Multimedia Displays

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Objective of Lecture

• Understanding of applications of electronic displays

• Know how of advanced display technologies

• Knowledge of relationships between electronics ↔ interface ↔ display

• Capability to design embedded (information) systems with the ‘best’ display
Recommended Textbooks

- L.W. MacDonald, A.C. Lowe: Display Systems, WILEY SID

- P.A. Keller: Electronic Display Measurement, WILEY SID

- Green, MacDonald: Color Engineering, WILEY SID

- Ernst Lueder: LCDs : Addressing Schemes and e-o Effects, WILEY SID

- Willem de Boer: AM Liquid Crystal Displays, NEWNES

- R.L. Myers: Display Interfaces, WILEY SID

- G. Berbecel: Digital Image Display, WILEY SID
Overview

• Introduction

- Market overview
- Some basics of metrology

• Selected Topics on Advanced LCDs, OLEDs and PDPs

• 3D & E-Paper (flexible) Display Technologies

• Touch Screen Technologies

• Display Interfaces
**Worldwide Flat Panel Market**

- 50% of FPD in 2006
- PC and TV only in developing countries

Source: iSupply

- AM LCD
- PDP
- PM LCD
- Other FPDs

Bill. $
Top 7 FPD Applications

Worldwide Turnover / B$

~ 100% AM LCD except for TV

2004
2007
2009
Worldwide Flat Panel Market by Regions

MUnits

<table>
<thead>
<tr>
<th>Year</th>
<th>ROW</th>
<th>Western Europe</th>
<th>USA</th>
<th>Japan</th>
<th>China</th>
</tr>
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<tbody>
<tr>
<td>2003</td>
<td>417</td>
<td>1.151</td>
<td>881</td>
<td>1.545</td>
<td>2.555</td>
</tr>
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<td>2004</td>
<td>1.151</td>
<td>881</td>
<td>1.545</td>
<td>2.555</td>
<td></td>
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<td>2005</td>
<td>2.555</td>
<td>881</td>
<td>1.545</td>
<td>2.555</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>4.683</td>
<td>2.070</td>
<td>1.545</td>
<td>2.555</td>
<td></td>
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<tr>
<td>2007</td>
<td>6.677</td>
<td>2.070</td>
<td>1.545</td>
<td>2.555</td>
<td></td>
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<tr>
<td>2008</td>
<td>8.740</td>
<td>2.520</td>
<td>2.830</td>
<td>3.055</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>10.400</td>
<td>2.830</td>
<td>3.055</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>11.865</td>
<td>3.055</td>
<td>3.220</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Worldwide Flat Panel Market by Applications

- **NB PCs**
- **Mobile Phones**
- **Monitors**
- **TVs**
- **Other**
- **Auto/DVD**
- **Indust./Public Display**
- **Other Handheld**
Worldwide Units by Applications

2007: Production 60,000 m²
Shift of FPD Production

From Japan to Korea & Taiwan to (?) China
AM LCD  “Application Waves”

- First wave - notebook
- Second wave - monitor
- Third wave - TV
- Fourth wave - Signage?

- Notebook
- Monitor
- TV

Millions of US Dollars
- $0
- $10,000
- $20,000
- $30,000
- $40,000
- $50,000
- $60,000
- $70,000
- $80,000

Years
- 1990
- 1991
- 1992
- 1993
- 1994
- 1995
- 1996
- 1997
- 1998
- 1999
- 2000
- 2001
- 2002
- 2003
- 2004
- 2005
- 2006
- 2007
- 2008
- 2009
- 2010

Price (↓) performance (↑)
Worldwide Flat Panel Market: Small / Medium LCDs (< 10”)

Price per display shrinks!

Ranked acc. turn-over: compare e.g. SHARP and CPT

Ranked acc. turn-over: compare e.g. SHARP and CPT
Worldwide Flat Panel Market: LED Backlight for LCDs

- LCD TV
- LCD Monitor
- Notebook PC
- Other LCD applications

LCD < 5": ~ 100% LED
Worldwide Flat Panel Market: OLEDs

- Left: Linear rise or S-curve – compare to mobile devices (right)
- Left: 10 M$ ticks reasonable?
- OLEDs in total are about 1.5% of total LCD-market in 2006
Worldwide Flat Panel Market: Car Navigation

- ROW
- Western Europe
- USA
- China
- Japan

[Bar chart showing market growth from 2003 to 2011 for different regions]
Worldwide Market: Head-Up Displays

- 2006: $20
- 2007: $30
- 2008: $40
- 2009: $50
- 2010: $80
- 2011: $100
- 2012: $120

Value $M
Worldwide Market: Touch Screens
Worldwide Market: Low Power and Zero Power Displays
LCD TV Race (Prototypes)

2004: 57"

2005: 82"

2006: 108"

Commodity up to 65” (2007)

Gen 10

108” WORLD’S LARGEST LCD TV
The Race for Size is limited by Mother Glass Size

Commericially in MP available:
- LCD up to 70”
- PDP up to 70” (PANASONIC 103”: 100,000 $)

Forced by trend to signage (POI, small sized indoor billboards, …)
The Race for Size (I)

Production issue
Micrometer precision required in meter range!
The Race for Size (II)

- Gen 8 = 1 B$
- SHARP announced Gen 10 for 2010
Flat Panel Display World

Resolution

QXGA
HDTV
SXGA
XGA
SDTV
VGA
QVGA

150 ppi
p-Si
a-Si

Notebook
PC-monitor

LCD TV

Projection system

Car
MP, PDA

Low information content displays

Display Size /“
How to Select a Display

User quality → Technical specification

'Good readability'          Optics, electronics, application, ...

Magic Circle

Pixel driving,
e-o characteristics,
rise & fall time,
ghosting, ...

Electro-optics          Optics

Electronics          Application

Driving, voltages,
signal processing,
power consumption,
EMI, data input, ...

Luminance, contrast,
grey scale, colour,
response time, uniformity
viewing angle, reflections, ...

Size, weight, price, lifetime,
power supply, reliability,
mature technology,
temperature, vibration,
displayed data, ...
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
## Basic Characteristics of Vision

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Spectral Sensitivity for Day and Night</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Angular resolution : 1° at optical axis</td>
<td></td>
</tr>
<tr>
<td>Example: 0.3mm @ 1m</td>
<td></td>
</tr>
<tr>
<td>• Time resolution ~ 50 ms (20 Hz) up to 100 Hz flicker sensitive</td>
<td></td>
</tr>
<tr>
<td>• ~ 500,000 colors can be distinguished</td>
<td></td>
</tr>
</tbody>
</table>

... plus 'signal processing' (brain)
**Sea of Measurement Tasks**

- **Environment**
  - Temperature,
  - % rH, EMI,
  - power supply,
  - ...

- **Signal processing**

- **Driving system**

- **Test patterns**
  - Full, box, checkerboard, grille,
  - grey level, color, dynamic, moving,
  - ...

- **Measurement of luminance and/or color**

- **Viewing angle**

- **Procedure, data storage**

- **Dark room or (simulated) ambient light**

- **Procedure**
  - Spatial
    - Jitter
  - Temporal
    - Warm up
    - T-change
    - Lifetime
Overview

• Introduction

• Basic Parameters (Merits)
  - B/W, GS, color
  - L, C_R, GS, color
  - Parameters & vision

• Common Issues

• Display Technology Dependent Issues (Shortcomings)

• Summary

Color Calculator: www.radiantimaging.com/
Photometric Units

- **Luminous flux** (power) \( : F / \text{lm} \)
- **Luminance** \( : L / \frac{\text{cd}}{\text{m}^2} \) (emitter)
- **Illuminance** \( : E / \text{lx} = \frac{\text{lm}}{\text{m}^2} \) (receiver)

\[
\text{Illuminance} = \text{power} / \text{area} \quad : \quad E = \frac{dF}{dA} = \frac{F}{A}
\]

**Examples**
- Luminous flux \( F = 1,000 \) ANSI lm for projector
- Luminance \( L = 300 \text{ cd/m}^2 \) for AMLCD
- Illuminance for 1,000 lm projector at 2 x 3 m\(^2\) \( \rightarrow E = 167 \text{ lx} \)
  
  compare to 500 lx recommended at workplace!
Luminance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Condition</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminance (center of screen)</td>
<td>Lw</td>
<td>at center</td>
<td>-</td>
<td>1600</td>
<td>-</td>
<td>cd/m²</td>
</tr>
</tbody>
</table>

• \([L] = \text{cd/m}^2\)

• Typical values: Displays 50 … 1,000 cd/m², bulb 10,000 cd/m², sun at noon \(10^8\) cd/m², full moon 100 cd/m²

• Basic value for contrast, grey scale, uniformity, viewing angle, ...

• One of three parameters for color measurements (Tristimulus)

• Measurement conditions
  - Dark room unless otherwise noted
  - Centre of display, perpendicular incidence
  - Usually F.O.V. of > 25 pixel for monitors
  - \(V(\lambda)\) corrected devices

Same for color
Example of Optical Specification for AM LCD (II)

Photodetector
Viewing angle/Response time: BM-5A (TOPCON)
Contrast ratio/Luminance of white/Chromaticity: SR-3(TOPCON)

Recommendation: Use same device as in spec!

Fig. 3 Optical characteristics measurement method
Contrast Ratio ... is not a measure for readability of text (full screen)!

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

- **Contrast ratio**

\[
C_R = \frac{L_{\text{bright}}}{L_{\text{dark}}} = \frac{L_{\text{white}}}{L_{\text{black}}} \quad \text{... Example}
\]

Paper ≈ 10 : 1

Remarks

- High \(C_R\) can be critical because of measurement error for \(L_{\text{black}}\)
- Vision range: \(C_R = 3 : 1 - 500 : 1\)
- \(C_R \approx 10 : 1\) 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!  \(\text{E} \rightarrow C_R\)
- Various conditions like full screen, checkerboard, …
Contrast Ratio Test Patterns

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Condition</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contrast ratio</td>
<td>CR</td>
<td>$\Theta_y=-5^\circ$, $\Theta_x=\pm0^\circ$</td>
<td>-</td>
<td>350:1</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- **Full screen**
  - LCD, OLED, PDP $C_R \approx 100:1$
  - Used for PDP $\rightarrow C_R \approx 1,000:1$

- **Centered box**

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

- **Intra-Character**
LED LCD - Backlight Improvements: Local Dimming

Traditional Full-On LED

Individual LED On/Off & Level Control

High Contrast

$L_{\text{max}} = 630 \text{ cd/m}^2$

$L_{\text{min}} = 0.03 \text{ cd/m}^2$

$C_R = \frac{630}{0.03} = 21,000 : 1$

Power saving 50% average (image dependant)
Modulation Transfer Function & Resolution

- Contrast modulation = MTF
  \[ C_M^{\text{Grille}} = \frac{L_{\text{bright}} - L_{\text{dark}}}{L_{\text{bright}} + L_{\text{dark}}} \]

- Threshold
  - Text  \[ C_M^{\text{Grille}} \geq 0.5 \]
  - Images  \[ C_M^{\text{Grille}} \geq 0.25 \]

- Resolution
  \[ R = \frac{\text{Number of lines}}{n_{T,I}} \]

  - (Analogue) bandwidth
  - Ghosting, …
Grey Scale Measurements

- Greyscale for images, ...
- Results: Gamma, GS resolution, ...
- Gamma is seldom specified

![Graph showing rel. Luminance vs rel. Grey Level for LCD 18", LCD 8.4", L ~ D^{2.3}, and CRT.]

![Graph showing log (norm. Luminance) vs log (norm. Grey Level) with Deviations and Contrast ratio only max / min.]

- Greyscale for images, ...
- Results: Gamma, GS resolution, ...
- Gamma is seldom specified
Color Space CIE 1931

- Oldest CIE standard
- Still in use today but CIE 1976 UCS recommended in display metrology specs!
- Problem: Co-ordinate differences ≠ color differences (Mac Adam)
- Linear transformation of Tristimulus values, \( L = Y \),
  \[
  x = \frac{X}{X+Y+Z} ; \quad y = \frac{Y}{X+Y+Z}
  \]
# LCD CIE 1931 Specification

Ta = 25°C

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Condition</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromaticity of white</td>
<td>x</td>
<td></td>
<td>0.263</td>
<td>0.313</td>
<td>0.363</td>
</tr>
<tr>
<td></td>
<td>y</td>
<td></td>
<td>0.279</td>
<td>0.329</td>
<td>0.379</td>
</tr>
<tr>
<td>Chromaticity of red</td>
<td>x</td>
<td>θ = 0°</td>
<td>(0.546)</td>
<td>(0.596)</td>
<td>(0.646)</td>
</tr>
<tr>
<td></td>
<td>y</td>
<td></td>
<td>(0.279)</td>
<td>(0.329)</td>
<td>(0.379)</td>
</tr>
<tr>
<td>Chromaticity of green</td>
<td>x</td>
<td></td>
<td>(0.260)</td>
<td>(0.310)</td>
<td>(0.360)</td>
</tr>
<tr>
<td></td>
<td>y</td>
<td></td>
<td>(0.502)</td>
<td>(0.551)</td>
<td>(0.602)</td>
</tr>
<tr>
<td>Chromaticity of blue</td>
<td>x</td>
<td></td>
<td>(0.117)</td>
<td>(0.167)</td>
<td>(0.217)</td>
</tr>
<tr>
<td></td>
<td>y</td>
<td></td>
<td>(0.132)</td>
<td>(0.182)</td>
<td>(0.232)</td>
</tr>
</tbody>
</table>

This shall be measured at center of the screen.

Plot these tolerances in CIE 1931 with Δx and Δy = 0.1!
Color Space CIE 1976 UCS

- CIE 1976 UCS recommended in display metrology specs!
- Co-ordinate differences ≈ colour differences
- Linear transformation

\[
\begin{align*}
    u' &= \frac{4X}{X+15Y+3Z} = \frac{4x}{-2x+12y+3} \\
    v' &= \frac{9Y}{X+15Y+3Z} = \frac{9y}{-2x+12y+3}
\end{align*}
\]

- Gamut (100% usually refers to NTSC)

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

- **YIQ : NTSC**

\[
\begin{align*}
Y &= 0.30 R + 0.59 G + 0.11 B \\
I &= 0.60 R - 0.28 G - 0.32 B \\
Q &= 0.21 R - 0.52 G + 0.31 B
\end{align*}
\]

- **YUV : PAL, SECAM**

\[
\begin{align*}
U &= 0.493 (B - Y) \\
V &= 0.877 (R - Y)
\end{align*}
\]

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

\[
\begin{align*}
Y &= 0.30 R + 0.59 G + 0.11 B \\
Cb &= -0.17 R - 0.33 G + 0.50 B \\
Cr &= 0.50 R - 0.42 G - 0.08 B
\end{align*}
\]

- All parameters are normalized
- \(Y\) ≡ Luminance, same formula for all TV color spaces
- \(IQ, UV, CbCr\) ≡ Chrominance
## Color Space Summary

<table>
<thead>
<tr>
<th></th>
<th>CIE 1931</th>
<th>CIE 1976 UCS</th>
<th>CIE Lab CIE Luv</th>
<th>RGB</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tristimulus</strong></td>
<td>Linear</td>
<td>Linear</td>
<td>Non-linear</td>
<td>n. a.</td>
</tr>
<tr>
<td><strong>transformation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Luminance</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>n. a.</td>
</tr>
<tr>
<td><strong>Plot</strong></td>
<td>2D</td>
<td>2D</td>
<td>3D</td>
<td>3D</td>
</tr>
<tr>
<td><strong>Pros</strong></td>
<td>history</td>
<td>∆co-cord. ≈ ∆color</td>
<td>JNDs</td>
<td>SW</td>
</tr>
<tr>
<td><strong>Cons</strong></td>
<td>∆co-cord. ≠ ∆color (Mac Adams)</td>
<td>L not brightness</td>
<td>3D, L* ≠ L</td>
<td>Device specific</td>
</tr>
<tr>
<td><strong>Used for</strong></td>
<td>Specs (recomm.)</td>
<td>Specs</td>
<td>∆E</td>
<td>SW</td>
</tr>
</tbody>
</table>
Overview

- Introduction

- Basic Parameters (Merits)

- Common Issues

- Display Technology Dependent Issues (Shortcomings)

- Spatial domain:
  Uniformity, MTF, gamma,
  color tracking, …

- Time domain:
  - Short: Flicker, jitter, swim, blur, …
  - Medium: Warm up, …
  - Long: Lifetime, …

- Ambient light: C_R, GS, color, …

- Signal processing

- Summary

Here: Some examples
Uniformity

• Deviation of a display parameter, e.g. luminance within display area

• 5, 9 or 13 spots method (ISO 9241)

Definitions

- \( \emptyset L \pm x\% \)
- \( 100 \frac{L_{\text{max}} - L_{\text{min}}}{L_{\text{max}}} < x\% \)
- \( 100 \frac{L_{\text{max}}}{L_{\text{min}}} < x\% \)

Examples*

190 cd/m\(^2\) ± 5%
10%
111%

*: \( L_{\text{max}} = 200 \text{ cd/m}^2, L_{\text{min}} = 180 \text{ cd/m}^2 \)

• Area (linear or false color)
Examples of Uniformity Measurement in Spec

[Note 5] Definition of white uniformity:
White uniformity is defined as the following with five measurements (A ~ E).

\[ \delta_w = \frac{\text{Maximum Luminance of five points (brightness)}}{\text{Minimum Luminance of five points (brightness)}} \]

Spot size acc. FOV and distance

Luminance variations outside this points are not specified like degradations due to burn-in or image sticking!
Color Tracking

Color Tracking 20" LCD, CIE 1976 UCS

Color coordinate of white depends here on grey level!

γ ≠ γ ≠ γ!
**Contrast Ratio with Ambient Light**

$$C_R = \frac{L_{\text{white}}}{L_{\text{black}}} + \text{ambient light}$$

$$C_R \approx \frac{L_{\text{white}}(0 \text{ lx}) + L_{\text{reflected}}}{L_{\text{black}}(0 \text{ lx}) + L_{\text{reflected}}} \approx \frac{L_{\text{white}}(0 \text{ lx})}{L_{\text{reflected}}} \approx \frac{\pi L_{\text{white}}(0 \text{ lx})}{r E}$$

**Components of reflections**

- **LCD (left)**: specular & haze
- **OLED (right)**: mainly specular (diffuse with low intensity)
ISO 15008 Sunlight Simulation

Diffuse or specular geometry

Contrast Ratio Diffuse Geometry

4.3.1 Minimum contrast
The minimum contrast ratio
- 5:1 for night conditions,
- 3:1 for day conditions, and
- 2:1 for sunlight conditions.
### Examples for Contrast Ratio Degradation

<table>
<thead>
<tr>
<th>$L_{\text{White}}$</th>
<th>$L_{\text{Black}}$</th>
<th>$C_R(0 \ \text{lx})$</th>
<th>$C_R$ with $L_{\text{Reflected}} = 10 \ \text{cd/m}^2$ *</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>1</td>
<td>500</td>
<td>510 / 11 = 46</td>
</tr>
<tr>
<td>100</td>
<td>1</td>
<td>100</td>
<td>110 / 11 = 10</td>
</tr>
<tr>
<td>500</td>
<td>5</td>
<td>100</td>
<td>510 / 15 = 34</td>
</tr>
<tr>
<td>100</td>
<td>5</td>
<td>20</td>
<td>110 / 15 = 7</td>
</tr>
</tbody>
</table>

* : $L_{\text{Reflected}}(W) = L_{\text{Reflected}}(K)$

- Factor 5 for white luminance, $L(K) = \text{const.} \rightarrow$ factor $\sim 4.7$ in $C_R$ for ambient light
- Factor 5 for black luminance, $L(W) = \text{const.} \rightarrow$ factor $\sim 1.4$ in $C_R$ for ambient light

For $L_{\text{White}} = 100 \ \text{cd/m}^2$ and $L_{\text{White}} = 500 \ \text{cd/m}^2$,

Luminance of white has more influence on $C_R$ with ambient light than luminance of black and $C_R$ under dark room conditions!
Ambient Light & Grey Scale

- Ambient light reduces the number of distinguishable grey shades (JND)
- Grey shades below 80 (of 255) can't be resolved for 2,000 lx
Ambient Light & Color

Reflections shift the color coordinates towards the locus of the light source.
Display Technology vs. Ambient Light: Sunlight Outdoor

- Transmissive color AM LCD
- Transflective Color AM LCD
- Reflective E-Paper
- Reflective b/w PM LCD
- Reflective MUX LCD

Display is ON!
E-Paper is close to paper

for white luminance, \( L(W) = L_{\text{white}} \)
for black luminance, \( L(W) = L_{\text{black}} \)

Calculated with \( L_{\text{white}} = 150 \text{ cd/m}^2 \)

High power backlight for transmissive LCDs moves curve to higher brightness
Blur Effects

- **Spatial Blur**
  
  by limited bandwidth, jitter, …
  
  e.g. MTF, analogue path
  
  see ‘Display Metrology’

- **Motion Blur**
  
  by hold type
  
  displays (e.g. AM)
Motion Blur Basics

- Motion blur is caused by AM techniques due to lack of 'auto-tracking' by human vision (PDP has similar issues on subframe coding)

- Impulsive displays like CRTs don’t suffer of motion blur

Visualization | Perceived
--- | ---
AM | ![Visualization AM]
   | 'Display & hold'
CRT | ![Visualization CRT]
   | 'Flashing'

Adapt AM to impulsive drive
Display & Observer Motion Blur

Input Image → Sample /Hold → LCD Response (LPF) → Human Visual System → Perceived Image

Direction of motion → Blurry edges!
Motion Blur Reduction Techniques

Only with LED backlight!
### Displaying Moving Objects

<table>
<thead>
<tr>
<th></th>
<th>Original (2 pictures ‘movie’)</th>
<th>Non - Hold Type (CRT)</th>
<th>Hold Type (AM technologies)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frame 1</strong></td>
<td><img src="image1" alt="Frame 1" /></td>
<td><img src="image2" alt="Frame 1" /></td>
<td><img src="image3" alt="Frame 1" /></td>
</tr>
<tr>
<td>(Picture 1 is completely written on the display)</td>
<td><img src="image4" alt="Frame 1" /></td>
<td><img src="image5" alt="Frame 1" /></td>
<td><img src="image6" alt="Frame 1" /></td>
</tr>
<tr>
<td><strong>Frame 2</strong></td>
<td><img src="image7" alt="Frame 2" /></td>
<td><img src="image8" alt="Frame 2" /></td>
<td><img src="image9" alt="Frame 2" /></td>
</tr>
<tr>
<td>(Half of picture 2 is written on the display)</td>
<td><img src="image10" alt="Frame 2" /></td>
<td><img src="image11" alt="Frame 2" /></td>
<td><img src="image12" alt="Frame 2" /></td>
</tr>
</tbody>
</table>

- **Original**
  - Picture 1 is completely written on the display.
- **Non - Hold Type (CRT)**
  - Leftover of frame 1 not visible due to phosphor decay.
- **Hold Type (AM technologies)**
  - Smearing!
Effect of Eye Movement on CRTs (Impulsive Drive)

White box is moved with 4 pixels per 60 Hz frame

Examined line

Display x

On Display, x

CRT

On eye, x

Eye movement

Perceived image by eye
Effect of Eye Movement on 60 Hz LCDs (Hold Type)

- On Display, x
- On eye, x

1 F

Eye movement

Unsharp edge ≡ blurring of 3 pixels

Perceived image by eye
Effect of Eye Movement on 120 Hz LCDs (Hold Type)

On Display, $x$

1 F

t

Eye movement

On eye, $x$

1 F

t

Perceived image by eye

Unsharp edge $\equiv$ reduced blurring of 1 pixel
Effect of Eye Movement on Displays

White box is moved with 4 pixels per 60 Hz frame

Examined line

Display x

Perceived image by eye

CRT

60 Hz LCD

120 Hz LCD

- CRT has best motion picture quality
- LCD with 120 Hz is better than 60 Hz
Black Frame Insertion

\[ L_{\text{peak BFI}} > L_{\text{Hold}} \]

Subjective Evaluation for Moving Picture

<table>
<thead>
<tr>
<th>ITU Grade</th>
<th>(International Telecommunication Union)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excellent</td>
<td>CRT</td>
</tr>
<tr>
<td>Good</td>
<td>OCB w. LED</td>
</tr>
<tr>
<td>Fair</td>
<td>Black frame insertion</td>
</tr>
<tr>
<td>Poor</td>
<td>TN</td>
</tr>
</tbody>
</table>

OLED: ‘Easy’
- Fast OLED response
- Only SW required

LCD
- High LC switching speed required
- Black frame insertion or impulsive LED backlight
Impulsive Backlight for LCD Hold-Type Technologies

Frame 1
- Write grey level data to display
- Backlight OFF

Frame 2
- Write grey level data to display
- Backlight ON

No smearing

Backlight
- OFF
- ON
- OFF
- ON

\[ T_{\text{Blackframe}} = \frac{1}{2} T_{\text{Frame}} \]
\[ T_{\text{Display}} = \frac{1}{2} T_{\text{Frame}} \]

8.3 ms instead of 16.7 ms
→ fast switching LC required

Similar: Scrolling backlight with LEDs
Impulsive Backlight for LCD Hold-Type Technologies

Could be also made by 120Hz drive with GL = 0 insertion.

Application: Rolling backlight / black frame
Impulsive Backlight for LCD Hold-Type Technologies

No BFI  

With BFI
Impulsive Backlight for LCD Hold-Type Technologies

Scrolling of 'black' backlight sections
**Motion Blur Reduction by Higher Frame Rate**

Motion blur reduction using high frame rate driving: **120Hz/100Hz**

Requires new panel design, also video sources low frame rates

(NTSC = 60Hz, PAL = 50Hz, Film = 24Hz)

→ Motion interpolated frame technology or Black Frame Insertion needed such as McFi (Motion Compensated Frame Interpolation)
Comparison by SAMSUNG

Conventional 60Hz (MPRT ~ 15ms)

Impulsive driving (MPRT ~ 12ms)

120Hz McFi driving (MPRT ~ 8ms)
Comparison by SIEMENS

M. Zachmann (Pforzheim U) et al.

Evaluate your display with PIXPERAN (freeware)
CLEAR MOTION DRIVE by JVC

100 or 120 Hz & interpolated images
Motion Blur Reduction Using 120 Hz & 72 Hz Driving with Motion - Compensated Frame Interpolation

NTSC Video

<table>
<thead>
<tr>
<th>60 Hz</th>
<th>calculated</th>
<th>120 Hz 'cheaper' than backlight methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>B</td>
<td></td>
</tr>
</tbody>
</table>

Movie

For LCD and PDP

<table>
<thead>
<tr>
<th>24 Hz (Camera)</th>
<th>60 Hz (Set) (DVD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 Hz</td>
<td>60 Hz</td>
</tr>
<tr>
<td>72 Hz</td>
<td></td>
</tr>
</tbody>
</table>

Motion judder for 3:2 pull-down!
Frame Rate Conversion Techniques (I)

**PAL Video 50 Hz** ⇒ Motion blur on Hold type displays (LCD, …)

**PAL Video 100 Hz** repeated ⇒ judder

**PAL Video 100 Hz** motion compensated ⇒ no judder (if algorithm OK)
Frame Rate Conversion Techniques (II)

Movie 24 Hz (24p) Original

Movie 60 Hz 3:2 pull down repeated ⇒ judder, jerkiness

Movie 72 Hz 3:3 pull down repeated ⇒ judder

Movie 120 Hz motion compensated ⇒ no judder (if algorithm OK)

calculated
PDPs: Motion Artefacts by Sub-Frame Driving

Many motion artifacts etc. of PDPs can be minimized by massive signal processing
Overview

- **Introduction**
- **Luminance domain**: Loading, halation
- **Time domain**: Burn-in, differential ageing, image sticking
- **Observer domain**: Spatial & time invariant
- **Response time**
- **Viewing angle**: L, C<sub>R</sub>, GS, color

**Common Issues**

**Display Technology Dependent Issues (Shortcomings)**

**Summary**

Here: Some examples
**LCDs: Response Time Effects**

Grey level transition

<table>
<thead>
<tr>
<th>Grey level transition</th>
<th>$T_{\text{Rise}}$/ms</th>
<th>$T_{\text{Fall}}$/ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 ↔ 255</td>
<td>20</td>
<td>9</td>
</tr>
<tr>
<td>110 ↔ 192</td>
<td>32</td>
<td>24</td>
</tr>
<tr>
<td>170 ↔ 215</td>
<td>23</td>
<td>19</td>
</tr>
</tbody>
</table>

- $T >$ frame time (16.7 ms)
- $T_{\text{Rise}} > T_{\text{Fall}}$
- $T = T(\text{grey 1} \leftrightarrow \text{grey 2})$

Grey level & color shifts

$T_{\text{ambient}} = 25^\circ C$
LCD Motion Blur caused by Slow Response Time

- Rise time often ≠ fall time
- Response time depends on grey level (start, final)

Moving Picture Response Time (MPRT) by Brightness Edge Width
Measurement setup: Camera and screen (one moving, one fixed)

Motion blur occurs for all AM technologies due to vision (Hold type)
Motion Blur Measurement Procedures

Capturing so that image ‘stands still’ on the camera (chip)

High speed sensor, problem: \( t \rightarrow x \)
MPRT & Perceived Motion Blur (I)

Test patterns for LCD (Crisp edge)

Test patterns for CRT (Adjustable edge blur)

Moving on each monitor

Displayed images on LCD (same blur)

Displayed images on CRT
MPRT & Perceived Motion Blur (II)

![Graph showing measured EBET and perceived motion blur width across different combinations of gray level.](image-url)
**Motion Picture Response Time by Brightness Edge Width**

\[ \text{Normalising: } N-\text{BEW} = \frac{\text{BEW}}{\text{moving speed}} \]

\[ \text{MPRT} = \emptyset N-\text{BEW} \text{ (G2G)} \]
Motion Picture Response Time by Brightness Edge Width

MPRT = 16 ms
### Motion Picture Response Time by Brightness Edge Width

<table>
<thead>
<tr>
<th>Display Model</th>
<th>Description</th>
<th>MPRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMD SID 05 pp 132</td>
<td>OCB with black insertion and backlighting blinking</td>
<td>6.5 ms</td>
</tr>
<tr>
<td>Sharp SID 05 pp 1734</td>
<td>ASV with two temporally sub-pixels</td>
<td>6.6 ms</td>
</tr>
<tr>
<td>Hitachi SID 05 pp1848</td>
<td>IPS- Pro at 120Hz or with black insertion and backlighting blinking.</td>
<td>9.3 ms</td>
</tr>
</tbody>
</table>
MPRT Measurements by Grey-to-Grey Response Time

CIE 1976 UCS
6 equidistant brightness

\[ L_0 = 903.3 \times \frac{Y_0}{Y_6} \text{ for } \frac{Y_0}{Y_6} \leq 0.008856 \]

\[ Y_n = Y_6 \times \left( \frac{L_0 + \left(100 - L_0\right) \cdot n/6 + 16}{116} \right)^3 \]

\[ n \in \{0, 1, 2, 3, 4, 5, 6\} \]

Initial gray level

<table>
<thead>
<tr>
<th>Y0</th>
<th>Y1</th>
<th>Y2</th>
<th>Y3</th>
<th>Y4</th>
<th>Y5</th>
<th>Y6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y0</td>
<td>Y0</td>
<td>Y0</td>
<td>Y0</td>
<td>Y0</td>
<td>Y0</td>
<td>Y0</td>
</tr>
<tr>
<td>Y1</td>
<td>Y0</td>
<td>Y1</td>
<td>Y1</td>
<td>Y1</td>
<td>Y1</td>
<td>Y1</td>
</tr>
<tr>
<td>Y2</td>
<td>Y1</td>
<td>Y2</td>
<td>Y2</td>
<td>Y2</td>
<td>Y2</td>
<td>Y2</td>
</tr>
<tr>
<td>Y3</td>
<td>Y2</td>
<td>Y2</td>
<td>Y2</td>
<td>Y2</td>
<td>Y2</td>
<td>Y2</td>
</tr>
<tr>
<td>Y4</td>
<td>Y3</td>
<td>Y3</td>
<td>Y3</td>
<td>Y3</td>
<td>Y3</td>
<td>Y3</td>
</tr>
<tr>
<td>Y5</td>
<td>Y4</td>
<td>Y4</td>
<td>Y4</td>
<td>Y4</td>
<td>Y4</td>
<td>Y4</td>
</tr>
<tr>
<td>Y6</td>
<td>Y5</td>
<td>Y5</td>
<td>Y5</td>
<td>Y5</td>
<td>Y5</td>
<td>Y5</td>
</tr>
</tbody>
</table>

Final gray level

e.g. \( L = 0, 2.2, 7.7, 18.4, 36.2, 62.8, 100 \text{ cd/m}^2 \)
MPRT Measurements by Grey-to-Grey Response Time

Extended Blurred Edge Time

\[
EBET = \frac{t_f - t_i}{0.9 - 0.1} = (t_f - t_i) \cdot 1.25
\]

\[
EBET_{if} = \begin{cases} 
    i = Y0,Y1,Y2...Y6 \\
    f = Y0,Y1,Y2...Y6 \\
    i \neq i 
\end{cases}
\]

\[
MPRT = \frac{1}{42} \sum EBET_{if}
\]
Viewing Angle

L, C_R, ...

-80° 0° +80° Angle

Lambertian (paper)
Emissive displays, diffuse LEDs, standard screen
Clear LEDs
LCDs, high gain-screen

'Angle isn't everything'!

Measurements: 2D, 3D, value: ± or Σ
Viewing Angle Basics

PM LCD

6:00 AM LCD seen from 12:00 displaying green

Sensor

Display

2D

3D

Display

2D

Sensor

θ

φ

0° / 3° ° 9° / 12° ° 180° / 9° ° 270° / 6° °
Specify viewing angle only with the minimum contrast ratio (or better color difference $\Delta E$)

here: $40^\circ @ C_R > 100 : 1$ ; $70^\circ @ C_R > 50 : 1$ ; $125^\circ @ C_R > 20 : 1$ ; $??\,^\circ @ C_R > 5 : 1$
Example from LCD - Specification

Threshold definition

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Condition</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viewing</td>
<td>Horizontal</td>
<td>$\phi_x^+$, $\phi_y = \pm 0^\circ$</td>
<td>-</td>
<td>60</td>
<td>-</td>
<td>deg.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\phi_x^-$, $\phi_y = \pm 0^\circ$</td>
<td>-</td>
<td>60</td>
<td>-</td>
<td>deg.</td>
</tr>
<tr>
<td>Angle</td>
<td>Vertical</td>
<td>$\phi_y^+$, $\phi_x &gt; 10$, $\phi_y = \pm 0^\circ$</td>
<td>-</td>
<td>45</td>
<td>-</td>
<td>deg.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\phi_y^-$, $\phi_x &gt; 10$, $\phi_x = \pm 0^\circ$</td>
<td>-</td>
<td>50</td>
<td>-</td>
<td>deg.</td>
</tr>
</tbody>
</table>
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 $\theta \approx 15^\circ$ is recommended.
Grey Scale Inversion

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

\[ \Delta L = L_{\text{dark grey}} - L_{\text{black}} \]
Contrast Ratio vs. Grey Scale Performance

Contrast Ratio values are misleading here because a reduction of ‘only’ 2 occurs but the grey level representation is completely vanished (flat curve, blue) compared to perpendicular incidence (OK, brown) → no grey shades visible for 20° off!
Color Dependency from Viewing Angle of LCDs

Measured color representation, black was shown on the screen!

Visual test pattern

Inversion!
Colour Wash Out

Electro-optical curve changes with viewing angle!
Luminance Domain: Loading of Plasma Panels

Luminance of centered white box depends on their size, this is called ‘loading’.

Why? Power limitation

This can be also observed for CRTs (incl. image size variations).
Aging of Displays

- **Lifetime (50%)**
  
  Full screen white measured

  \[ \text{Note: Life time measured at } \sim 75^\circ \text{C, and extrapolated to } 25^\circ \text{C in specs!} \]

  \[\text{Temperature } \uparrow \rightarrow \text{Life time } \downarrow\]

- **Differential Aging**
  
  Different lifetimes of color subpixel \( \rightarrow \) color shift

  Static content like on airport information displays can cause burn-in and image sticking
Burn-In of Emissive Displays and LCD Image Sticking

- CRT
- PDP
- LCD

Several hours display dark grey
Burn-In and LCD Image Sticking Measurement

- **T = 0**: Display 5 x 5 (black & white) checkerboard and mark 3 boxes (2 white, 1 black)
- Measure ‘initial’ luminance for the 3 boxes for black and white: $L_{WL}$, $L_{WC}$, … $L_{BL}$, … $L_{BR}$
- Burn-in display when showing the checkerboard, if applicable
  with high temperature for speeding up the effect, e.g. for OLEDs
- Wait x hours
- Measure luminance of the same locations for full white ($K_{WL}$, $K_{WC}$, $K_{WR}$)
- Measure luminance of the same locations for full black ($K_{BL}$, $K_{BC}$, $K_{BR}$)
- Calculate residual image factors by

\[
R_{\text{white}} = \frac{\text{MAX} \left[ \left( K_{WR} + K_{WL} \right) L_{WC} , \left( L_{WL} + L_{WR} \right) K_{WC} \right]}{\text{MIN} \left[ \left( K_{WR} + K_{WL} \right) L_{WC} , \left( L_{WL} + L_{WR} \right) K_{WC} \right]} ;
R_{\text{black}} = \frac{\text{MAX} \left[ \left( K_{BR} + K_{BL} \right) L_{BC} , \left( L_{BL} + L_{BR} \right) K_{BC} \right]}{\text{MIN} \left[ \left( K_{BR} + K_{BL} \right) L_{BC} , \left( L_{BL} + L_{BR} \right) K_{BC} \right]}
\]

R’s are greater than 1 because of aged luminance ‘K’ is lower than initial luminance ‘L’

Simpler test:

\[
\text{Burn in (\%)} = 100 \left( 1 - \frac{L_{WL}(x) + L_{WR}(x)}{2L_{WC}(x)} \right)
\]

- Checkerboard as burn-in
- White screen as test pattern after x hours

**IS:**
Test at grey (60/255)
Overview

• Introduction

• Basic Parameters (Merits)

• Common Issues

• Display Technology Dependent Issues (Shortcomings)

• Summary
Parameters Affecting Measurements & Visual Perception

- Photometric
- Colorimetric
- Resolution

- Temporal ~
- Directional variations
- Lateral ~
### Example of Optical Specification for AM LCD

#### Optical Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Condition</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Unit</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viewing angle range</td>
<td>Horizontal, Vertical</td>
<td>θ 21, θ 22</td>
<td>CR&gt;10</td>
<td>60</td>
<td>70</td>
<td>-</td>
<td>Deg. [Note1]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>θ 11</td>
<td></td>
<td>35</td>
<td>50</td>
<td>-</td>
<td>Deg. [Note4]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>θ 12</td>
<td></td>
<td>55</td>
<td>60</td>
<td>-</td>
<td>Deg. [Note4]</td>
</tr>
<tr>
<td>Contrast ratio</td>
<td>CRn</td>
<td>θ =0°</td>
<td>300</td>
<td>-</td>
<td>-</td>
<td></td>
<td>[Note2] [Note4]</td>
</tr>
<tr>
<td></td>
<td>CRo</td>
<td>Optimum viewing angle</td>
<td>-</td>
<td>(600)</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Response time</td>
<td>Rise</td>
<td>τ r</td>
<td>-</td>
<td>10</td>
<td>-</td>
<td>ms</td>
<td>[Note3] [Note4]</td>
</tr>
<tr>
<td></td>
<td>Decay</td>
<td>τ d</td>
<td>-</td>
<td>25</td>
<td>-</td>
<td>ms</td>
<td></td>
</tr>
<tr>
<td>Chromaticity of white</td>
<td>x</td>
<td></td>
<td>0.263</td>
<td>0.313</td>
<td>0.363</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>y</td>
<td>0.279</td>
<td>0.329</td>
<td>0.379</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chromaticity of red</td>
<td>x</td>
<td></td>
<td>(0.546)</td>
<td>(0.596)</td>
<td>(0.646)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>y</td>
<td>(0.279)</td>
<td>(0.329)</td>
<td>(0.379)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chromaticity of green</td>
<td>x</td>
<td></td>
<td>(0.260)</td>
<td>(0.310)</td>
<td>(0.360)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>y</td>
<td>(0.502)</td>
<td>(0.551)</td>
<td>(0.602)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chromaticity of blue</td>
<td>x</td>
<td></td>
<td>(0.117)</td>
<td>(0.167)</td>
<td>(0.217)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>y</td>
<td>(0.132)</td>
<td>(0.182)</td>
<td>(0.232)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luminance of white</td>
<td>Y_l1</td>
<td></td>
<td>360</td>
<td>450</td>
<td>-</td>
<td>cd/m²</td>
<td>[Note5]</td>
</tr>
<tr>
<td>White Uniformity</td>
<td>δW</td>
<td></td>
<td>-</td>
<td>-</td>
<td>1.25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*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.
# Overview of Standards

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Standard</th>
<th>Display</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminance</td>
<td>CIE 18,15.2</td>
<td>All</td>
</tr>
<tr>
<td></td>
<td>IEC 47(CO)16</td>
<td>LCD</td>
</tr>
<tr>
<td></td>
<td>IEC 61747*</td>
<td></td>
</tr>
<tr>
<td>Chromaticity</td>
<td>CECC 20000 A3</td>
<td>LCD</td>
</tr>
<tr>
<td></td>
<td>IEC 47(CO)16</td>
<td>LCD</td>
</tr>
<tr>
<td></td>
<td>ISO 9241/3</td>
<td>CRT</td>
</tr>
<tr>
<td></td>
<td>ISO 13406</td>
<td>FPD</td>
</tr>
<tr>
<td></td>
<td>IEC 61747*</td>
<td></td>
</tr>
<tr>
<td>Luminance and chromaticity uniformity</td>
<td>ISO 9241/3</td>
<td>CRT</td>
</tr>
<tr>
<td></td>
<td>ISO 13406</td>
<td>FPD</td>
</tr>
<tr>
<td></td>
<td>CECC WG 20B</td>
<td>LCD</td>
</tr>
<tr>
<td></td>
<td>IEC 61747*</td>
<td></td>
</tr>
<tr>
<td>Response time</td>
<td>ISO 13406</td>
<td>FPD</td>
</tr>
<tr>
<td></td>
<td>CECC 20000 A3</td>
<td>LCD</td>
</tr>
<tr>
<td></td>
<td>IEC 47(CO)16</td>
<td>LCD</td>
</tr>
<tr>
<td></td>
<td>IEC 61747*</td>
<td></td>
</tr>
<tr>
<td>Reflections</td>
<td>ISO 13406</td>
<td>FPD</td>
</tr>
<tr>
<td></td>
<td>CECC 20000 A3</td>
<td>LCD</td>
</tr>
<tr>
<td></td>
<td>IEC 47(CO)16</td>
<td>LCD</td>
</tr>
<tr>
<td></td>
<td>ISO 9241/7</td>
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* : for LCD matrix displays

**Common:** VESA FPDM, SPWG, TCO