HEBS: Histogram Equalization for Backlight Scaling

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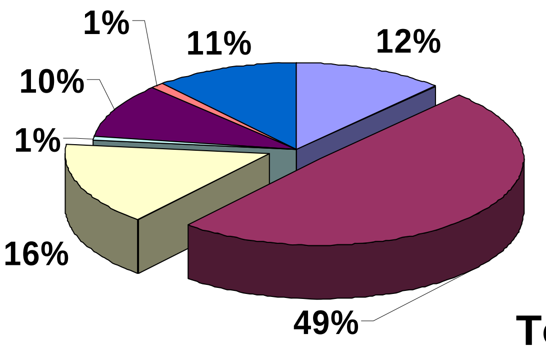
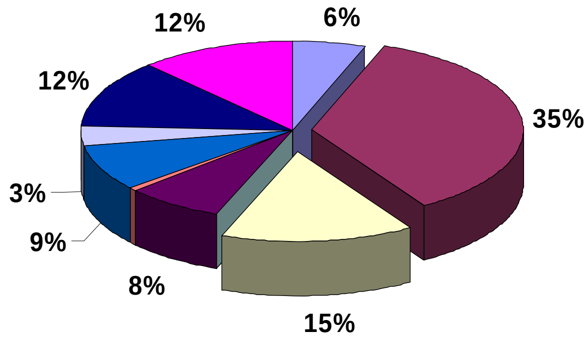
Motivation

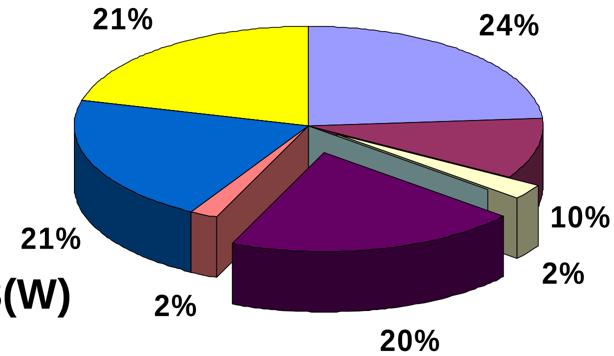


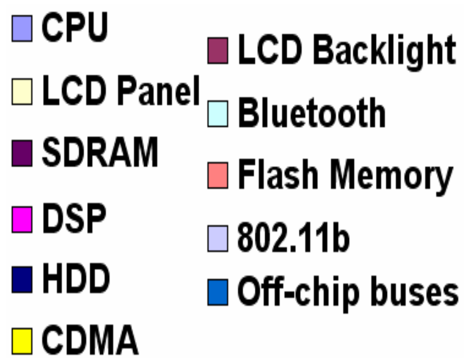
Total Power = 2.96(W)

Total Power = 7.27(W)



Total Power = 1.63(W)





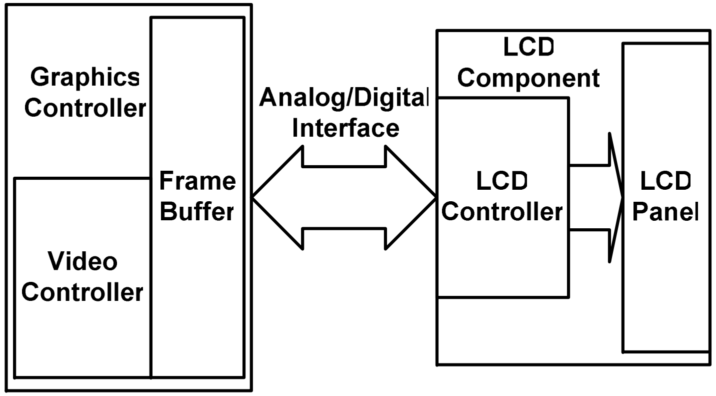
Data from H. Shim et. al., ESTIMEDIA 2004

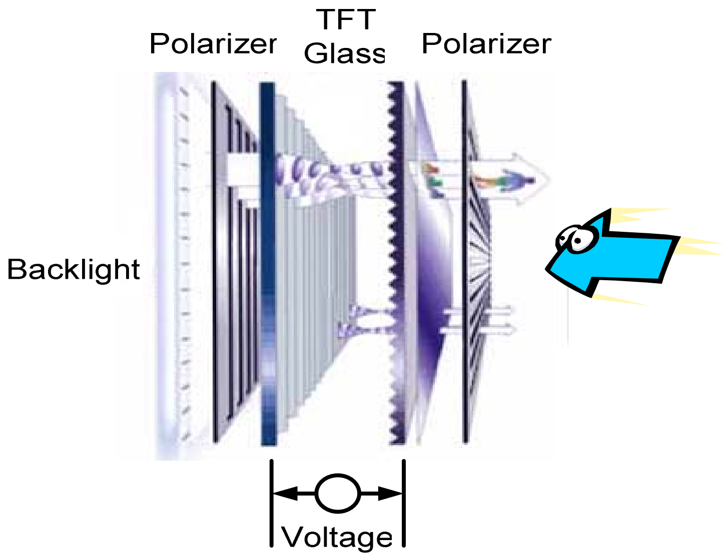
Outline

- Background
- Display Energy Management Solutions
- Backlight Scaling Technique
  - Previous works
  - Histogram Equalization for Backlight Scaling (HEBS)
- Simulation results
- Conclusion & future directions

Display Architecture

- The image data is first saved into the frame buffer memory by the video controller and then it is transmitted to the LCD
- LCD controller receives the video data and generates a proper grayscale for each pixel
- A displayed pixel looks bright if its transmittance is high, meaning it passes the backlight. On the other hand, a displayed pixel looks dark if its transmittance is low, meaning that it blocks the backlight



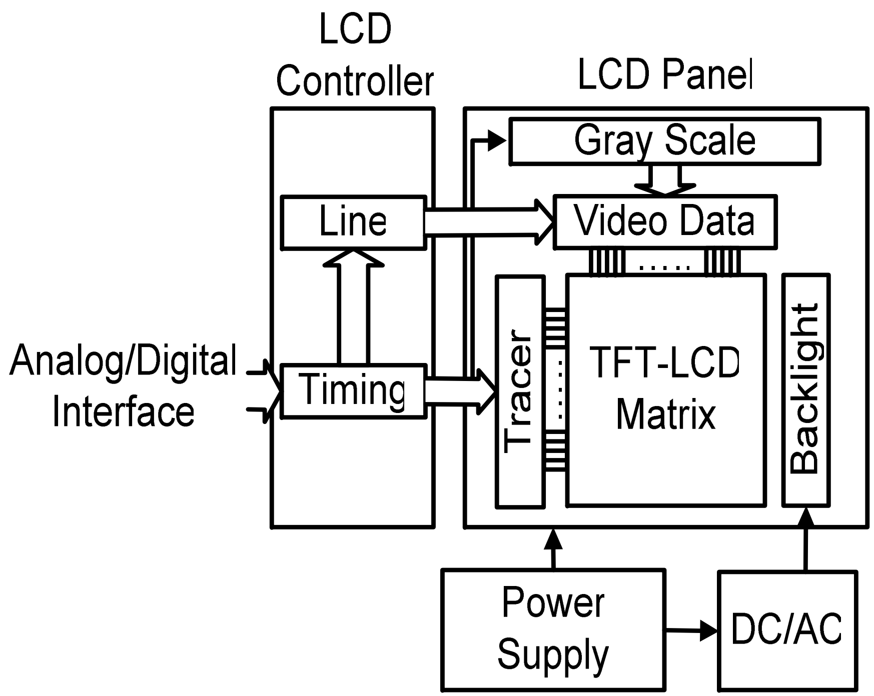


LCD Component

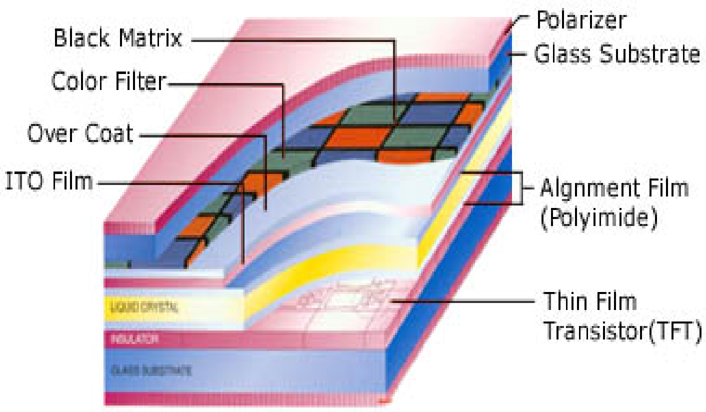
- LCD controller extracts timing information and grayscale level of each pixel from the video interface signal

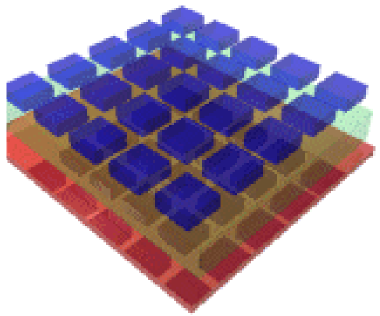
- Tracer scans rows of LCD matrix one-by-one to refresh the grayscale level of each row

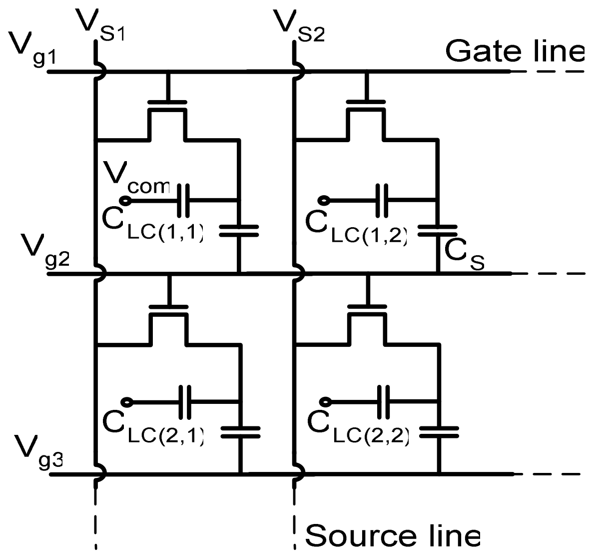
- Different grayscale levels are represented by different voltage values at the output of the grayscale block



Thin Film Transistor Cell



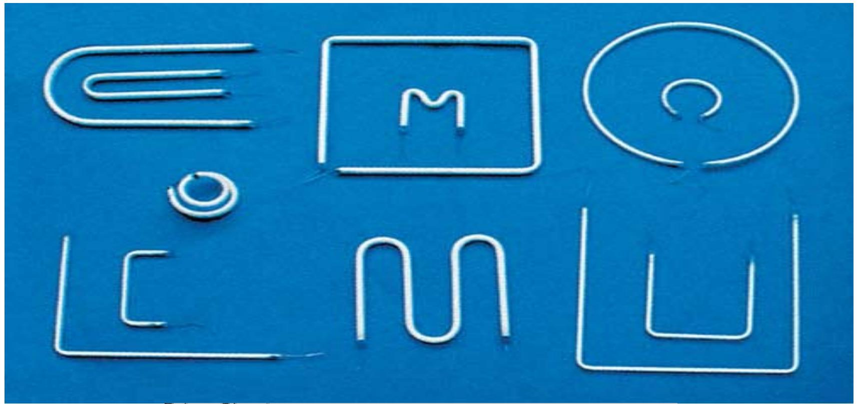


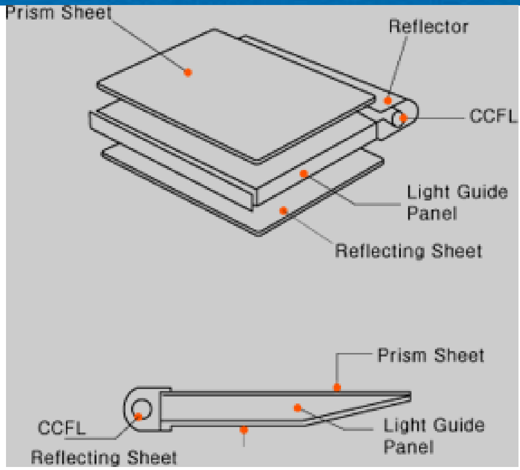


- Each pixel on screen is a capacitor applying electrical field to the corresponding liquid crystal cell

- Different voltage levels on each capacitor produce different transmittance for each liquid crystal cell, and hence, different grayscale levels for the corresponding pixel

Cold Cathode Fluorescent Lamp (CCFL)



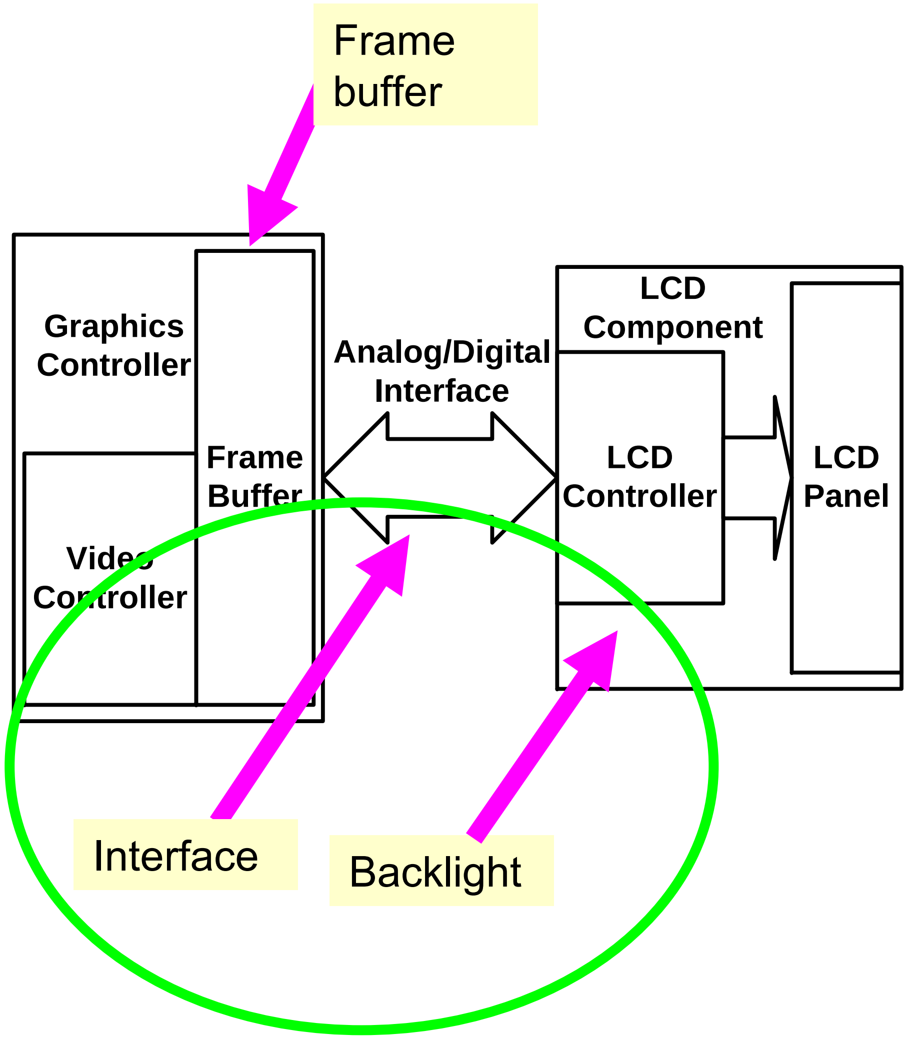


- CCFL is the most efficient electrical-to-optical energy transducer with efficiencies of about 20%
- Conversion efficiency is a function of
  - Current
  - Temperature
  - Drive waveform
  - Length, width, and gas type
- LCD displays usually have one or two CCFL's and a light guide panel to evenly distribute light behind the LCD

Energy Management Solutions

Focusing on:

- Frame buffer
  - Reduce the number of updates in frame buffer e.g., compressed buffer
- Digital/analog interface between the graphics controller and the LCD controller
  - Minimize the switching activity on the video display e.g., chromatic encoding
- LCD controller and the backlight
  - Dim the display backlight to consume less energy e.g., backlight scaling



Backlight Scaling

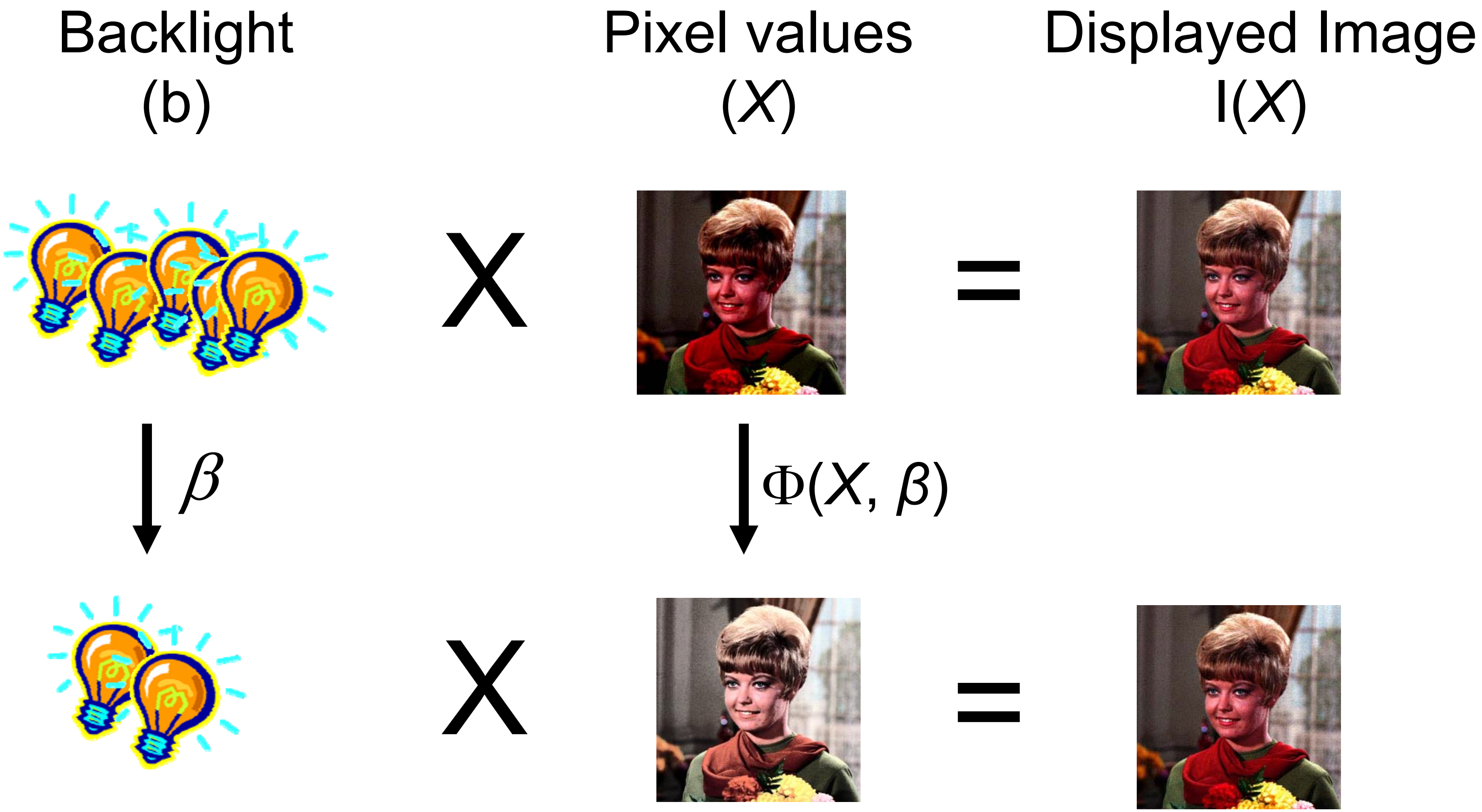
- Key idea: Measured output light, which is emitted from the LCD panel, is a function of two parameters
  - Luminous intensity of the backlight
  - Transmittance of the LCD panel

- By adjusting the backlight intensity and the LCD transmittance one can achieve the same output image with different sets of these parameter values

- Amount of change in energy consumption of the backlight lamp as a function of a change in the backlight intensity tends to be much higher than energy consumption change of the LCD panel as a function of a change in the LCD transmittance

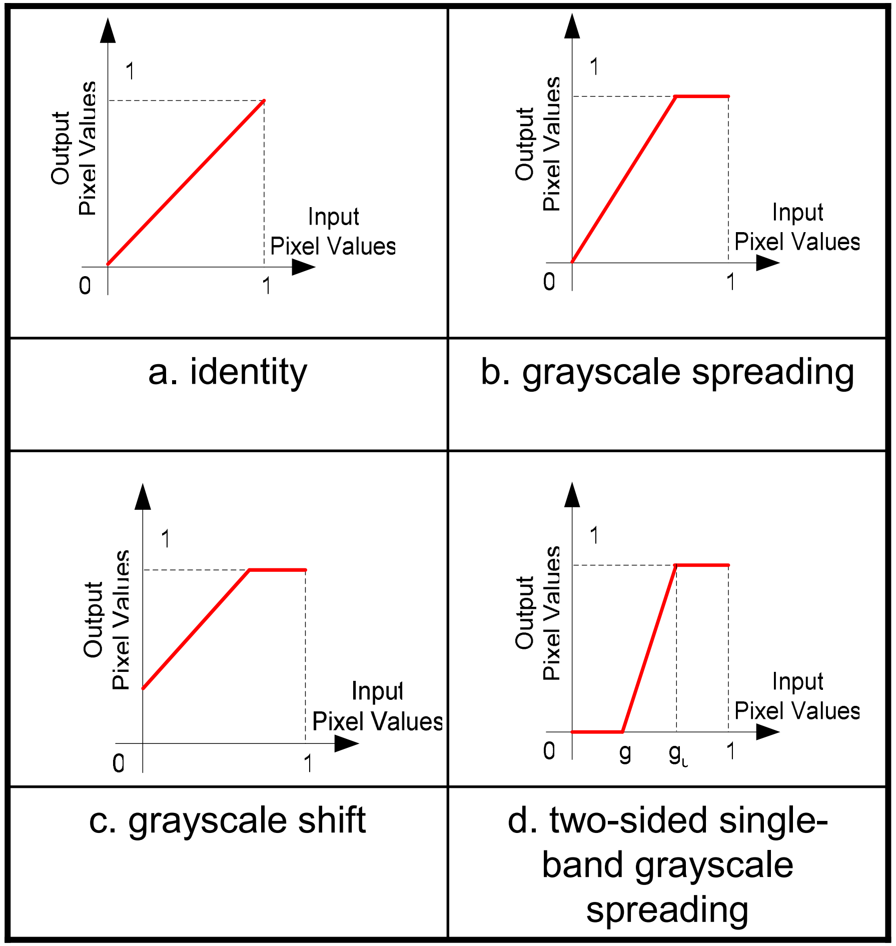
- Reduce energy consumption of the LCD by simply dimming the backlight while increasing the LCD transmittance to compensate for the loss of backlight

Backlight Scaling (cont'd)



Previous Work

- Chang et. al., 2003, proposed grayscale spreading and grayscale shift techniques for backlight scaling (cf. figures b, c)
- Cheng and Pedram, 2004, proposed two-sided single band grayscale spreading (cf. figure d)



a. identity

b. grayscale spreading

c. grayscale shift

d. two-sided single-band grayscale spreading

Pros and Cons

- Pros
  - Preserve brightness/contrast of the displayed image
  - Minimize image distortion by saturating minimal number of pixels
  - Achieve 20~30% power saving in the display system
- Cons
  - Pixel-by-pixel manipulation of the image ➔ applicable to still images
  - Requires image histogram information
  - Do not accurately model the human visual system, i.e. relies on relatively inaccurate image distortion metric
  - Do not fully utilize the power saving potential of dynamic backlight dimming approach

Dynamic Backlight Scaling (DBS) Problem

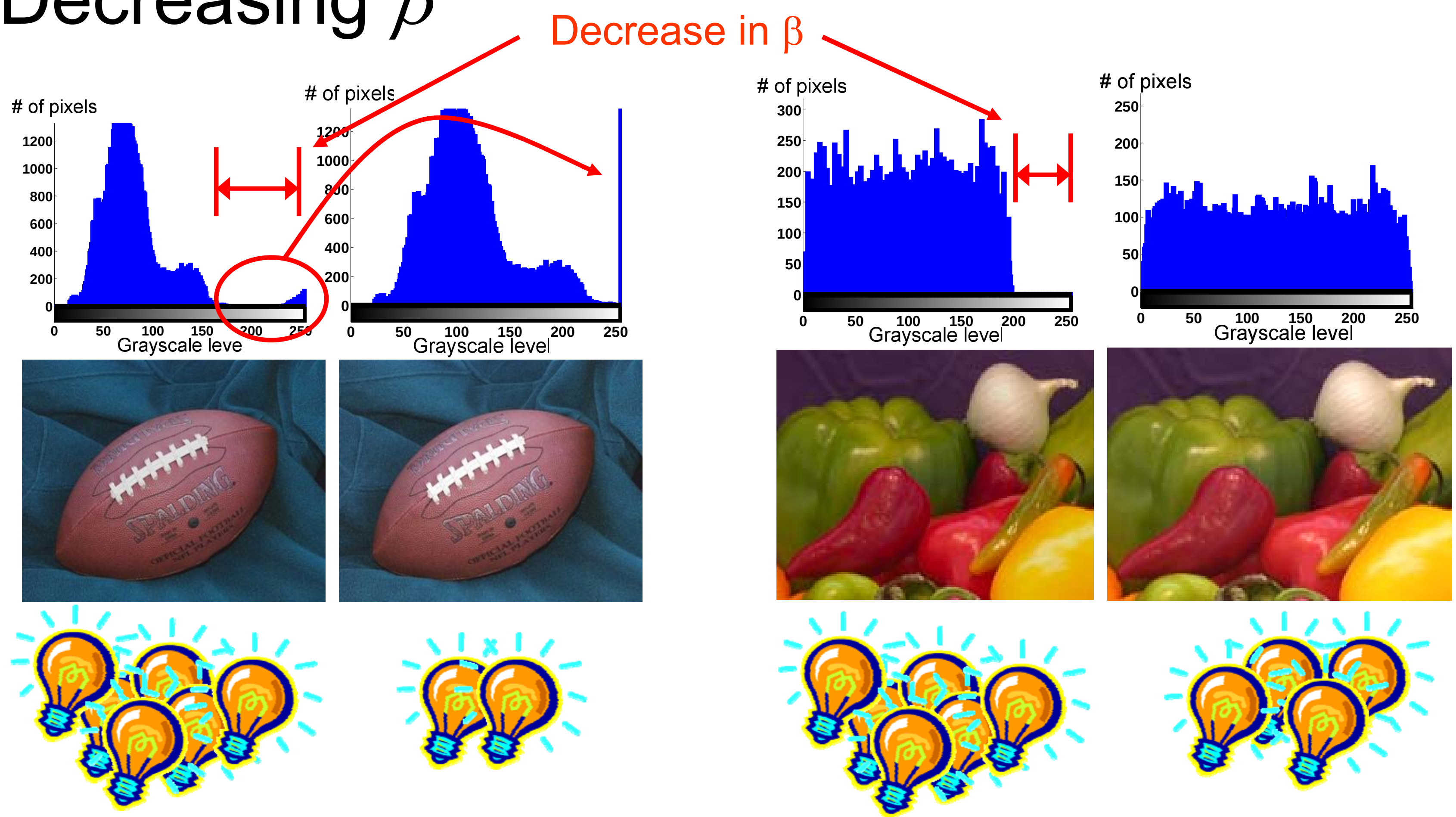
- Let χ and $\chi' = \Phi(\chi, \beta)$ denote the original and the transformed image data, respectively.
- Moreover, let $D(\chi, \chi')$ and $P(\chi', \beta)$ denote the distortion of the images χ and χ' and the power consumption of the LCD-subsystem while displaying image χ' with backlight scaling factor, β.
- **Dynamic Backlight Scaling (DBS) Problem**: Given the original image χ and the maximum tolerable image distortion D_{max}, find the backlight scaling factor β and the corresponding pixel transformation function $\chi'=\Phi(\chi,\beta)$ such that $P(\chi', \beta)$ is minimized and $D(\chi, \chi') \leq D_{max}$.

Observations about DBS

- DBS is hard to solve because
  - Image distortion function, D, is complex
  - Optimization involves a nonlinear minimization, which cannot be done in real time with low computational overhead and low energy cost

- Observations and problem simplifications
  - Power consumption $P(\chi, \beta)$ is strong function of β, but only a weak function of χ
    - Reducing β ➔ Decreasing $P(\chi, \beta)$
    - The optimizer should minimize β as much as possible
  - Can approximate function D by using pre-characterized models to simplify the optimization process
  - Must constrain the pixel transformation function $\Phi(\chi, \beta)$ to a family of piecewise linear functions
    - Such piecewise linear functions are desirable from implementation point of view with available hardware

Decreasing β



- Smaller dynamic range of the image results in larger decrease in β, and therefore, larger energy saving for a given bound on the distortion level

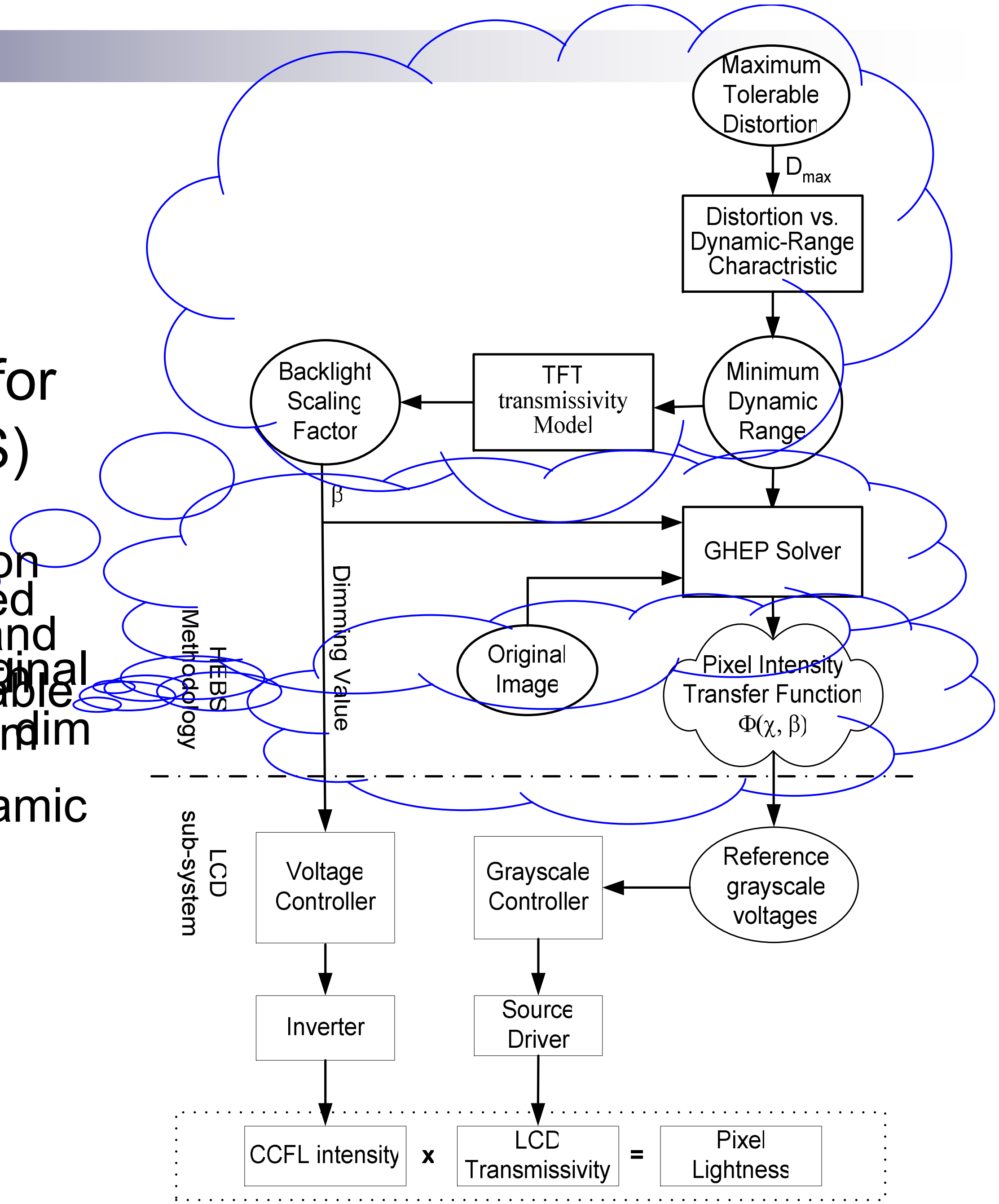
Key Assumptions

- The optimal solution to the DBS problem $\Phi^*(\chi, \beta)$ should generate a transformed image χ' with minimal dynamic range to achieve the maximum energy saving
- χ' should have a uniform histogram
- Image distortion should be less than the user specified limit D_{max}, *i.e.*, $D(\chi, \chi') \leq D_{max}$

DBS solution

- Histogram Equalization for Backlight Scaling (HEBS)

1. Given an original image, χ, and an upper bound on the tolerable image distortion D_{max}, we determine the minimum dynamic range, R, of pixel values in a transformed image.
2. We determine a transformation function, Φ, which takes the original image histogram with dynamic range R to a uniform distribution histogram with a range of R.
3. We construct the transformed image by applying Φ to the original image χ. At the same time, we dim the backlight by factor β.



Global Histogram Equalization

- **Global Histogram Equalization Problem (GHEP):** Given the original image cumulative histogram H, find a monotonic transformation $\Phi : G \to G$ where *G*=[0,1]

such that

$$\int_G \left| U(\Phi(x)) - H(x) \right| \cdot dx$$

is minimized.

Note that *U* is the uniform cumulative histogram.

Solution to GHEP

- Assuming U is defined between lower and upper limits g_{min}, and g_{max}, we have

$$\Phi(x) = U^{-1}(H(x)) = g_{min} + (g_{max} - g_{min}) \cdot \frac{H(x)}{N}$$

Simplifying in terms of the image histogram, we obtain

$$\Phi(x_i) = g_{min} + (g_{max} - g_{min}) \cdot \sum_{k=0}^{i-1} \Delta x_k \cdot \frac{h(x_k)}{N}$$

$$\Delta x_k \equiv x_{k+1} - x_k$$

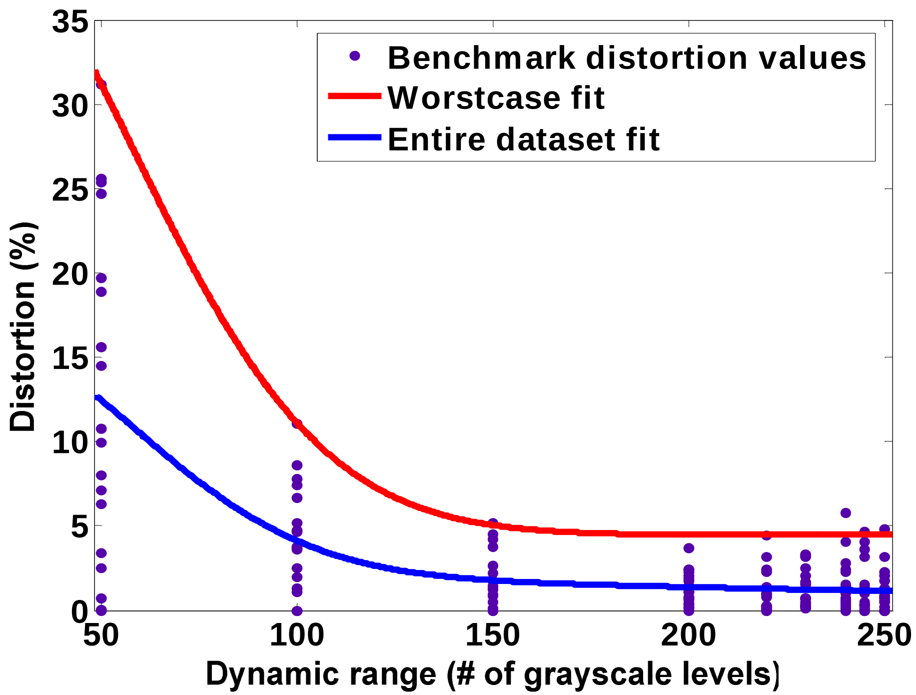
x_k : Histogram bucket value

$h(x_k)$: Histogram bucket count

N : Total number of pixels

Image Distortion Characterization

- *"Universal image quality index"* developed in NYU is used as our image distortion measure
- Benchmarks are from USC SIPI database

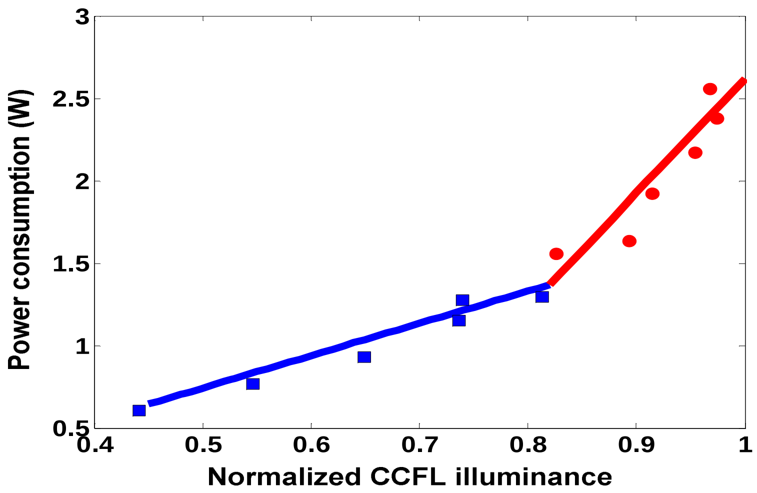


Energy Consumption Models

- CCFL power consumption for LG Philips TFT-LCD LP064V1,

$$P_{backlight}(\beta) = \begin{cases} A_{lin}.\beta + C_{lin} & 0 \le \beta \le C_s \\ A_{sat}.\beta + C_{sat} & C_s < \beta \le 1 \end{cases}$$

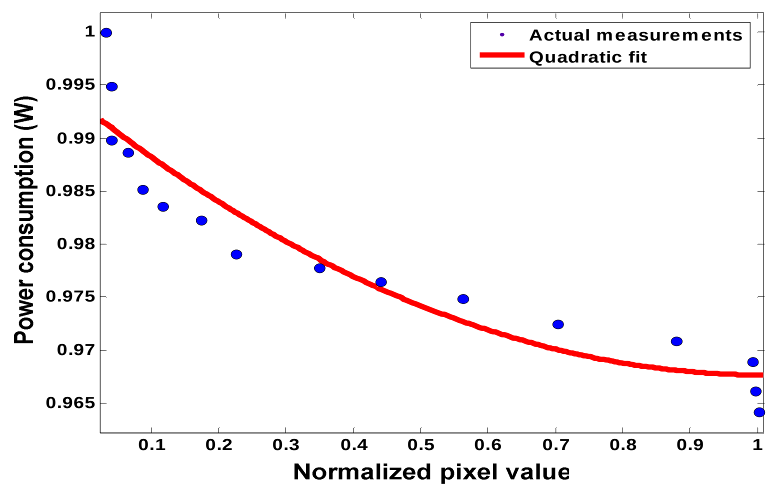
C_s=0.8234, A_{lin}=1.9600, C_{lin}=-0.2372, A_{sat}=6.9440, and C_{sat}= –4.3240



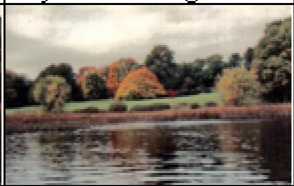
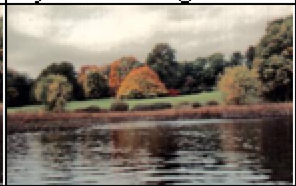
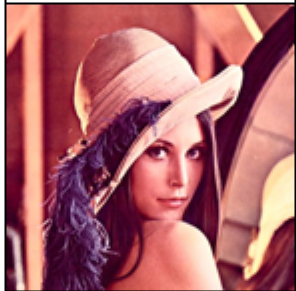
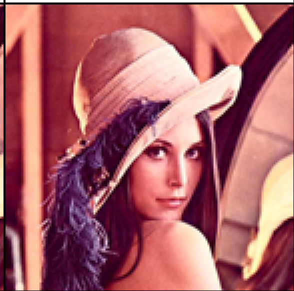
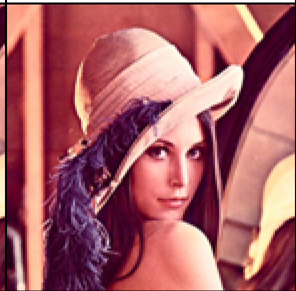
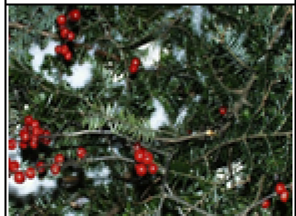
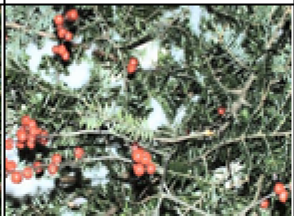
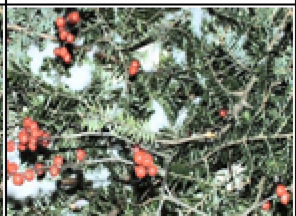
- TFT-LCD power consumption vs. transmittance *x*,

$$P_{TFT\ Panel}(x) = a.x^2 + b.x + c$$

a=0.02449, *b*= –0.04984, *c*=0.993



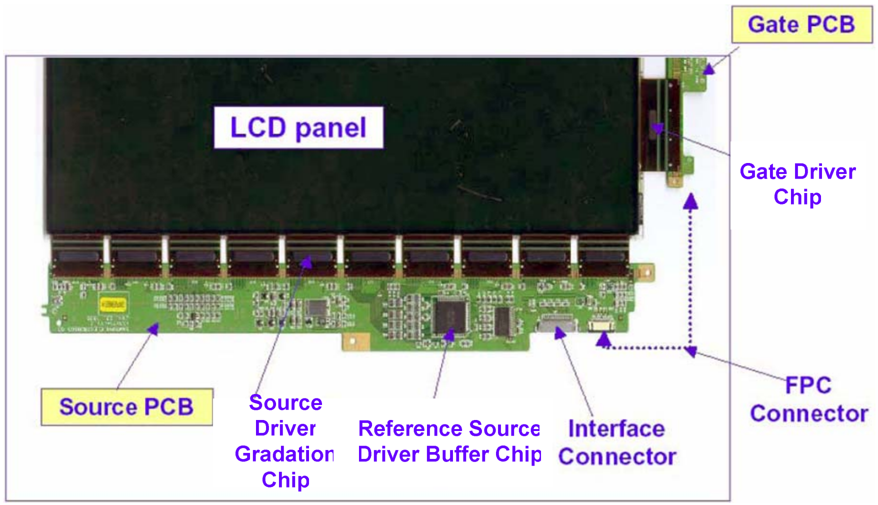
Experimental results

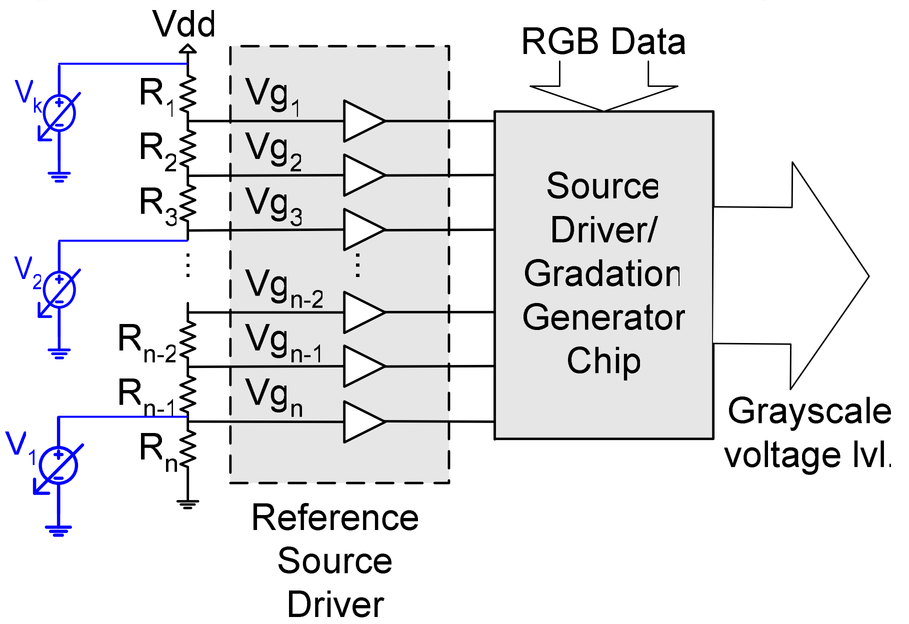
Original	Dynamic range=220	Dynamic range = 100	Original	Dynamic range=220	Dynamic range = 100
					
Normalized power =1	Distortion=3.1% Power saving =26.19%	Distortion=8.2% Power saving =55.24%	Normalized power =1	Distortion=1.2% Power saving =29.38%	Distortion=6.3% Power saving =50.35%
					
Normalized power =1	Distortion=1.1% Power saving =27.16%	Distortion=7.4% Power saving =54.28%	Normalized power =1	Distortion=0.9% Power saving =26.21%	Distortion=5.1% Power saving =42.57%
					
Normalized power =1	Distortion=2.1% Power saving =30.30%	Distortion=5.5% Power saving =46.32%	Normalized power =1	Distortion=2.1% Power saving =25.15%	Distortion=10.2% Power saving =61.18%

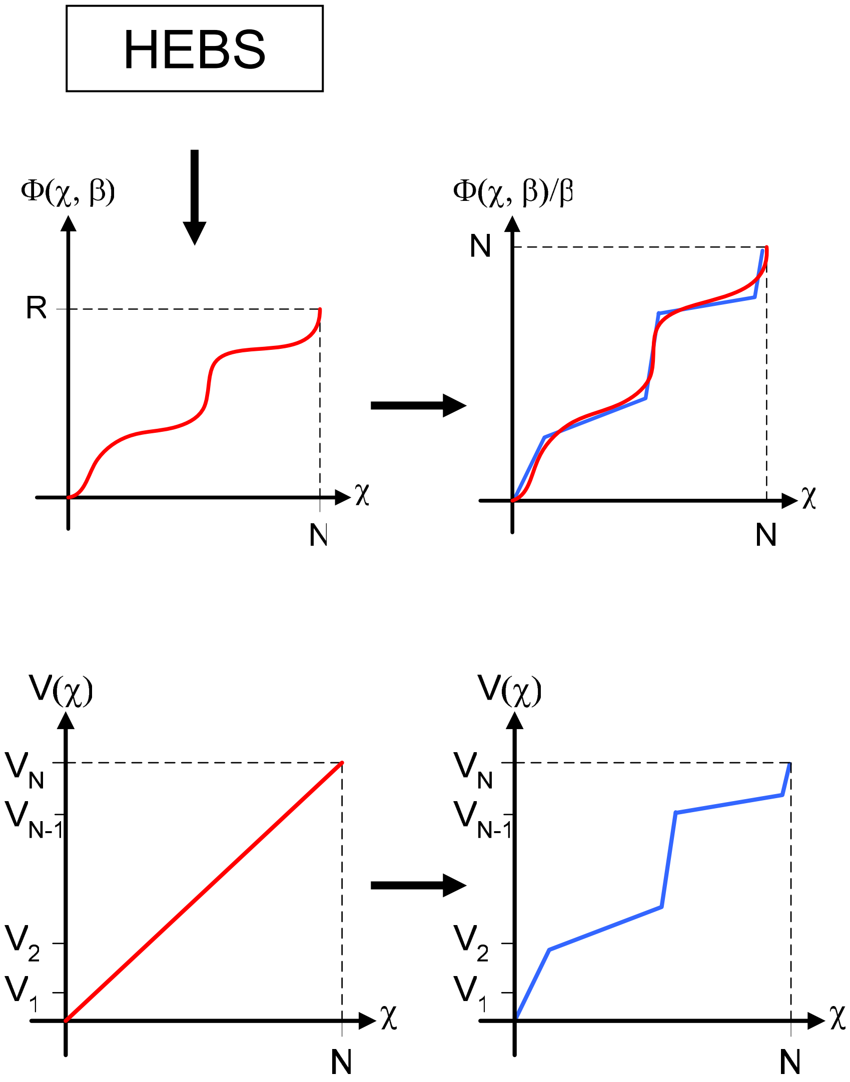
Experimental results (Cont.d)

	Power saving (%)		
Name	**Distortion = 5%**	**Distortion = 10%**	**Distortion = 20%**
Lena	47.53	58.18	69.52
Autumn	45.56	59.20	71.53
Football	46.62	55.25	65.57
Pepper	44.60	54.24	66.55
Green	45.63	55.26	63.58
Pears	47.51	57.16	64.49
Onion	44.56	58.21	70.53
Trees	46.69	54.31	64.62
West	48.52	61.18	67.50
Pout	42.57	53.22	59.54
Sail	42.53	49.18	56.51
Average	**45.88**	**56.16**	**64.38**

HEBS Implementation







HEBS – Pros and Cons

- Pros
  - Uses a more accurate image distortion measure
  - Easily implementable with minor changes to Reference Source Drivers
  - Achieves nearly 55% energy saving in display subsystem with merely 10% distortion in image quality

- Cons
  - Uses image histogram to calculate the image transformation function
  - Attempts to preserve actual luminance values instead of preserving the perceived brightness values

Conclusions and Future Directions

- Backlight scaling is an effective approach to energy saving in display subsystems
- Simulation results show up to 70% energy saving, approx. 25% system wide energy saving
- Relaxing the assumptions of DBS problem
  - Better solutions
- Apply and study the tradeoffs of Adaptive Tone Mapping Techniques
- Application of HEBS to video streams
- Survey and study of other display devices and technologies

Backup Slides

Why not use Dynamic Power Management?

- Display subsystem must be continuously refreshed, because
  - It is required to maintain a minimum frame rate
  - A pixel DC voltage should be avoided for stability and electrochemical reasons
- Display subsystem cannot be turned off or put to sleep without a significant penalty in Quality of Service (QoS)

Backlight Scaling (cont'd)

- Mathematically, Lets denote measured luminance of an image with pixel values *X* by I(*X*).
  I(*X*) basically means how "bright" the image appears to human eye

- In backlit LCD displays we have,

$$I(X)=b.\ t(X)$$

Where $t(X)$ is the transmissivity for pixel value
$b \in [0,1]$ is the normalized backlight illumination

- In backlight scaled LCD, *b* is scaled down and accordingly $t(X)$ is increased to achieve the same image luminance

How much power ?

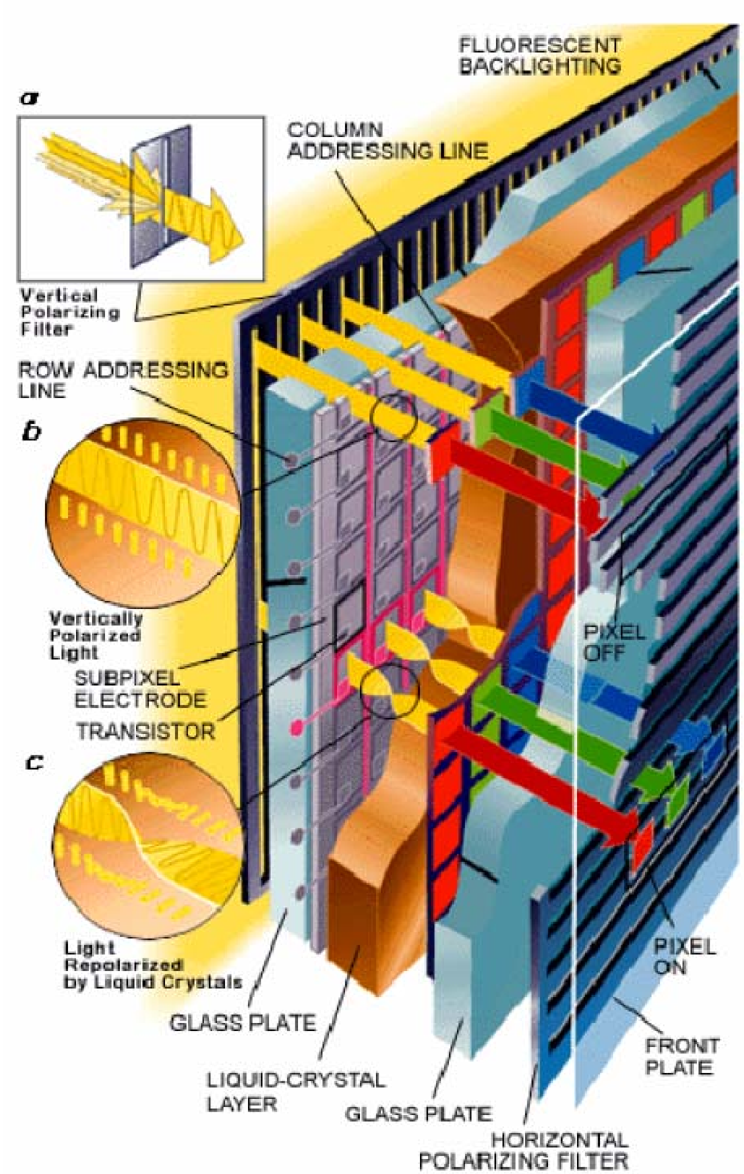
- Back of envelope estimates,
  - Signal Swing, 780mv
  - Cable Capacitance, 60pF/m ➔
  - Frequency, 250MHz
  - Cable Length, 5cm - 4.6m

$$P = CV^2 f = 400\mu W - 400mW$$

Total LCD Power, 32mW – 1.10 W

1.5% -- 36%

LCD structure



LC cell Inversion modes

	1	2	3	4	5
1	+	+	+	+	+
2	–	–	–	–	–
3	+	+	+	+	+
4	–	–	–	–	–
5	+	+	+	+	+

	1	2	3	4	5
1	+	–	+	–	+
2	+	–	+	–	+
3	+	–	+	–	+
4	+	–	+	–	+
5	+	–	+	–	+

	1	2	3	4	5
1	+	–	+	–	+
2	–	+	–	+	–
3	+	–	+	–	+
4	–	+	–	+	–
5	+	–	+	–	+

	1	2	3	4	5
1	–	–	–	–	–
2	+	+	+	+	+
3	–	–	–	–	–
4	+	+	+	+	+
5	–	–	–	–	–

	1	2	3	4	5
1	–	+	–	+	–
2	–	+	–	+	–
3	–	+	–	+	–
4	–	+	–	+	–
5	–	+	–	+	–

	1	2	3	4	5
1	–	+	–	+	–
2	+	–	+	–	+
3	–	+	–	+	–
4	+	–	+	–	+
5	–	+	–	+	–

Source Driver Architecture