easy to perform but sometimes of limited relevance
- 3D plots are more valuable
- Viewing angle dependencies are ‘forced’ in some applications. Name a few and explain them.
- OLEDs are emissive technologies which should show now viewing angle dependency. Explain the effects which cause that.

Summary „LCD related Issues“

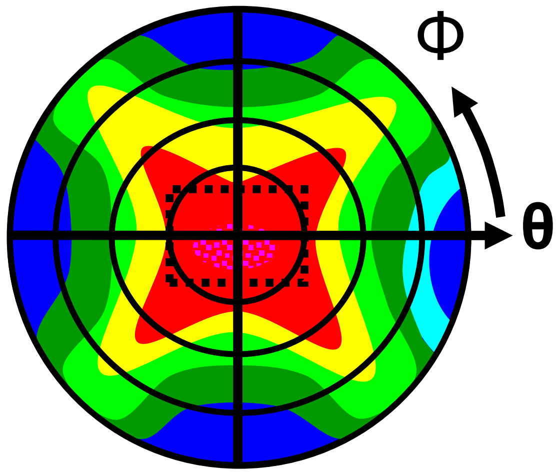
Response time

- Issue of LCDs and e-paper
- T-dependant
- Emissive displays are minor affected



Viewing angle

- Degradation of image quality
- CR not useful, better: GS, color



“To do”

- Measure under conditions which are typical for your application

Overview

Some selected topics, others - including for other display technologies - can be also relevant!

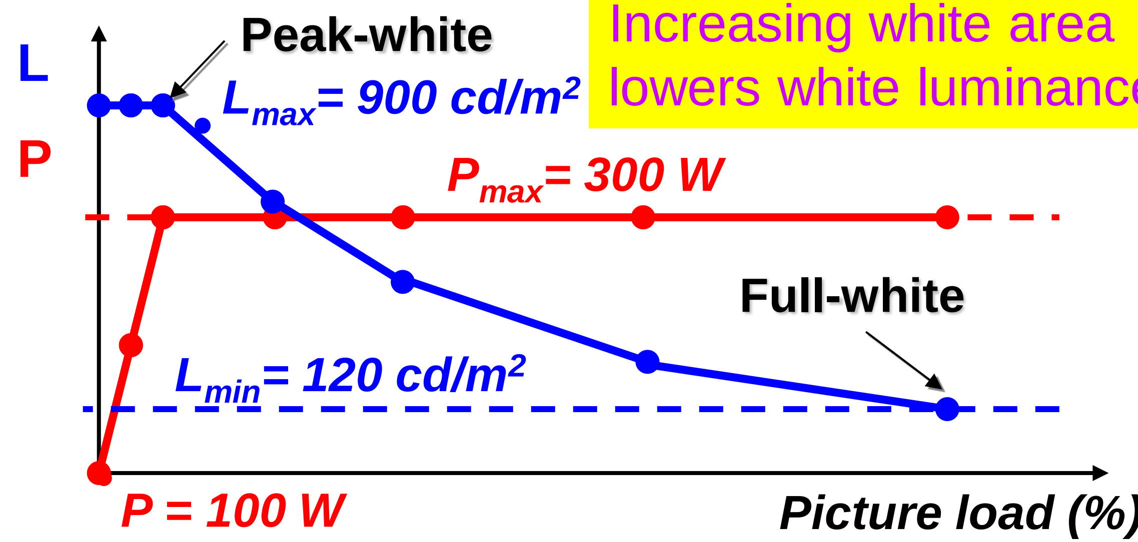
- Introduction
- Basic Parameters (Merits)
- Common Issues
- Display Technology Dependent Issues (Shortcomings)
- Summary

- LCD: Response time, viewing angle
- PDP: Loading, false contour

PDP Power Management

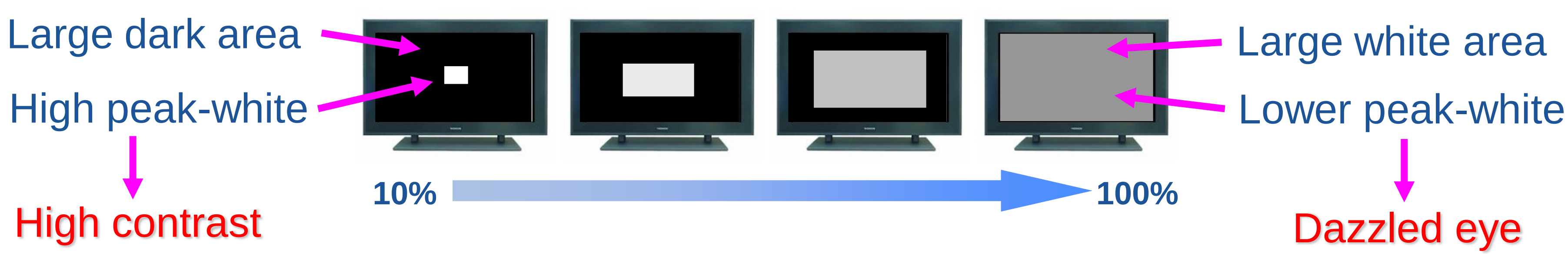
Definition: Peak-white is highest luminance at stable power consumption

Commonly used in standard displays: CRT, PDP…



Increasing white area lowers white luminance!

Suits very well to the human visual system



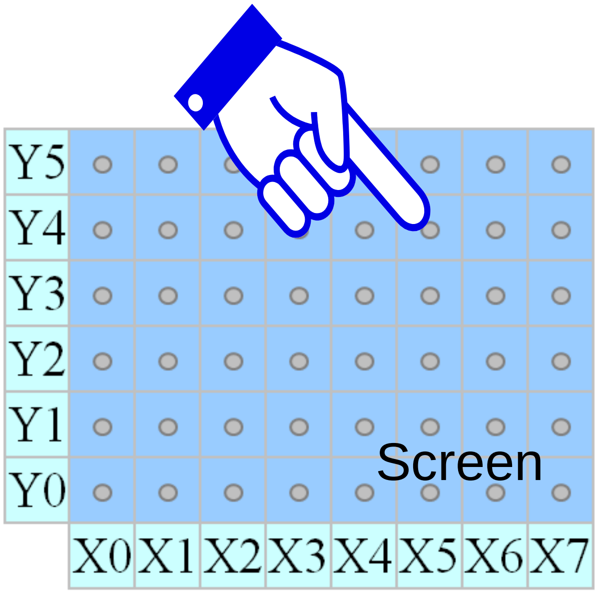
Summary & Questions

- Luminance output of PDPs are influenced by grey levels and their area.
- Full white luminance is about a factor of 5 … 10 lower than 1% highlight.
- PDP luminance limitation prevents somewhat from burn-in and saves power supply efforts
- White images for PDPs are not recommended for ambient light applications
- (Signal processing is difficult for PDPs due to sub-frames)
- Why are PDPs supposed to be ideal for home cinema ?

Overview

- Introduction
- Basic Parameters (Merits)
- Common Issues
- Display Technology Dependent Issues (Shortcomings)
- Touch
- Summary

Touch Tasks



Acquire

- Touch position

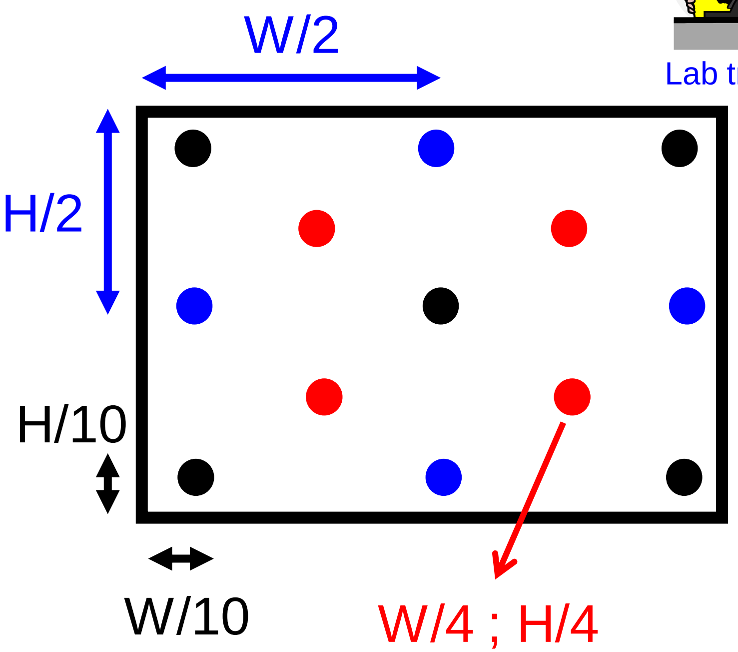
- Number of touches (fingers)
- Gestures, …

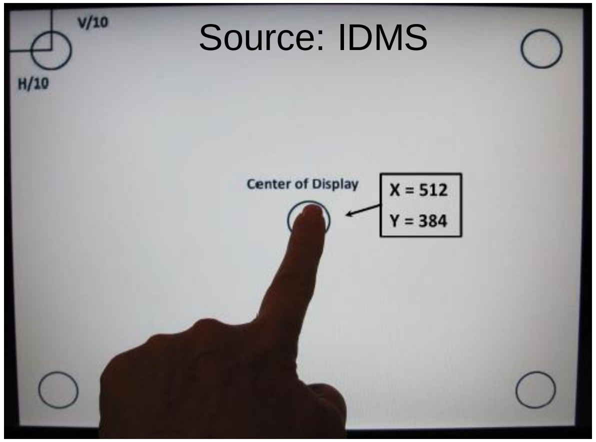
Equipment etc. needed:

- Software to visualize GUI etc and outputs (to e.g. file) touch parameters like co-ordinates
- High speed camera for touch events lag measurements or equipment similar to response time measurements
- Touch objects
- …

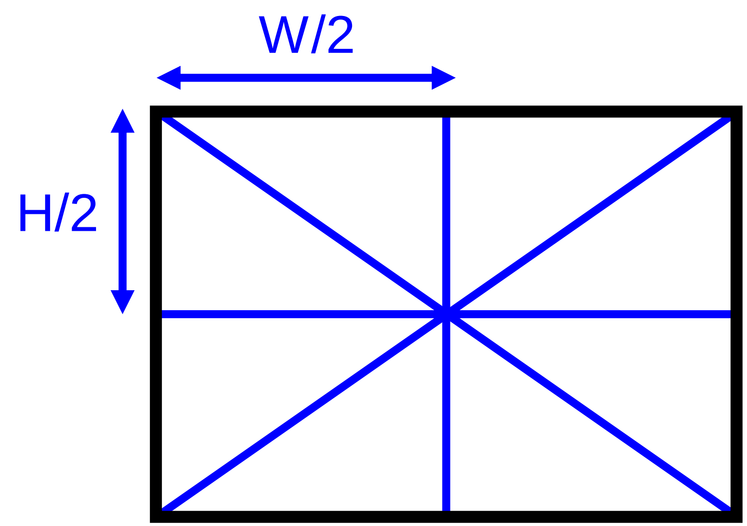
Touch TOUCH POSITION ACCURACY

- Simple test for controls etc.
- 5 or more point can be used, “same” as uniformity
- Touch co-ordinates should be located in the center of the circles
- Use software which shows buttons, circles, … and outputs the touch co-ordinates X/Y
- To be judged: Co-ordinate in the center of control if touched there

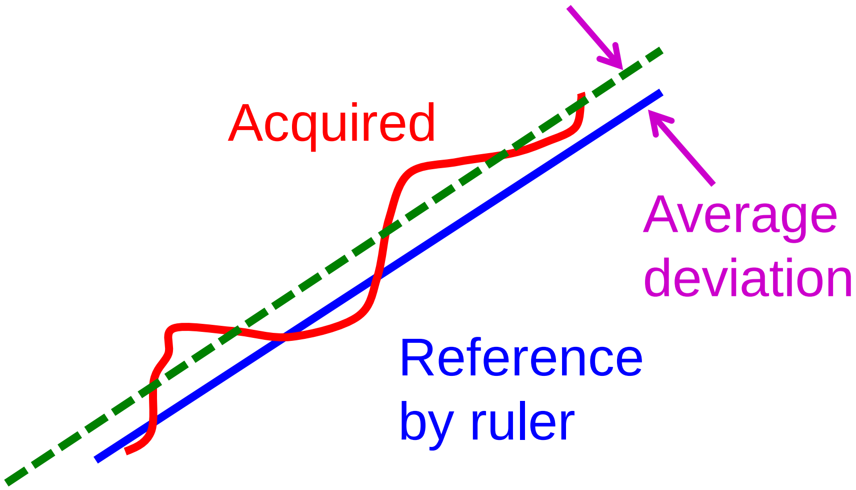




Touch LINEAR ACCURACY

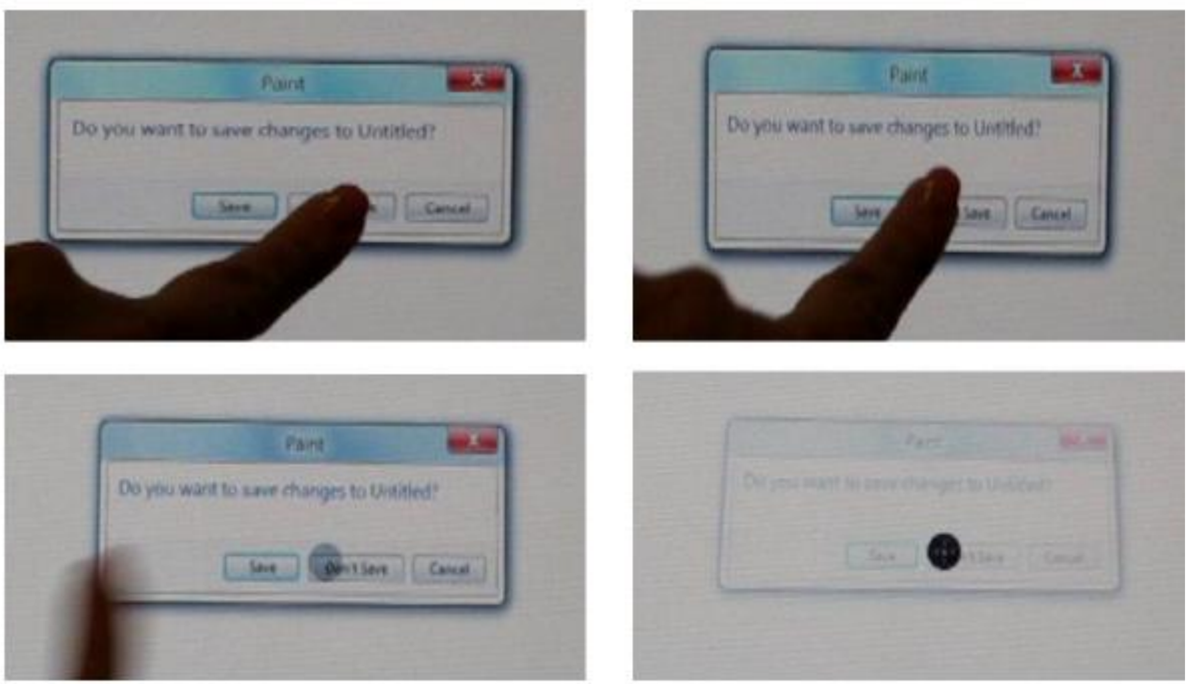


- Deviations from straight line, usually 4
- Move touch object along ruler
- Use “normal” speed
- Software stores touch co-ordinates
- Report on deviations:
  - Average deviation (difference)
  - Maximum difference
- To be defined: Acceptable deviations



Touch REACTION TIME: LATENCY OF A SINGLE TOUCH

- Measure how fast the whole system reacts on a touch event
- This duration is influenced by many parameters like response time of touch, touch signal processing, touch interface, operating system response time, …

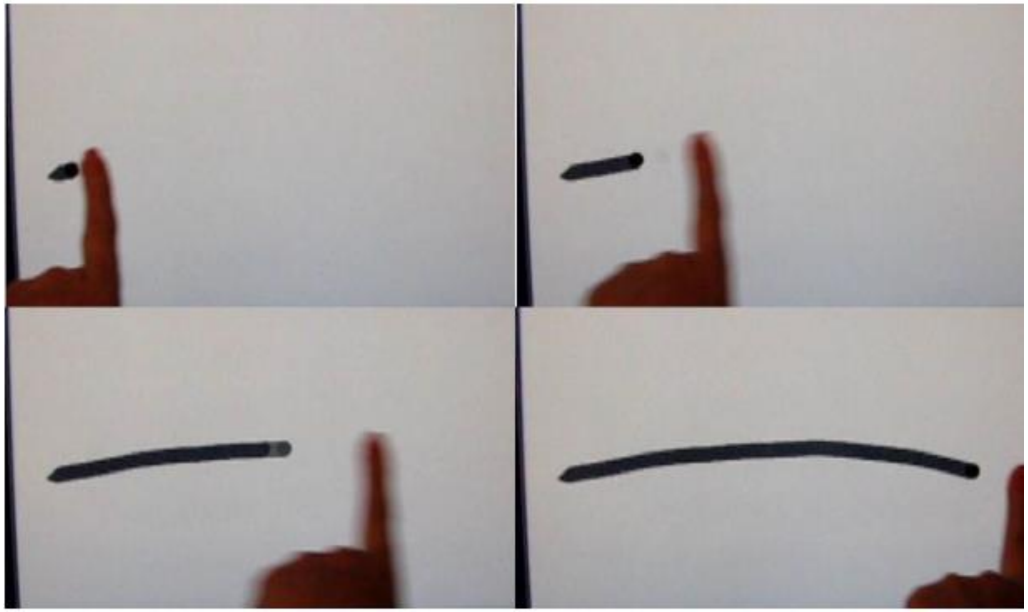


Lab training

Source: IDMS

Touch REACTION TIME: LATENCY OF A LATERAL MOTION

- Measure the latency time between the input and the system reaction
- Similar measurement: Fastest movement of touch object without noticeable latency between touch position and system reaction like curve
- This time is influenced by many parameters like response time of touch, touch signal processing, touch interface, operating system response time, …



Source: IDMS

Touch Summary

- Typical touch measurements are:
  - Position
  - Number of touch objects
  - Accuracy of lines
  - Speed
- There are a lot more like sensitivity to touch objects (like gloves), cover lens thickness, dust and dirt on touch screen
- Especially “speed” (and gesture) strongly depends on system reaction time where touch screen parameters are only a few among many influencing topics.

Overview

- Introduction
- Basic Parameters (Merits)
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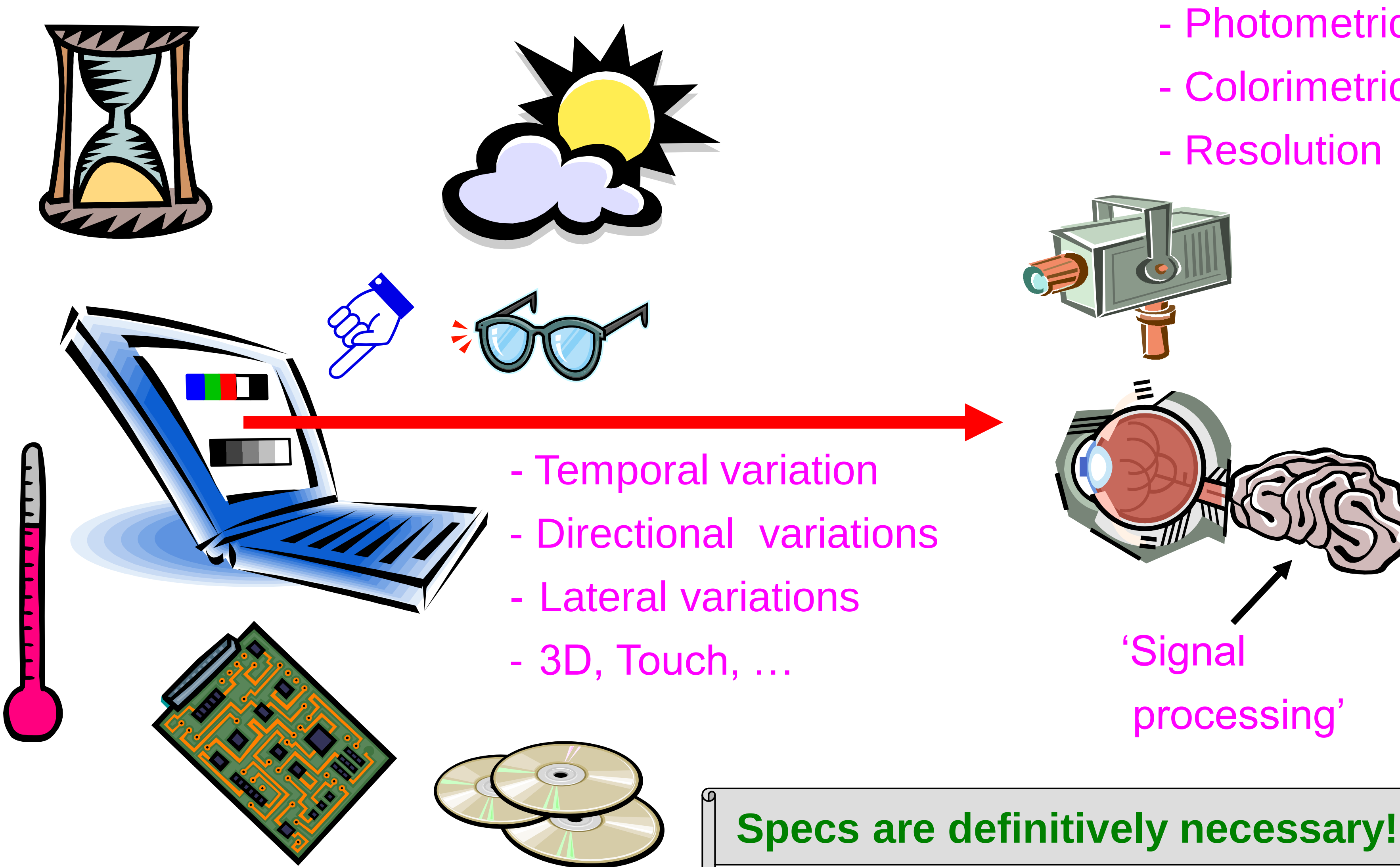
Parameters Affecting Measurements & Visual Perception



Specs are definitively necessary!

Summary (I)

Merits of display metrology

- Many standard measurement procedures
- Data sheets and specifications enable evaluation of a display for a specific application

Shortcomings of display metrology

- Degradations can occur due to various conditions
  - Environmental (ambient light, temperature, …)
  - Application (lifetime, static and moving content, …)
- Data sheets refer often to parameters which are not applicable to applications like dark room, 25°C, permanent ON, …
- Vision sees things that measurement can't capture and vice versa

Summary Metrology

- Evaluation is performed by measurements and visual inspection.
- "Limited data in specs" (e.g. 25°C, dark room) forces application specific measurements ⇨ select carefully the most relevant measurements.
- Fundamental measurements ("Fab 4"):
  Luminance, Contrast Ratio, Grey Scale & Color
- Most relevant measurements for evaluation:
  Ambient light, lifetime, viewing angle, response time

No display technology exists (yet) which fulfill all requirements !

⇨ Best compromise has to be evaluated by measurements

Overview of Standards … also: SID ICMD IDMS (but no offiicial standard)

- ANSI: American National Standards Institute (www.ansi.org)
- ASTM: American Society for Testing and Materials (www.astm.org)
- CIE: Commission Internationale de l'Eclairage (www.cie.co.at)
- DIN: Deutsches Institut für Normung (www.din.de)
- EIA: Electronics Industries Association (www.eia.org)
- International Committee for Display Metrology SID (www.icdm-sid.org)
- IEC: International Electrotechnical Committee (www.iec.ch)
- IEEE: Institute of Electrical and Electronics Engineers (www.ieee.org)
- ISO: International Organization for Standardization (www.iso.org)
- ITU: International Telecommunication Union (www.itu.int)
- JEITA: Japan Electronics and IT Industries Association (www.jeita.or.jp/english/)
- NEMA/DICOM: National Electrical Manufacturers Association/Digital Imaging and Communications in Medicine (DICOM) (www.medical.nema.org)
- SAE: Society of Automotive Engineers (www.sae.org)
- SMPTE: Society of Motion Picture and Television Engineers (www.smpte.org)
- SPIE: Society of Photo-Optical Instrumentation Engineers (www.spie.org)
- TCO 92 – TCO 07 Swedish Confederation of Professional Employees
- VESA: Video Electronics Standards Association (www.vesa.org)

Overview of Standards

- ISO 9241 Ergonomic requirements for office work with visual display terminals (VDTs); new: Ergonomics of Human System Interaction
- ISO 13406 Ergonomic requirements for work with visual displays based on flat panels. Part 2:Ergonomic requirements for flat panel displays
- IEC 61747 Liquid crystal and solid-state display devices. Environmental, endurance, and mechanical test methods
- ISO 15008 Road vehicles – Ergonomic aspects of transport information and control systems – Specifications and test procedures for in-vehicle visual presentation
- CECC 20000 Harmonized system of quality assessment for electronic components: Generic specification: Semiconductor optoelectronic and liquid crystal devices
- IEC 62341 Organic light emitting diode (OLED) displays
- IEC - TC 100 Audio, video, and multimedia equipment and systems
- TC 110 Flat panel display devices
- TC 159 Ergonomics
- IEC 61988 Plasma display panels
- CIE 44 Absolute methods for reflection measurement
- SAE J1757-1 Standard metrology for vehicular displays
- EU 642/2009 Power consumption of monitors and TV sets

ISO 9241

The standard ISO 9241 covers many tasks for human interaction with computers including software, and input and output devices such as displays:

- Part 300: Introduction to electronic visual display requirements
- Part 302: Terminology for electronic visual displays
- Part 303: Requirements for electronic visual displays
- Part 304: User performance test methods for electronic visual displays
- Part 305: Optical laboratory test methods for electronic visual displays
- Part 306: Field assessment methods for electronic visual displays
- Part 307: Analysis and compliance test methods for electronic visual displays
- Part 308: Surface-conduction electron-emitter displays (SED)
- Part 309: Organic light-emitting diode (OLED) displays

IEC TC100

The IEC TC100 has the following technical areas (TAs):

- TA 1 : Terminals for audio, video, and data services and contents
- TA 2 : Color measurement and management
- TA 4 : Digital system interfaces and protocols
- TA 5 : Cable networks for TV signals, sound signals, and interactive services
- TA 6 : Higher data rate storage media, data structures, and equipment
- TA 7 : Moderate data rate storage media, equipment, and systems
- TA 8 : Multimedia home server systems
- TA 9 : Audio, video, and multimedia applications for end-user networks
- TA 10 : Multimedia e-publishing and e-book