Computer Graphics

- HDR & Tone Mapping -

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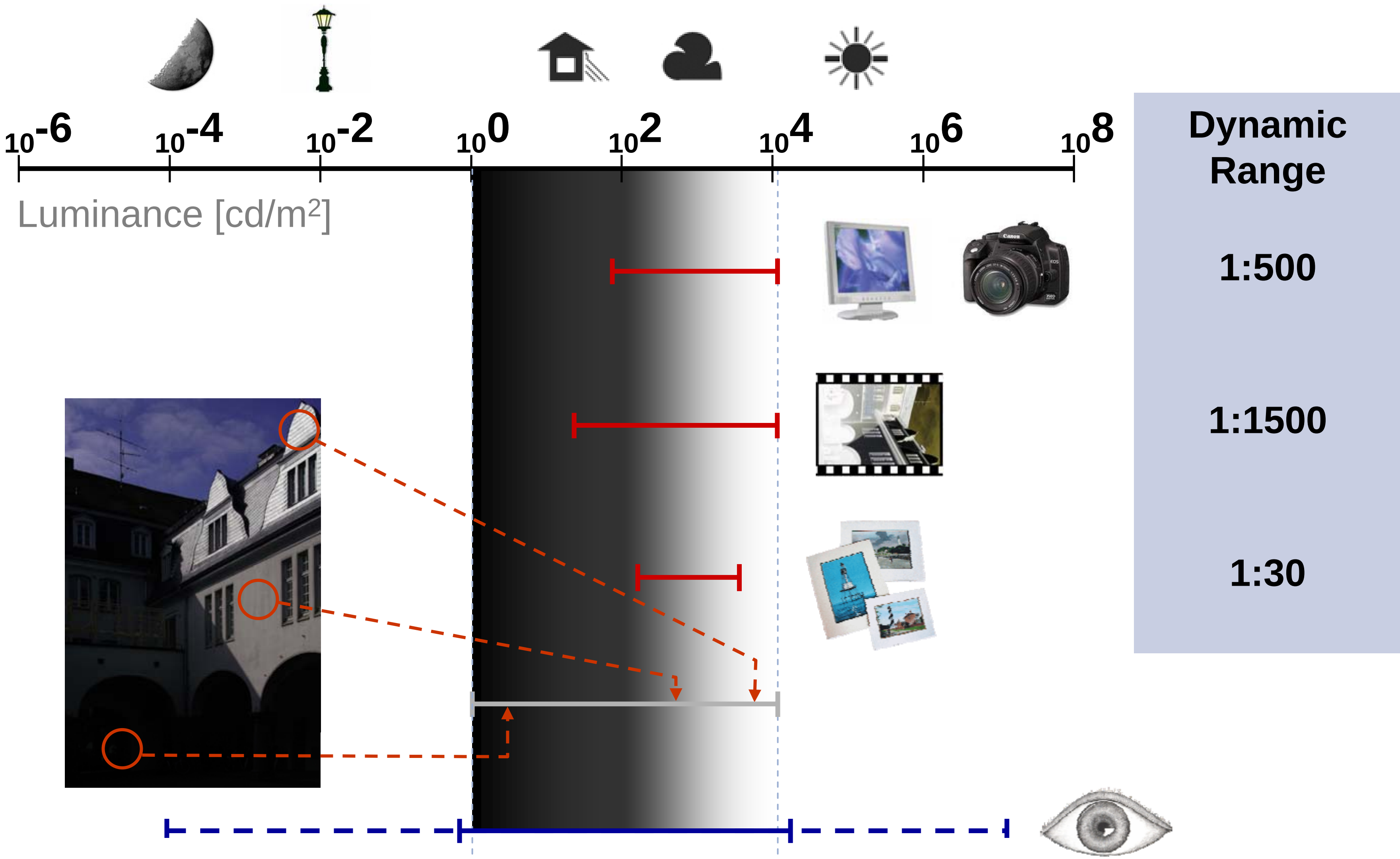
Overview

- **Last time**
  - Gamma Correction
  - Color spaces

- **Today**
  - Terms and Definitions
  - Tone Mapping

- **Next lecture**
  - Transformations

Dynamic Range



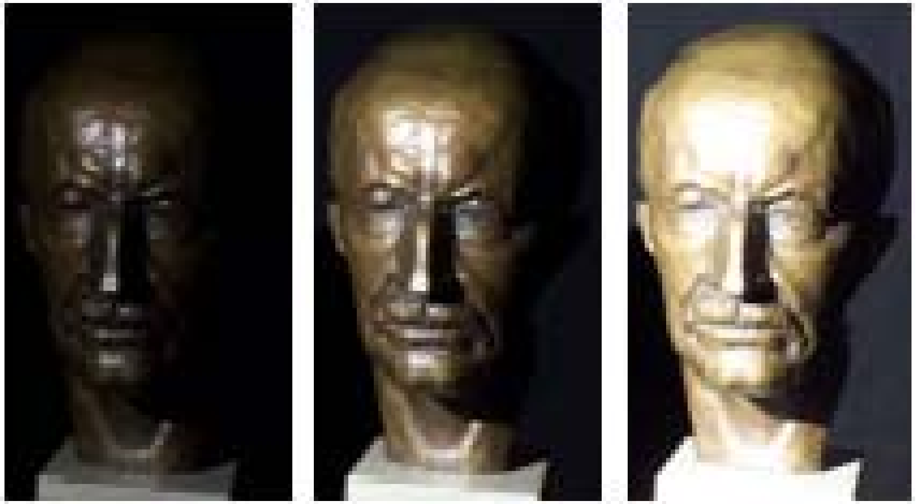
Acquisition and Display of HDR

- **Luminance in real-world scenes -> HDR**
- **Can be easily simulated**

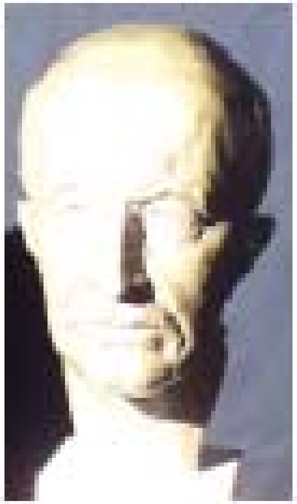
- **Acquisition with LDR cameras**
- **Display on LDR monitors**
- **HDR displays**

Exposure Bracketing

Exposure Bracketing



Exposure Bracketing

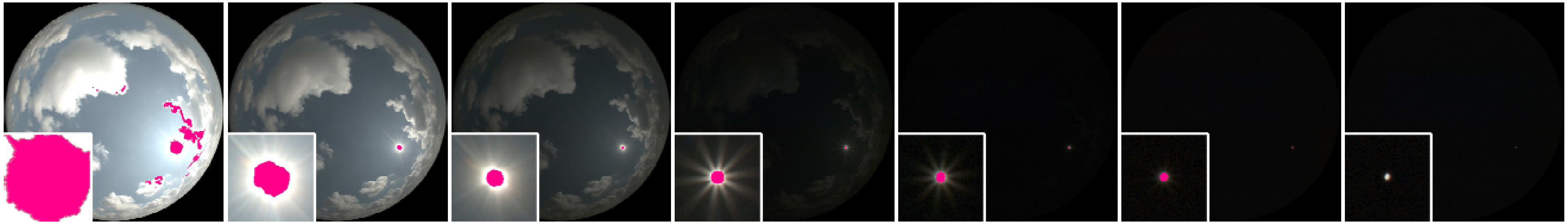


- capture additional over and underexposed images
- how much variation?
- how to combine?

Dynamic Range in Real World Images

- natural scenes: 18 stops (2^18)
- human: 17stops
  (after adaptation 30stops ~ 1:1,000,000,000)
- camera: 10-16stops

[Stumpfel et al. 00]



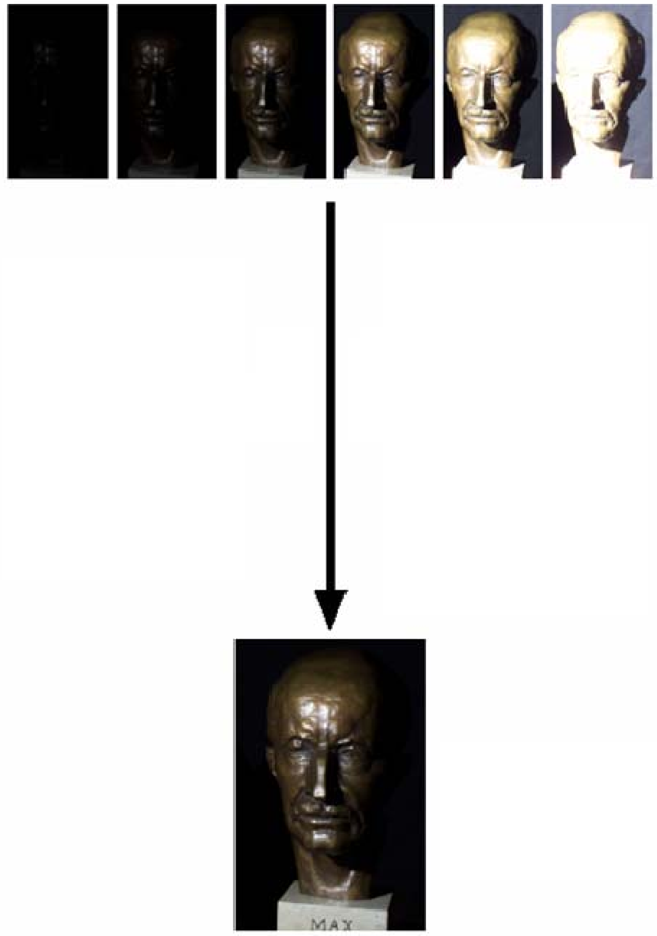
f/4, 1s　f/4, $\frac{1}{4}$s　f/4, $\frac{1}{32}$s　f/16, $\frac{1}{16}$s　f/16, $\frac{1}{125}$s　f/16, $\frac{1}{1000}$s　f/16, $\frac{1}{8000}$s

Dynamic Range of Cameras

- **example: photographic camera with standard CCD sensor**
  - dynamic range of sensor — 1:1000
  - exposure variation (handheld camera/non-static scene): 1/60th s – 1/6000th s exposure time — 1:100
  - varying aperture f/2.0 – f/22.0 — ~1:100
  - exposure bias/varying “sensitivity” — 1:10
  - total (sequential) — 1:100,000,000
- **simultaneous dynamic range still only 1:1000**
- **similar situation for analog cameras**

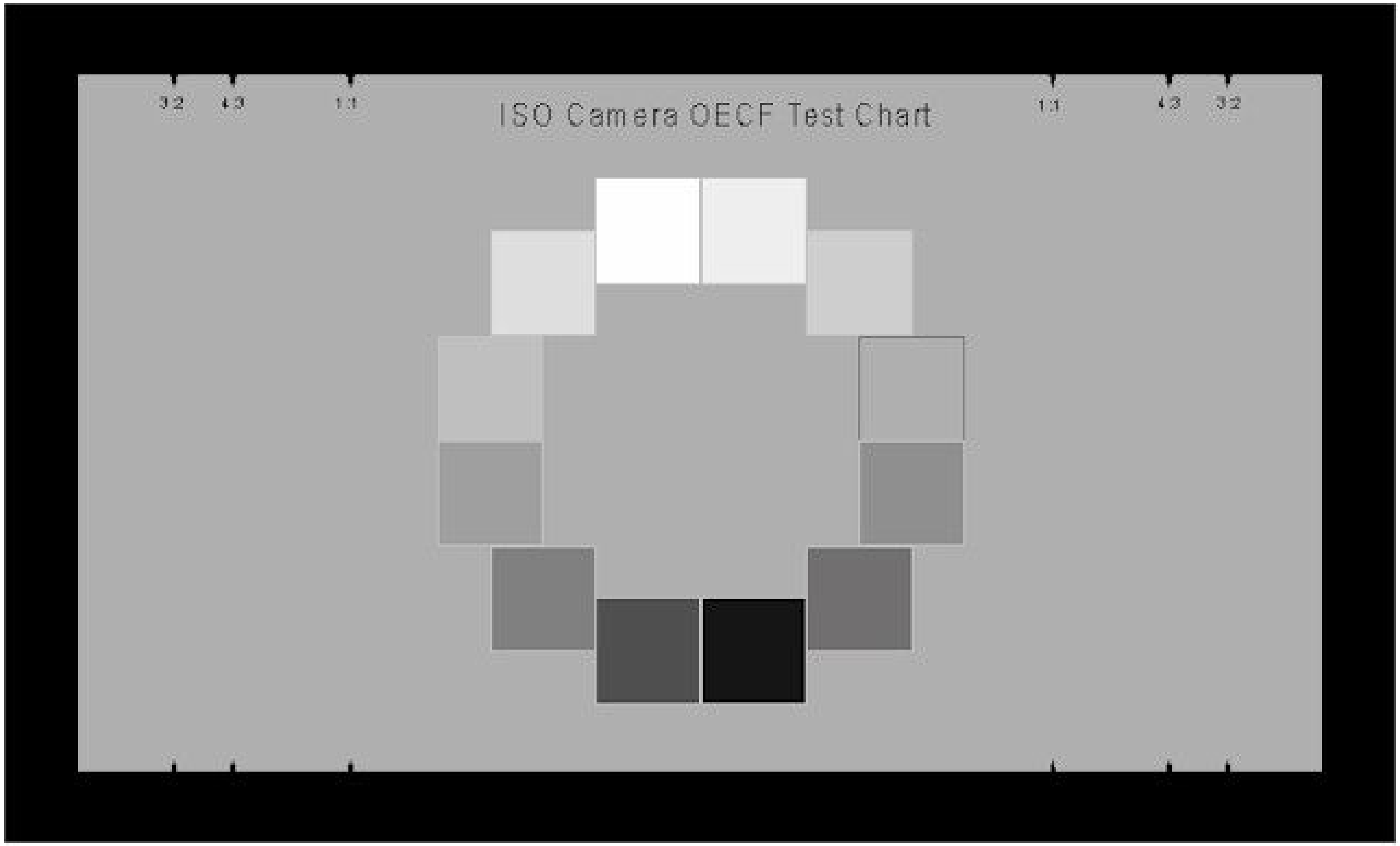
High Dynamic Range (HDR) Imaging

- **basic idea of multi-exposure techniques:**
  - combine multiple images with different exposure settings
  - makes use of available sequential dynamic range
- **other techniques available (e.g. HDR video)**



OECF Test Chart

- **absolute calibration**



High Dynamic Range Imaging

- limited dynamic range of cameras is a problem
  - shadows are underexposed
  - bright areas are overexposed
  - sampling density is not sufficient
- some modern CMOS imagers have a higher and often sufficient dynamic range than most CCD imagers

High Dynamic Range (HDR) Imaging

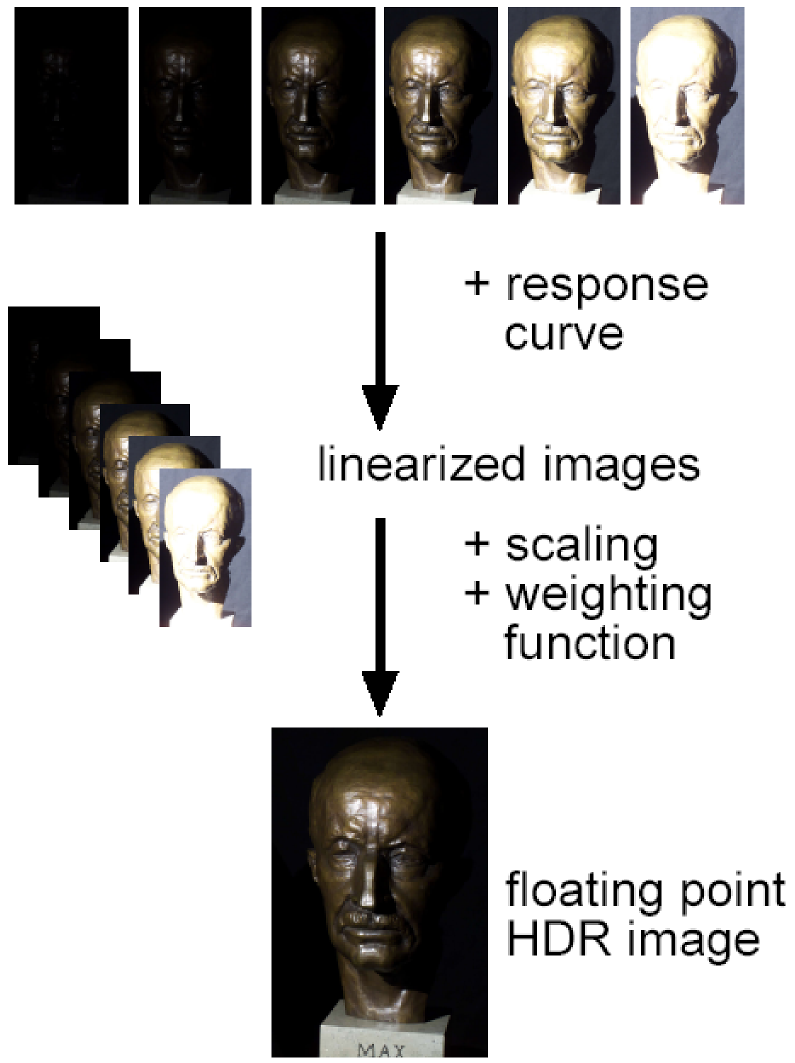
- analog film with several emulsions of different sensitivity levels by Wyckoff in the 1960s
  - dynamic range of about 10^8
- commonly used method for digital photography by Debevec and Malik (1997)
  - selects a small number of pixels from the images
  - performs an optimization of the response curve with a smoothness constraint
- newer method by Robertson et al. (1999)
  - optimization over all pixels in all images

High Dynamic Range Imaging

general idea of High Dynamic Range (HDR) imaging:

– combine multiple images with different exposure times
  - pick for each pixel a well exposed image
  - response curve needs to be known
  - don’t change aperture due to different depth-of-field

High Dynamic Range Imaging



HDR Imaging [Robertson et al.99]

Principle of this approach:

- calculate a HDR image using the response curve
- find a better response curve using the HDR image

(to be iterated until convergence)

HDR Imaging [Robertson et al.99]

input:

– series of **i** images with exposure times $\mathbf{t_i}$ and pixel values $\mathbf{y_{ij}}$

$$y_{ij} = f(t_i x_j)$$

task:

– find irradiance (luminance) $\mathbf{x_j}$

– recover response curve $I(y_{ij})$

$$f^{-1}(y_{ij}) = t_i x_j = I_{y_{ij}}$$

HDR Imaging [Robertson et al.99]

input:

- series of **i** images with exposure times $\mathbf{t_i}$ and pixel values $\mathbf{y_{ij}}$
- a weighting function $\mathbf{w_{ij} = w_{ij}(y_{ij})}$ (bell shaped curve)
- a camera response curve
  - initial assumption: linear response

$\Rightarrow$ calculate HDR values $\mathbf{x_j}$ from images using $I(y_{ij})$

$$x_j = \frac{\sum_i w_{ij} t_i I_{y_{ij}}}{\sum_i w_{ij} t_i^2}$$

HDR Imaging [Robertson et al.99]

optimizing the response curve $I(y_{ij})$ resp. $I(m)$:

– minimization of objective function **O**

$$O = \sum_{i,j} w_{ij} (I_{y_{ij}} - t_i x_j)^2$$

using Gauss-Seidel relaxation yields

$$I_m = \frac{1}{\mathrm{Card}(E_m)} \sum_{i,j \in E_m} t_i x_j$$

$$E_m = \{(i, j) : y_{ij} = m\}$$

– normalization of **I** so that $\mathbf{I_{128}}$=1.0

HDR Imaging [Robertson et al.99]

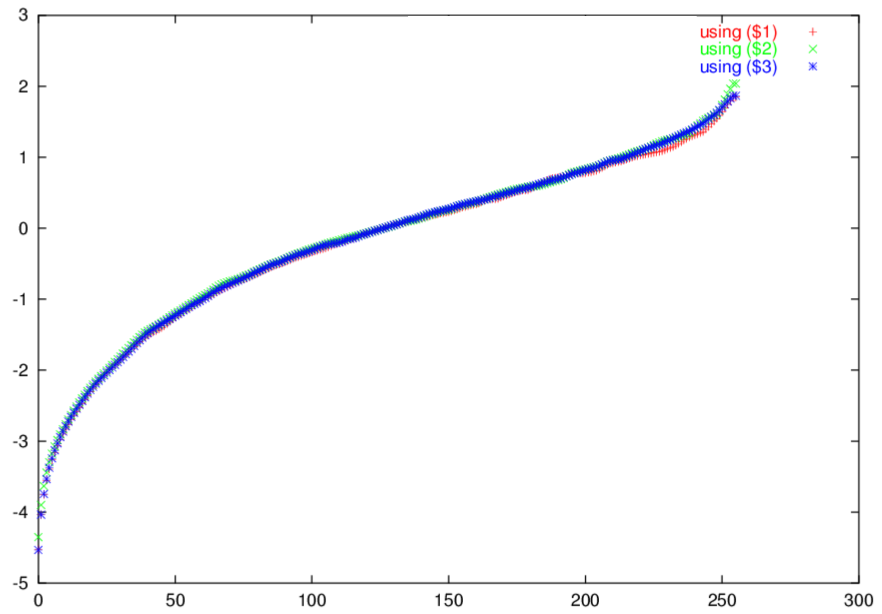
both steps

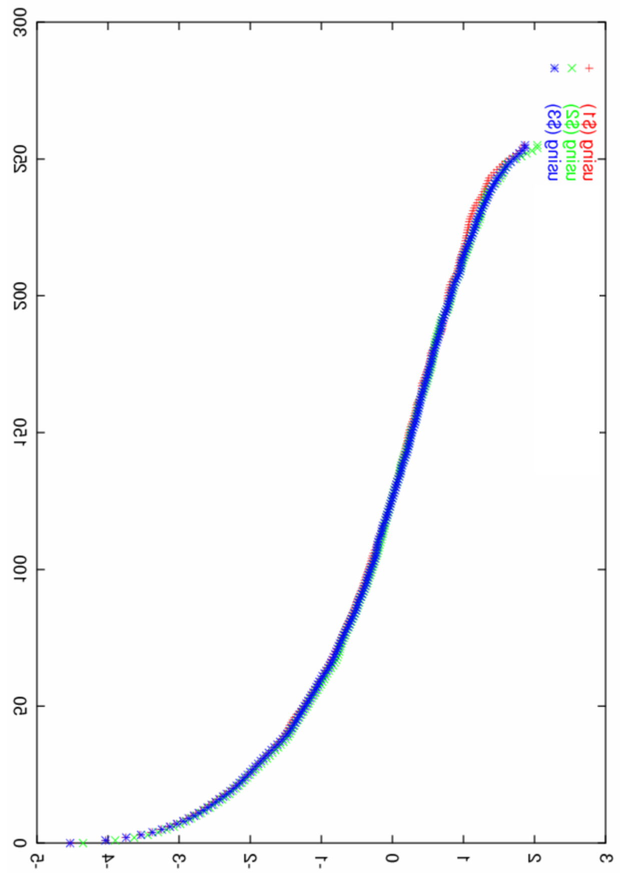
- calculation of a HDR image using **I**
- optimization of **I** using the HDR image

are now iterated until convergence

- criterion: decrease of **O** below some threshold
- usually about 5 iterations

HDR Imaging [Robertson et al.99]





$$\log(I(y_{ij}))$$

Capturing Environment Maps

1/2000s **1/500s** **1/125s** **1/30s** **1/8s**

series of input images

Capturing Environment Maps

Weighting Function

- **[Robertson et al.99]**

$$w_{ij} = \exp\left(-4 \frac{(y_{ij} - 127.5)^2}{127.5^2} \right)$$

- **choice of weighting function *$w(y_{ij})$* for response recovery**
  - for 8 bit images
  - possible correction at both ends (over/underexposure)
  - motivated by general noise model

Algorithm of Robertson et al.

- **discussion**
  - method very easy
  - doesn’t make assumptions about response curve shape
  - converges fast
  - takes all available input data into account
  - can be extended to >8 bit color depth
  - 16bit should be followed by smoothing

Input Images for Response Recovery

- **my favorite:**
  - grey card, out of focus, smooth illumination gradient
- **advantages**
  - uniform histogram of values
  - no color processing or sharpening interfering with the result

Input Images for HDR Generation

- **how many images are necessary to get good results?**
  - depends on scene dynamic range and on quality requirements
  - most often a difference of two stops (factor of 4) between exposures is sufficient
  - [Grossberg & Nayar 2003]

HDR-Video

– LDR [Bennett & McMillan 2005]
– HDR image formats [OpenExr, HDR JPEG]
– HDR MPEG Encoding [Mantiuk et al. 2004]
– HDR + motion compensation [Kang et al. 2003]

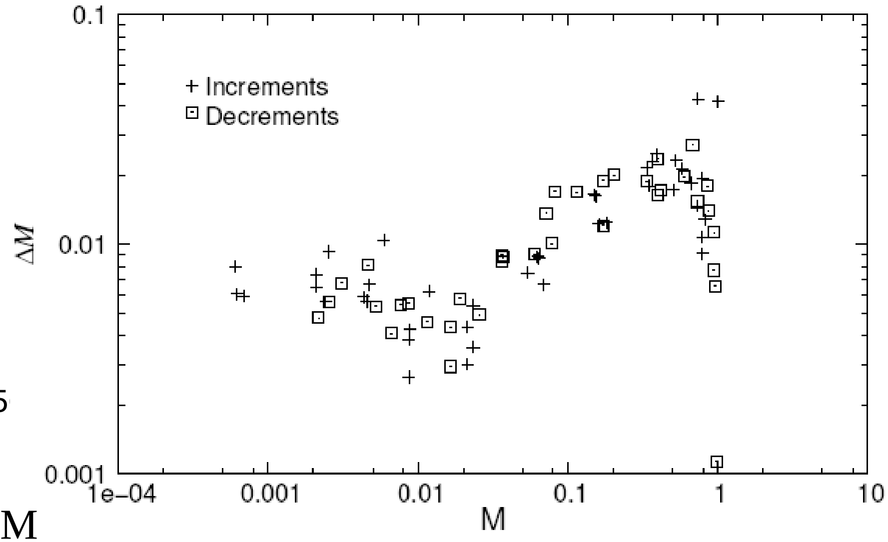
Tone-Mapping

Terms and Definitions

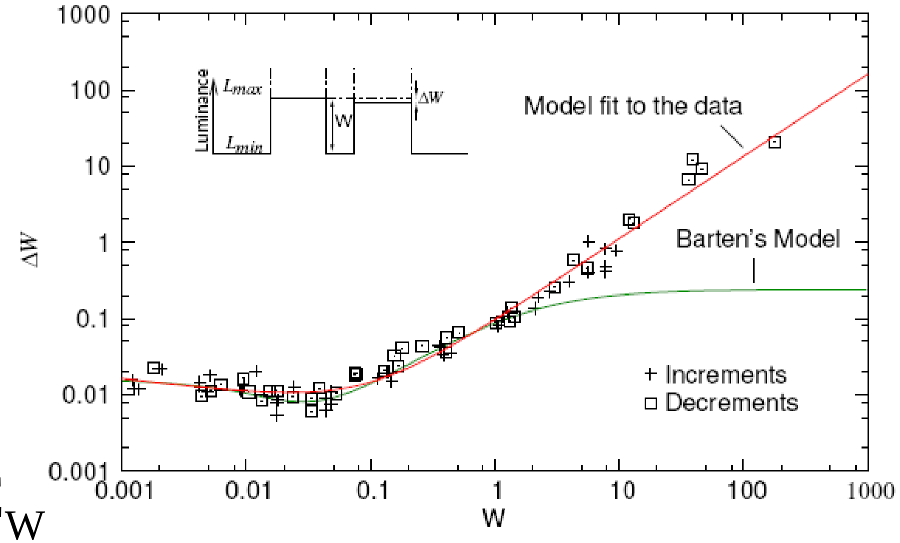
- **Dynamic Range**
  - Factor between the highest and the smallest representable value
  - Two strategies
    - Make white brighter
    - Make black darker
- **Contrast**
  - Simple contrast $$C_S = \frac{L_{max}}{L_{min}}$$
  - Weber fraction (step fct.) $$C_W = \frac{\Delta L}{L_{min}}$$
  - Michelson contrast (sinusoidal fct.) $$C_M = \frac{|L_{max} - L_{min}|}{L_{max} + L_{min}}$$
  - Logarithmic ratio $$C_L = \log_{10}\left(\frac{L_{max}}{L_{min}}\right)$$
  - Signal to noise ratio (SNR) $$C_{SNR} = 20 \cdot \log_{10}\left(\frac{L_{max}}{L_{min}}\right)$$
  - Best for HVS: C_W and C_L

Contrast Discrimination

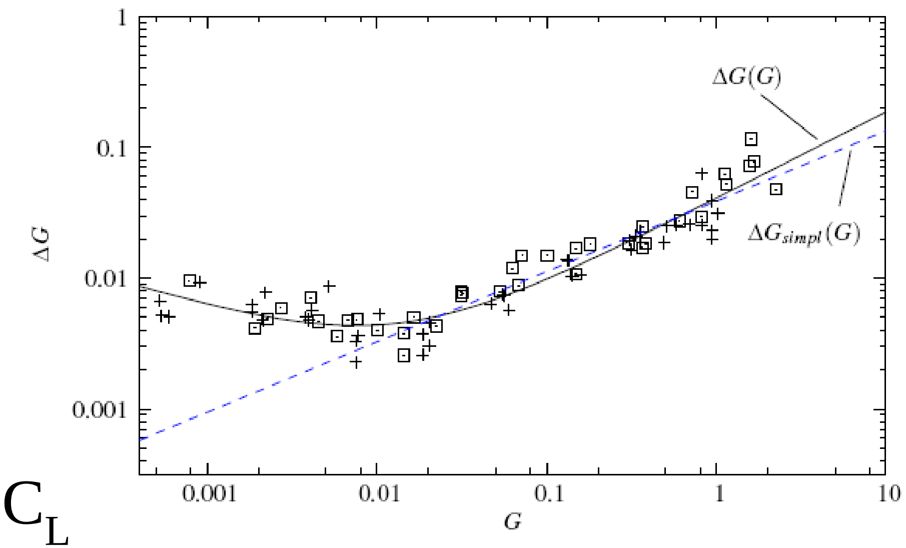
- **Experiments [Whittle 1986]**
  - Including high contrast
  - Michelson does not work too well
    - Particularly for high contrast
  - Good fits for C_W and C_L
  - Simplified linear model for CL
    - $\Delta C_{L,simpl}(C_L) = 0.038737 * C_L^{0.53775}$
  - [Mantiuk et al., 2006]



C_M



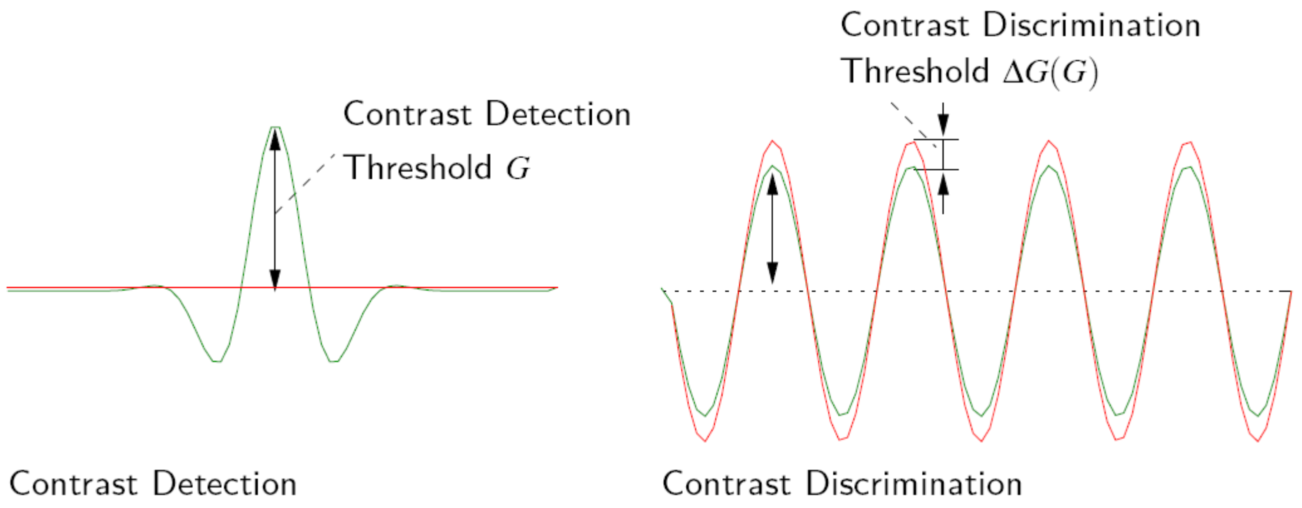
C_W



C_L

Contrast Measurement

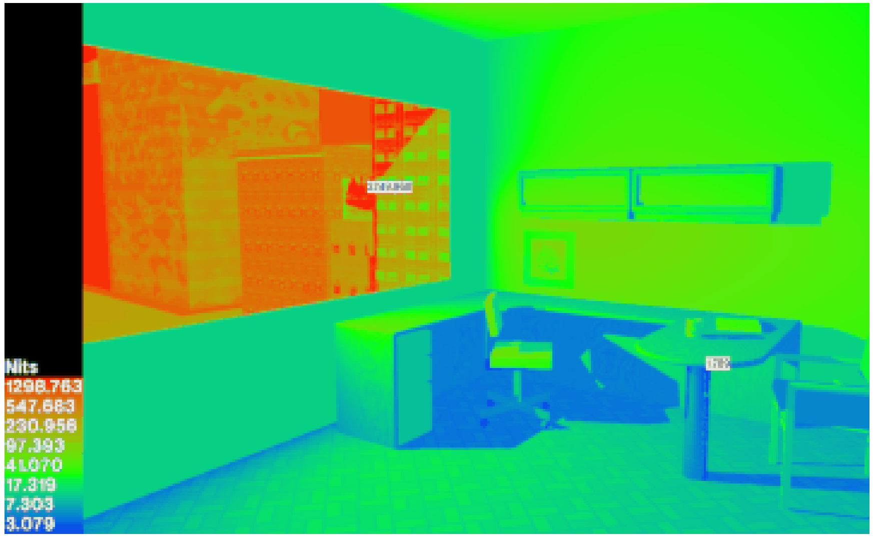
- **Contrast Detection Threshold**
  - Smallest detectable contrast in a uniform field of view
- **Contrast Discrimination Threshold**
  - Smallest visible difference between two similar signals
  - Works in the suprathreshold domain (signals above threshold)
    - Often sinusoidal or square wave pattern



Why Tone-Mapping?

- **Mapping radiance to pixel values?**
  - Luminance of typical desktop displays:
    - Up to a few 100 cd/m^2
  - Luminance range for human visual perception
    - Min 10^{-5} cd/m^2 Shadows under starlight
    - Max 10^5 cd/m^2 Snow in direct sun light
- **Goal**
  - Compress the dynamic range of an input image
  - Reproduce human perception to closely match that of the real scene
    - Brightness and contrast
    - Adaptation of the eye to environment
    - Other issues (glare, color perception, resolution)

Example

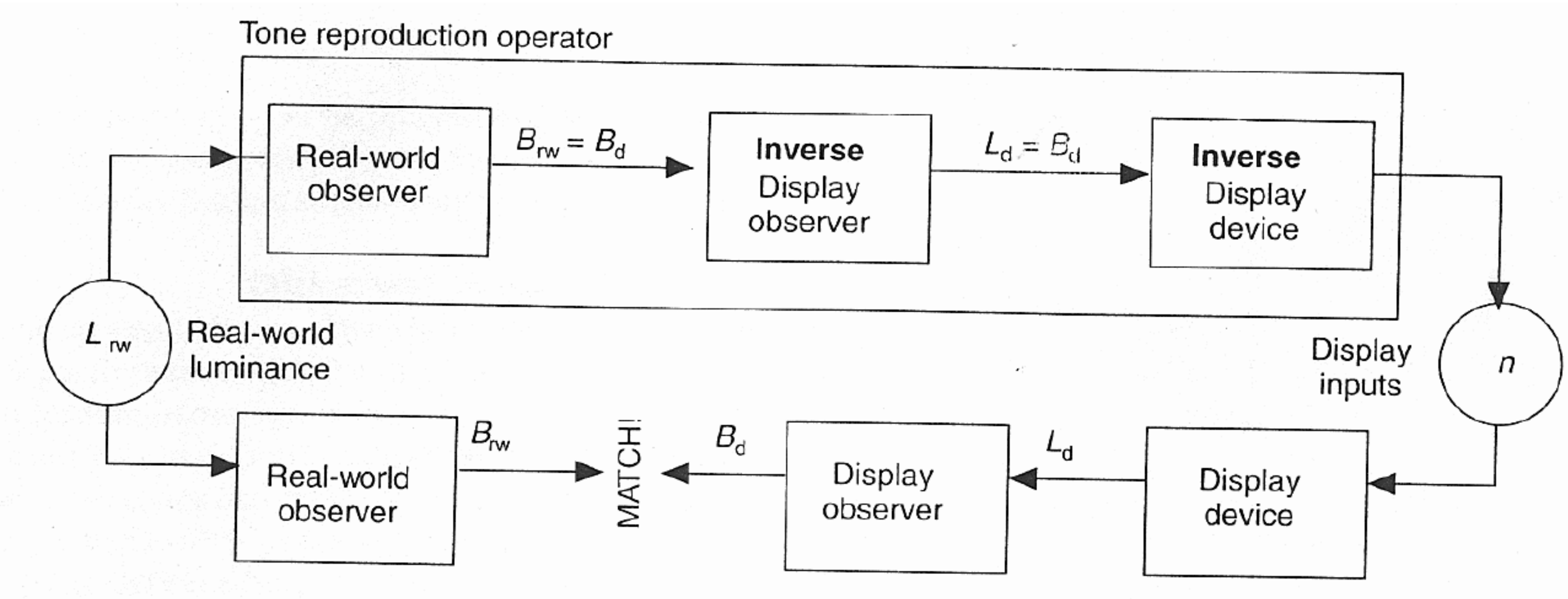


Heuristic Approaches

- **Scaling brightest value to 1 (in gray value)**
  - Problem: light sources are often several orders of magnitude brighter than the rest
    - ➔ Rest will be black
- **Scaling of brightest non-light-source value**
  - Scaling to a value slightly below 1
  - Capping light source values to 1
- **General problem of simple scaling**
  - Absolute brightness gets lost:
    - Dimming of light sources will have no effect
- **Much better: Logarithmic domain**
  - Linear scaling in the logarithmic domain
    - Much closer to human perception
  - Typically using $\log_{10}$

General Principle

- **Approach [Tumblin/Rushmeier]**
  - Create model of the observer
  - Requirement:
    - Observer should perceive same image from real and virtual display
  - Compute Tone-Mapping using concatenation and inversion of operators
  - Model usually operates only on luminance (no color)

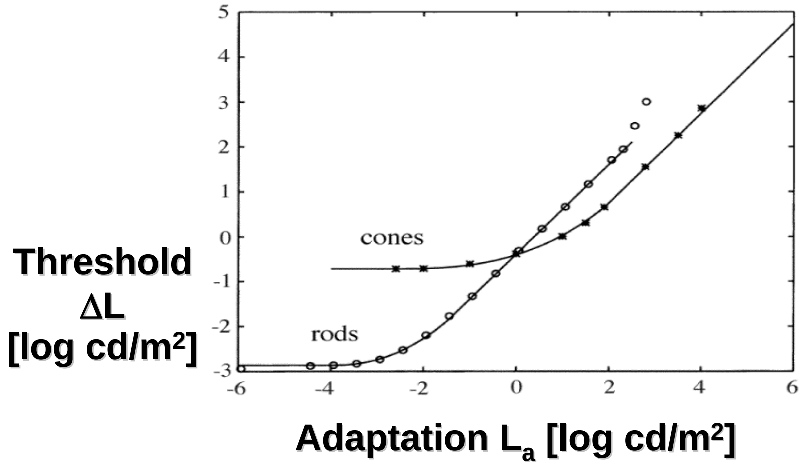


Maintaining Contrast

- **Contrast-based Scaling Factor [Ward `94]**
  - Maintain visible contrast differences in the image
    - Using Weber contrast
  - Just noticeable contrast according to Blackwell [CIE`81] (subjective measurements)

$$\Delta L(L_a) = 0.0594(1.219 + L_a^{0.4})^{2.5}$$

  - L_a: Adaptation level of eye (luminance)
  - Goal: linear scaling factor $m(L_a)$
    - $L_d = m(L_a)L_w$
    - L_d: display luminance
    - L_w: world luminance



Maintaining Contrast

- **Approach using „Just noticeable difference (JND)"**
  - Assume JND for real and virtual image are the same
    - JND of real world: $\Delta L(L_{wa})$
    - JND of display: $\Delta L(L_{da})$

$$\Delta L(L_{da}) = m(L_{wa})\,\Delta L(L_{wa})$$

  - Substitution results in

$$m(L_{wa}) = \left[\frac{1.219 + L_{da}^{0.4}}{1.219 + L_{wa}^{0.4}}\right]^{2.5}$$

  - With $L_{da}=L_{dmax}/2$ and scaling factor sf in [0..1]

$$sf = \frac{1}{L_{d\max}}\left[\frac{1.219 + (L_{d\max}/2)^{0.4}}{1.219 + L_{wa}^{0.4}}\right]^{2.5}$$

Maintaining Contrast

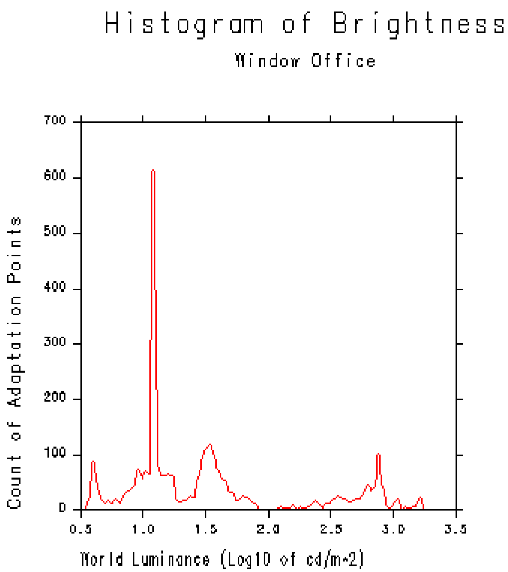
- **Deriving L_{wa}**
  - Depends on light distribution in field of view of observer
  - Simple approximation using a single value
    - Eyes try to adjust to average brightness
    - Brightness B:

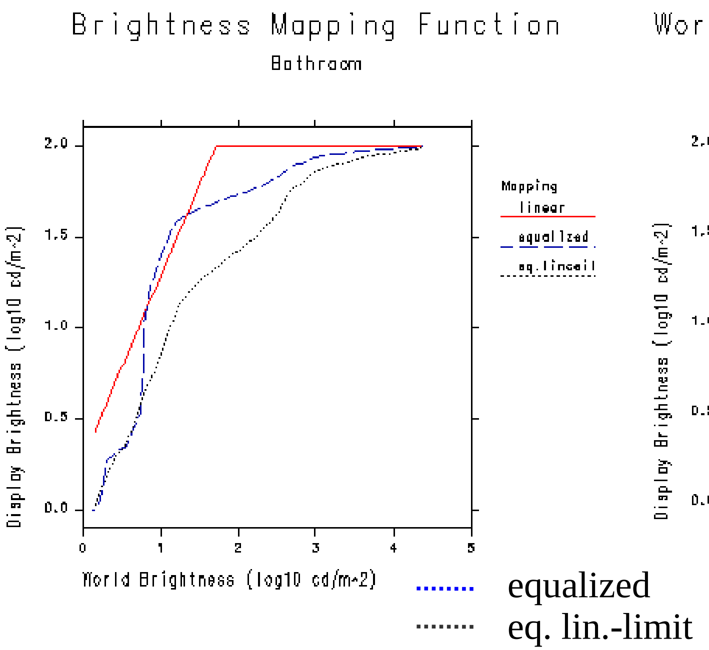
      $\log_{10}(B) = a(L_{in}) \log_{10}(L_{in}) + b(L_{in})$ Power-Law [Stevens`61]
    - Comfortable brightness

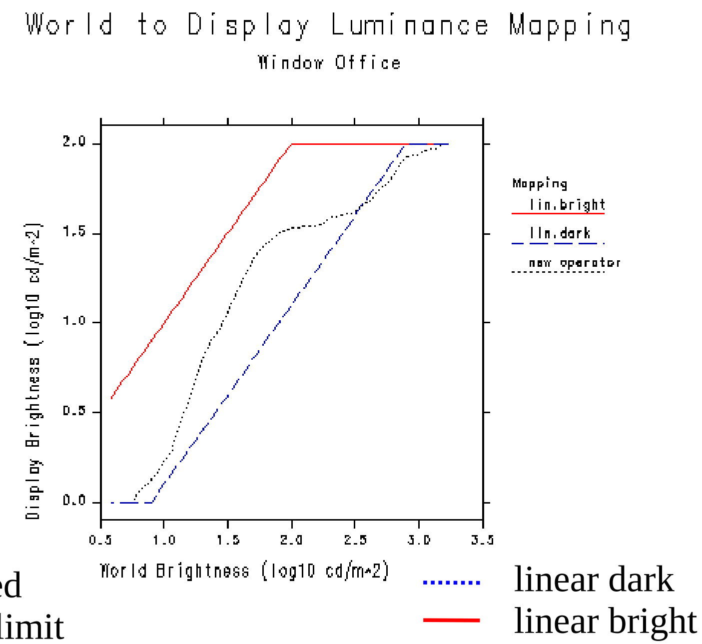
      $\log_{10}(L_{wa}) = E\{\log_{10}(L_{in})\} + 0.84$
- **Problems of this Approach**
  - Single factor for entire image
    - Different adaptation for different locations in image
    - We do not perceive absolute differences in luminance
  - Adaptation mainly acts on the 1 degree fov (fovea)
  - Results in clamping for too bright regions

Histogram-Adjustment

- **Optimal Mapping of the Dynamic Range [Ward`97]**
  - Computing an adjustment image
    - Averaging over 1 degree regions and reducing the resolution
  - Computing the histogram of the image
    - Binning of luminance values
  - Adjusting the histogram based on restrictions of human visual system
    - Limiting contrast enhancement







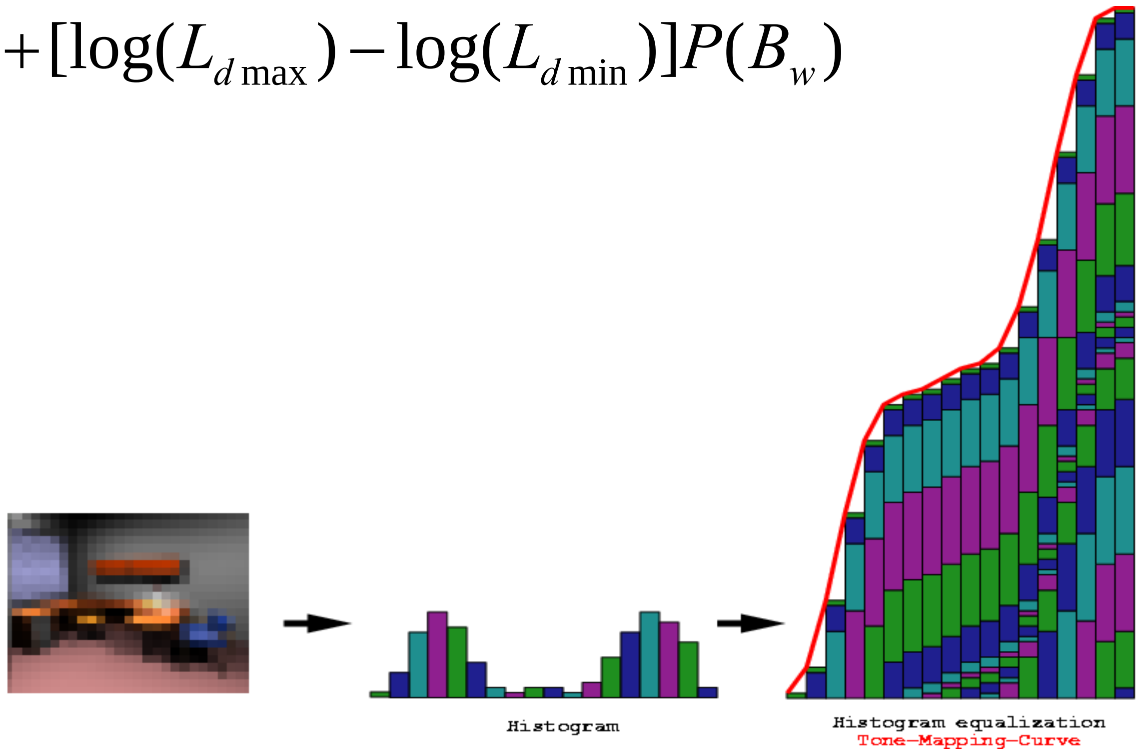
Histogram-Adjustment

- **Computing the Adjustment Image**
  - Assumes known view point
  - Average image
    - Filtering non-overlapping regions covering 1 degree fov
    - Reference uses simple box filter

Histogram-Adjustment

- **Naïve Histogram Adjustment (Equalization)**
  - $f(B_w)$: Number of sample per bin
  - $P(B_w)$: Accumulated probability (sum of sample counts)
  - T: Sum over all $f(B_w)$
  - Mapping

$$B_d = \log(L_{d\min}) + [\log(L_{d\max}) - \log(L_{d\min})]P(B_w)$$



Histogram-Adjustment

Linear Mapping

Naïve Histogram-Adjustment

Histogram-Adjustment considering the human visual system

Histogram-Adjustment

- **Problem**
  - Too strong emphasis on contrast in highly populated regions of the dynamic range
  - Idea:
    - Limiting the contrast enhancement (linear scaling works well for low contrast images)

$$\frac{dL_d}{L_d} \leq \frac{dL_w}{L_w} \Rightarrow \frac{dL_d}{dL_w} \leq \frac{L_d}{L_w}$$

    - Differentiate $\exp(B_d) = L_d$ with respect to L_w

$$B_d = \log(L_{d\min}) + [\log(L_{d\max}) - \log(L_{d\min})]P(B_w)$$

leads to

$$\frac{dL_d}{dL_w} = \exp(B_d) \frac{f(B_w)}{T\Delta b} \frac{\log(L_{d\max}) - \log(L_{d\min})}{L_w} \leq \frac{L_d}{L_w}$$

Histogram-Adjustment

- **Result**
  - Limiting the sample count per bin in histogram

$$f(B_w) \leq \frac{T\Delta b}{\log(L_{d\max}) - \log(L_{d\min})}$$

$$T = \sum f(b_i)$$

$$\Delta b = \frac{\log(L_{w\max}) - \log(L_{w\min})}{N}$$

  - Implementation
    - Truncating too large bins with redistribution
    - Ditto without redistribution (gives better results)

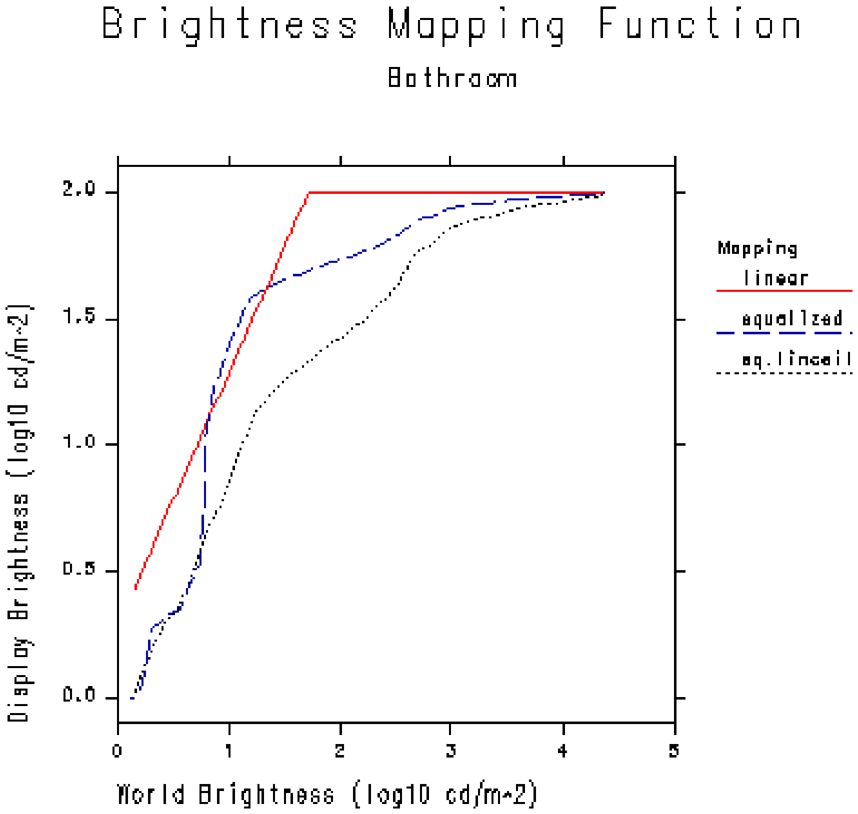
Histogram-Adjustment

- **Implementing the Limitation**

```
boolean function histogram_ceiling()
tolerance := 2.5% of histogram total
repeat {
      trimmings := 0
      compute the new histogram total T
      if T < tolerance then
            return FALSE
      foreach histogram bin i do
            compute the ceiling
            if f(bi) > ceiling then {
                  trimmings += f(bi) - ceiling
                  f(bi) := ceiling
            }
} until trimmings <= tolerance
return TRUE
```

  - Fails for cases where no compression is necessary
    - Can easily be detected
  - Use modified $f(B_w)$ in naïve histogram equalization

Histogram-Adjustment



Histogram-Adjustment

- **Adjustment for JND**
  - Limiting the contrast to the ratio of JNDs (global scale factor)

$$\frac{dL_d}{dL_w} \leq \frac{\Delta L_t(L_d)}{\Delta L_t(L_w)}$$

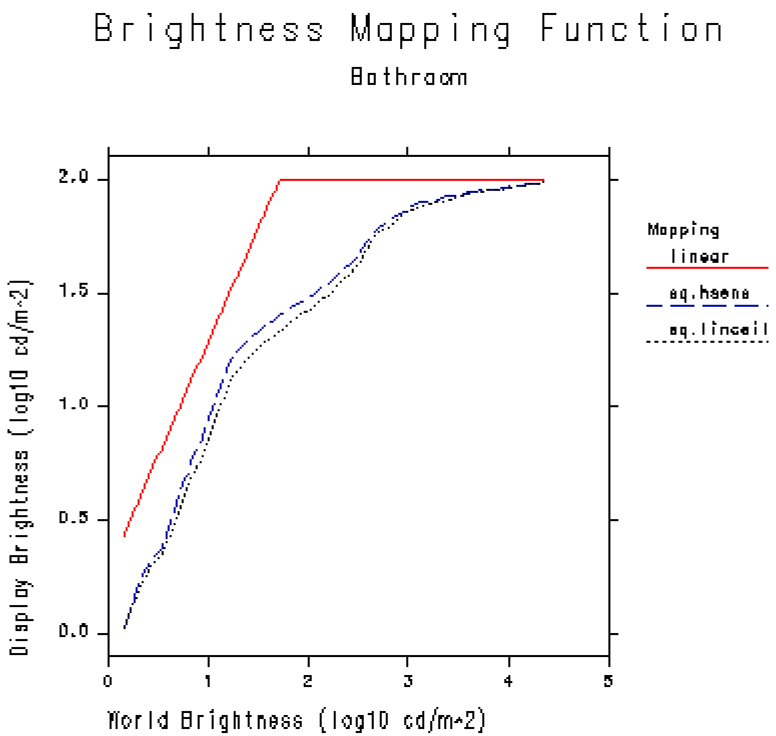
  - That results in

$$f(B_w) \leq \frac{\Delta L_t(L_d)}{\Delta L_t(L_w)} \frac{T \Delta b L_w}{[\log(L_{d\max}) - \log(L_{d\min})] L_d}$$

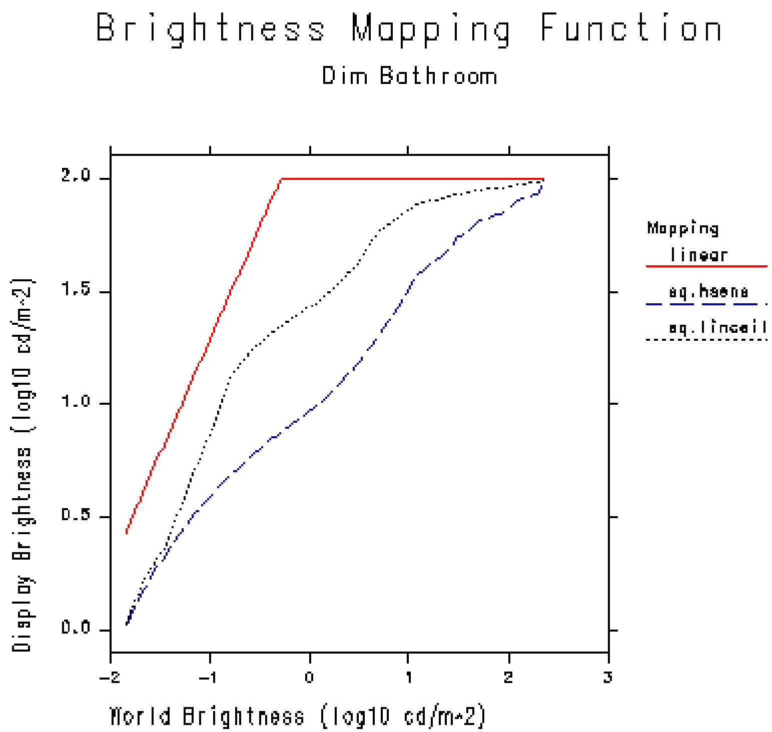
  - Implementation is the similar as for previous histogram limiting

Example: Darkening a Room

- **Reduction in Contrast Sensitivity in Dark Scenes**



Bright Bathroom



Dark Bathroom (1/100) with reduced contrast

Example: Darkening a Room

Bright Bathroom

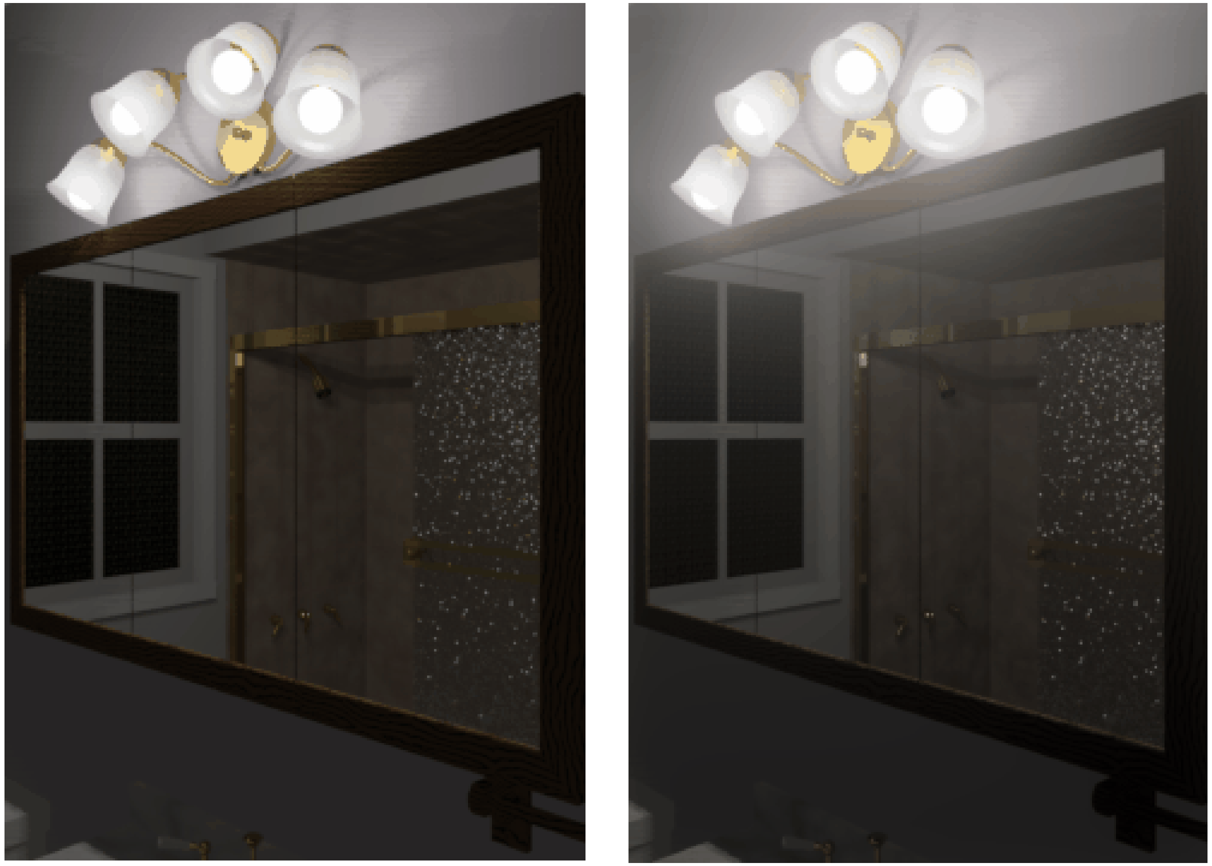
Dark Bathroom (1/100) with reduced contrast

Extensions: Glare

- **Considering Glare**
  - Bright light sources result in veiling (German: Schleier)
    - Due to scattering of strong illumination in the eye
  - Results in correction to adaptation level
- **Approach**
  - Moderate illumination in periphery does not contribute to adaptation
    - Depend exclusively on foveal region
  - But: glare in the periphery does change the adaptation
    - Scattered light is added even in foveal region
  - Compute a veiled image by filtering over peripheral region
    - Added to normal adaptation luminance L_f [Moon and Spencer,`45]

$$L_a = 0.913\, L_f + \frac{K}{\pi} \iint_{\theta > \theta_f} \frac{L(\theta,\phi)}{\theta^2} \cos(\theta) \sin(\theta)\, d\theta d\phi$$

Example: Veiling due to Glare



Extensions

- **Loss of color vision in dark areas**

- **Loss of visual resolution in dark areas**
  - Simple blur filter

Comparison

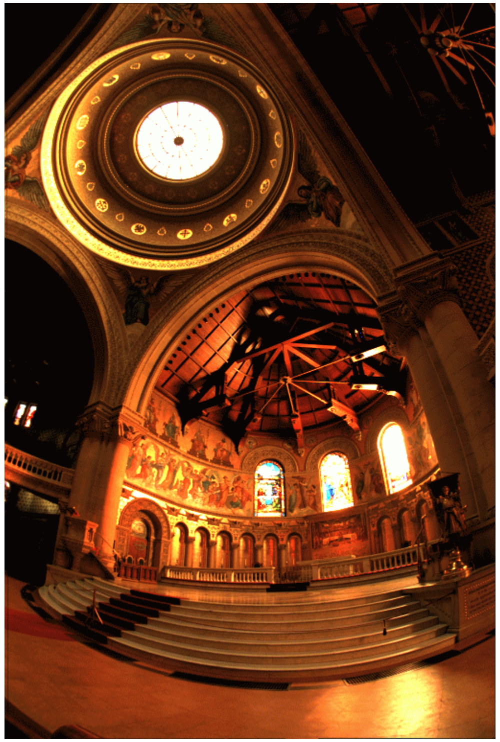
Maximum Tone-Mapping

Tumblin/Rushmeier Tone-Mapping

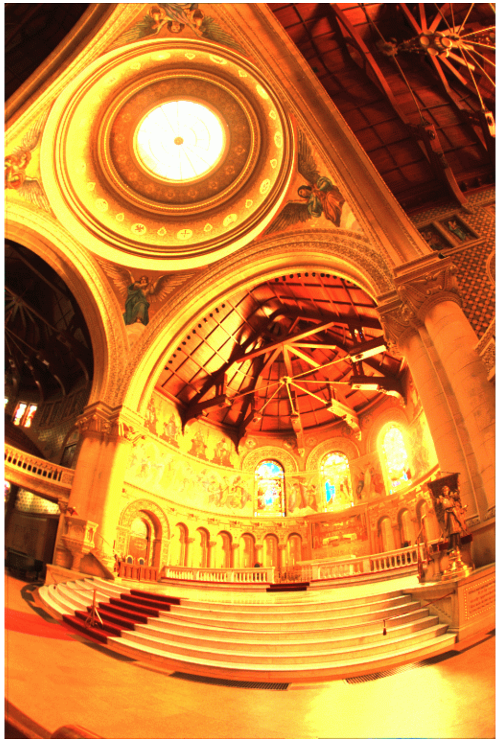
Ward`94 Tone-Mapping

Ward`97 Tone-Mapping

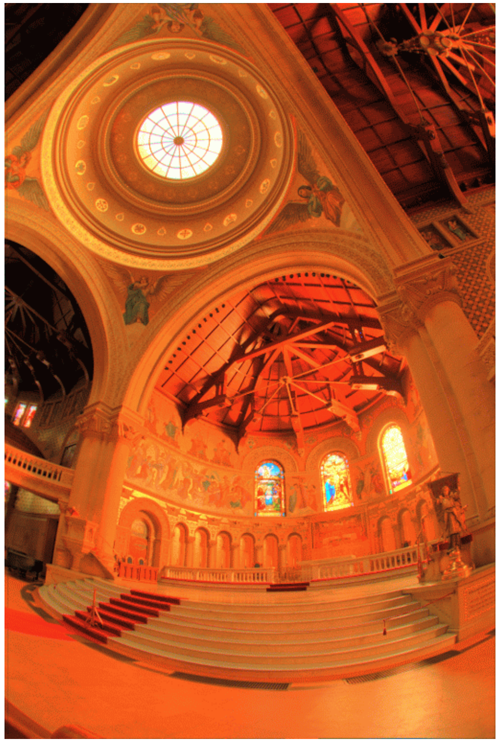
Comparison



Tumblin/Rushmeier Tone-Mapping



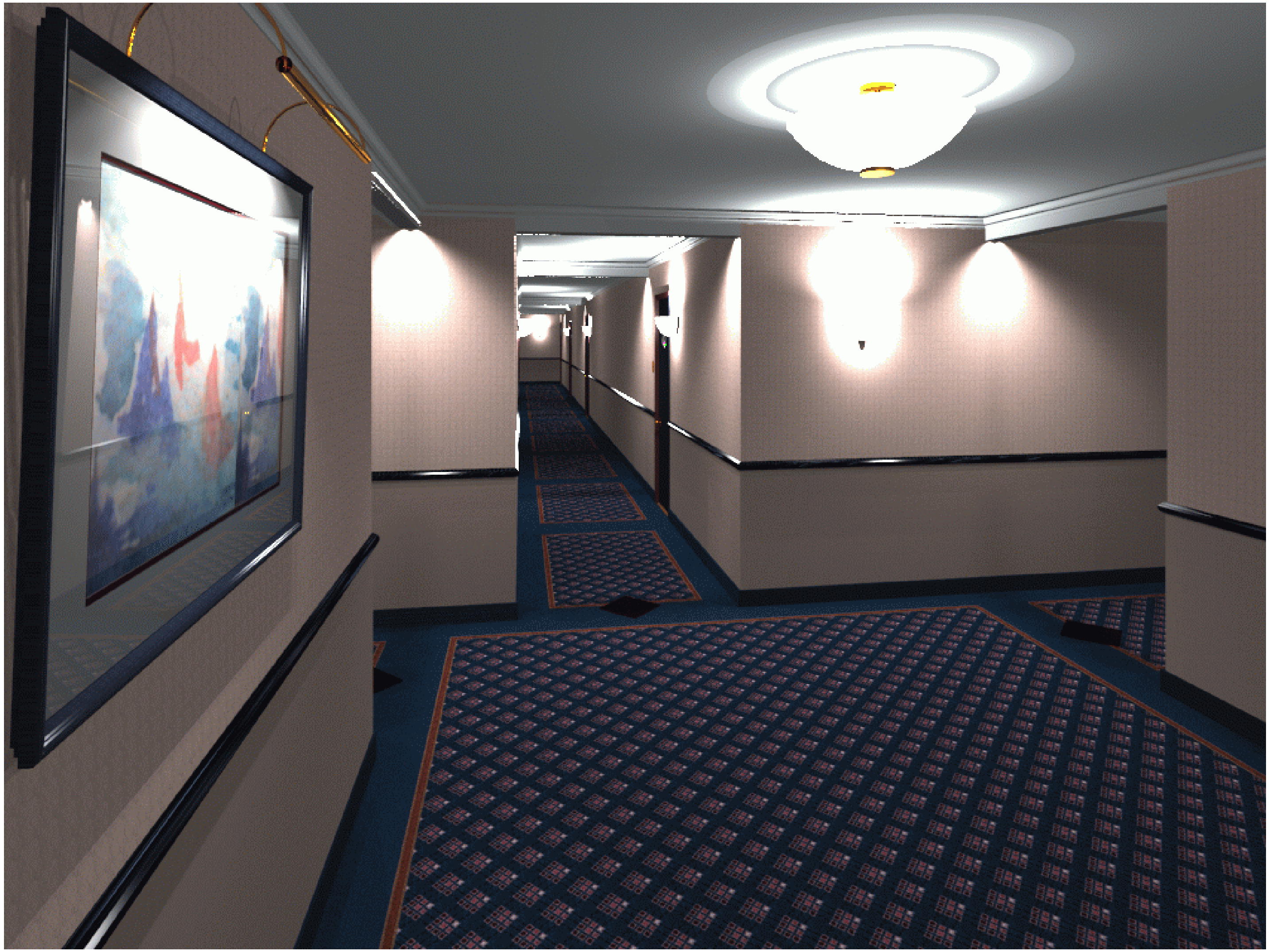
Ward`94 Tone-Mapping



Ward`97 Tone-Mapping

Comparison: Tumblin/Rushmeier

Comparison: Ward`94



Comparison: Ward`97

Local Tonemapping

HDR image
(reference)

restore missing contrast

tone mapping result

- **Usual contrast enhancement techniques**
  - either enhance everything
  - or require manual intervention
  - change image appearance
- **Tone mapping often gives numerically optimal solution**
  - no dynamic range left for enhancement

Idea: Enhance Local Contrast

Reference HDR Image

Measure Lost Contrast at Several Feature Scales

Tone Mapped Image

Enhance Lost Contrast in Tone Mapped Image

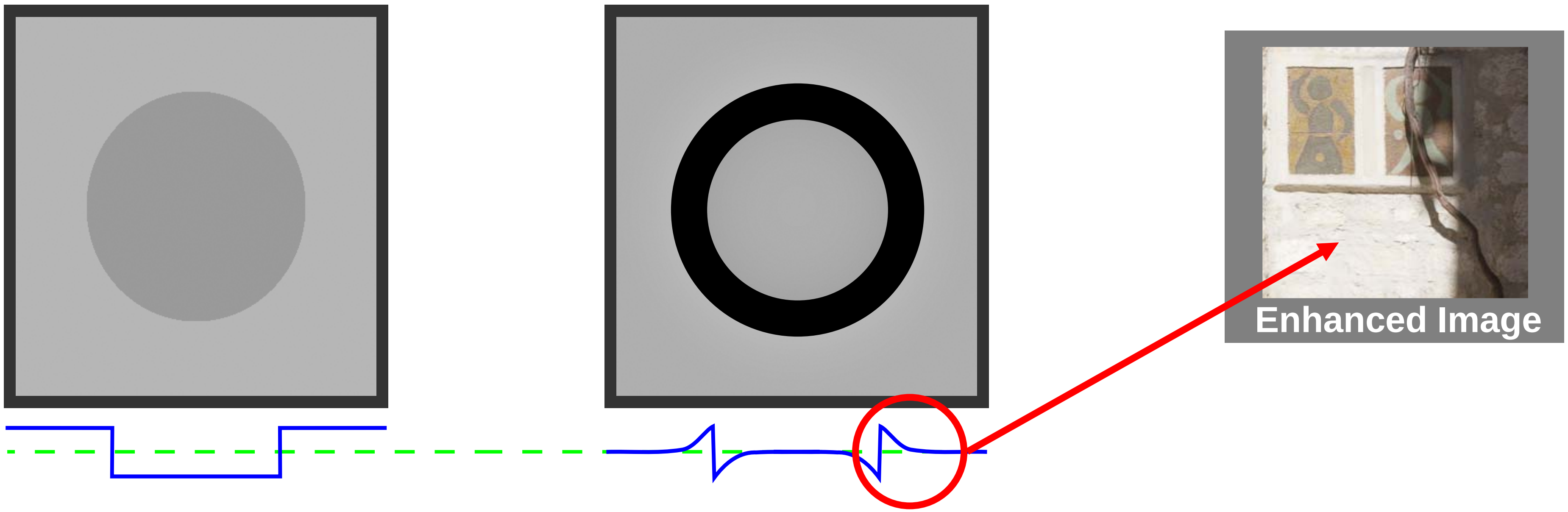
Enhanced TM Image

communicate lost image contents

maintain image appearance

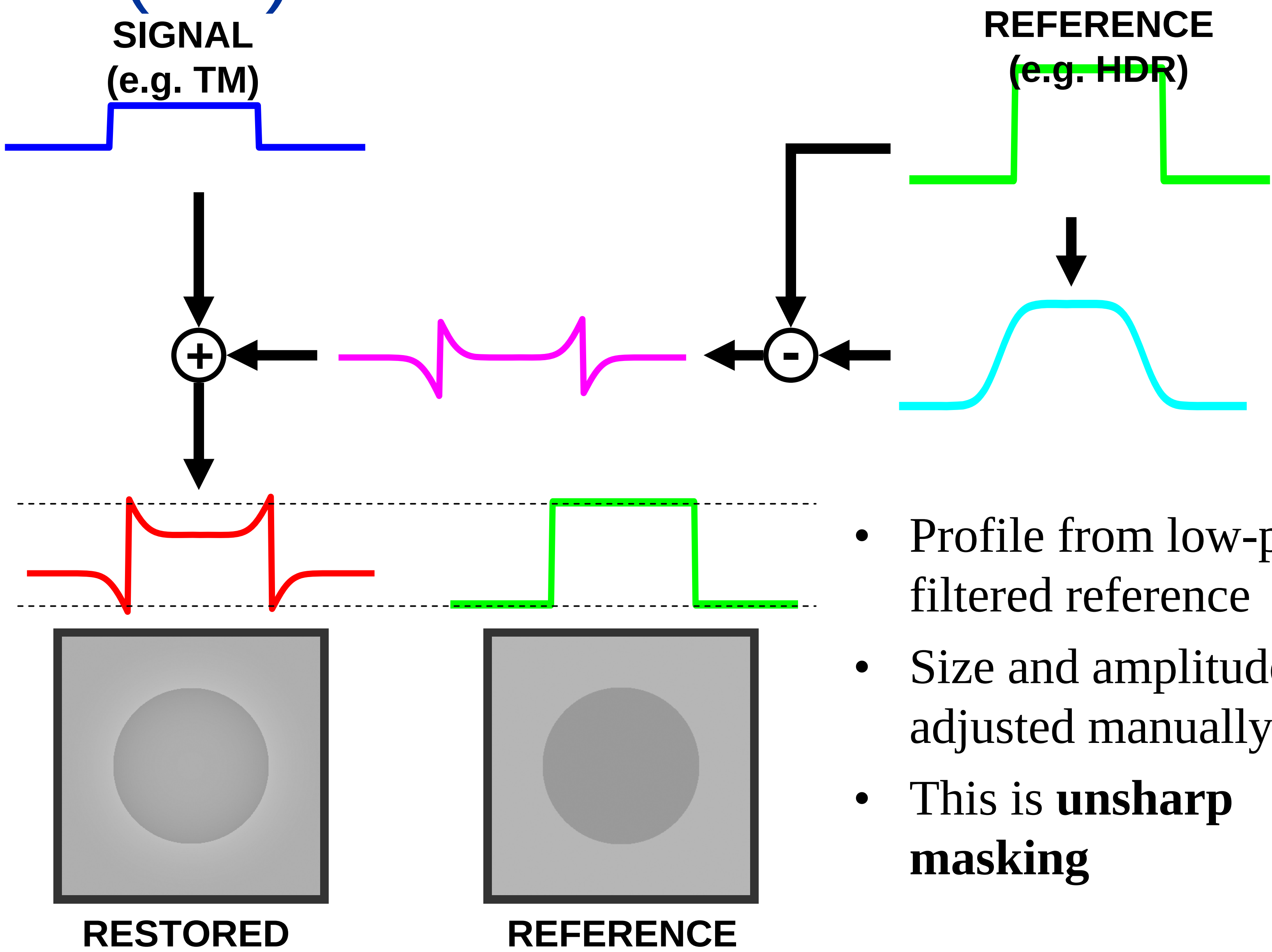
[Krawczyk06]

Method: Adaptive Countershading



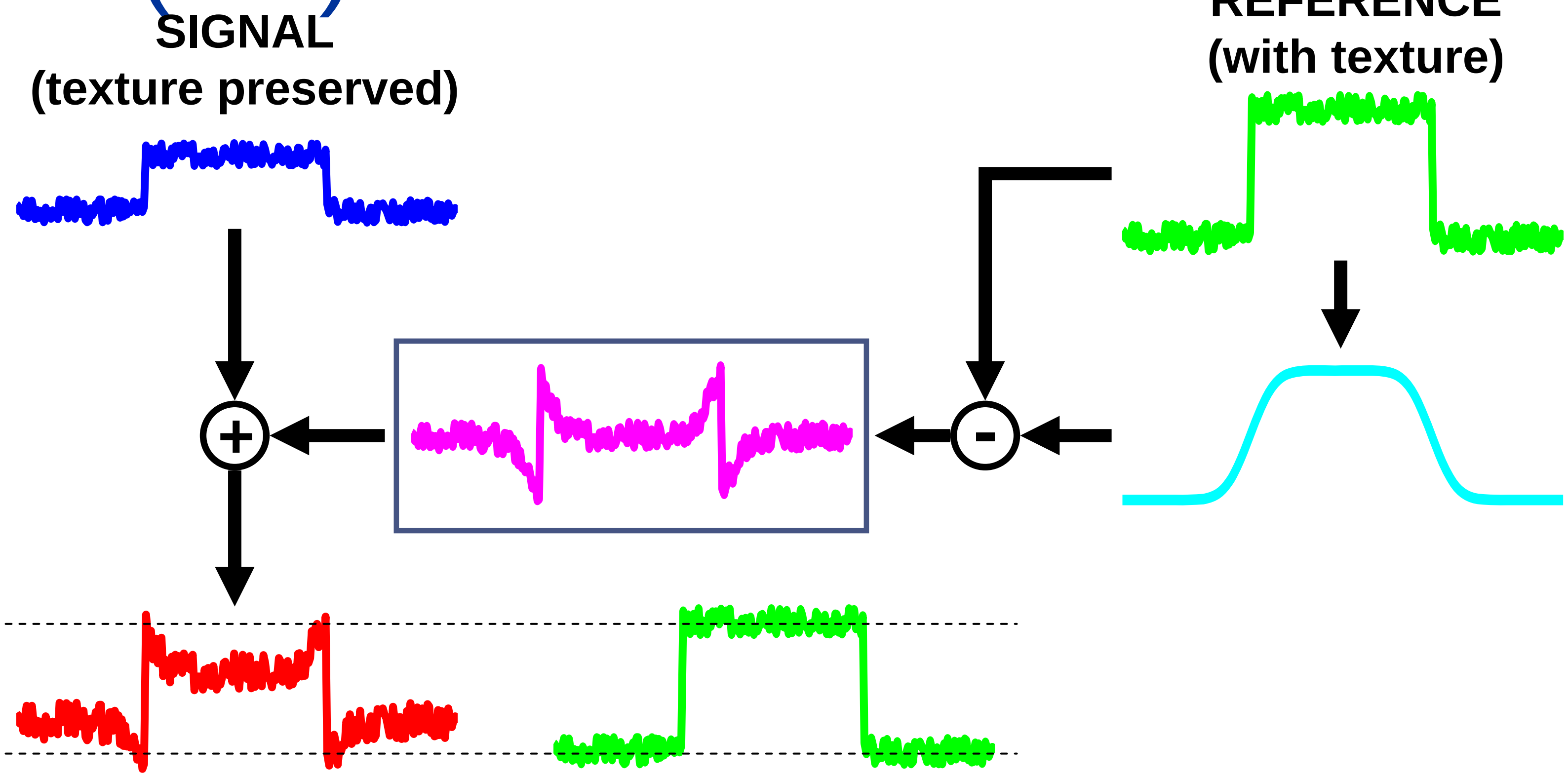
- **Create apparent contrast based on Cornsweet illusion**
- Countershading
  - **gradual darkening / brightening towards a contrasting edge**
  - contrast appears with ‘economic’ use of dynamic range

Construction of Simple Profile (1/2)



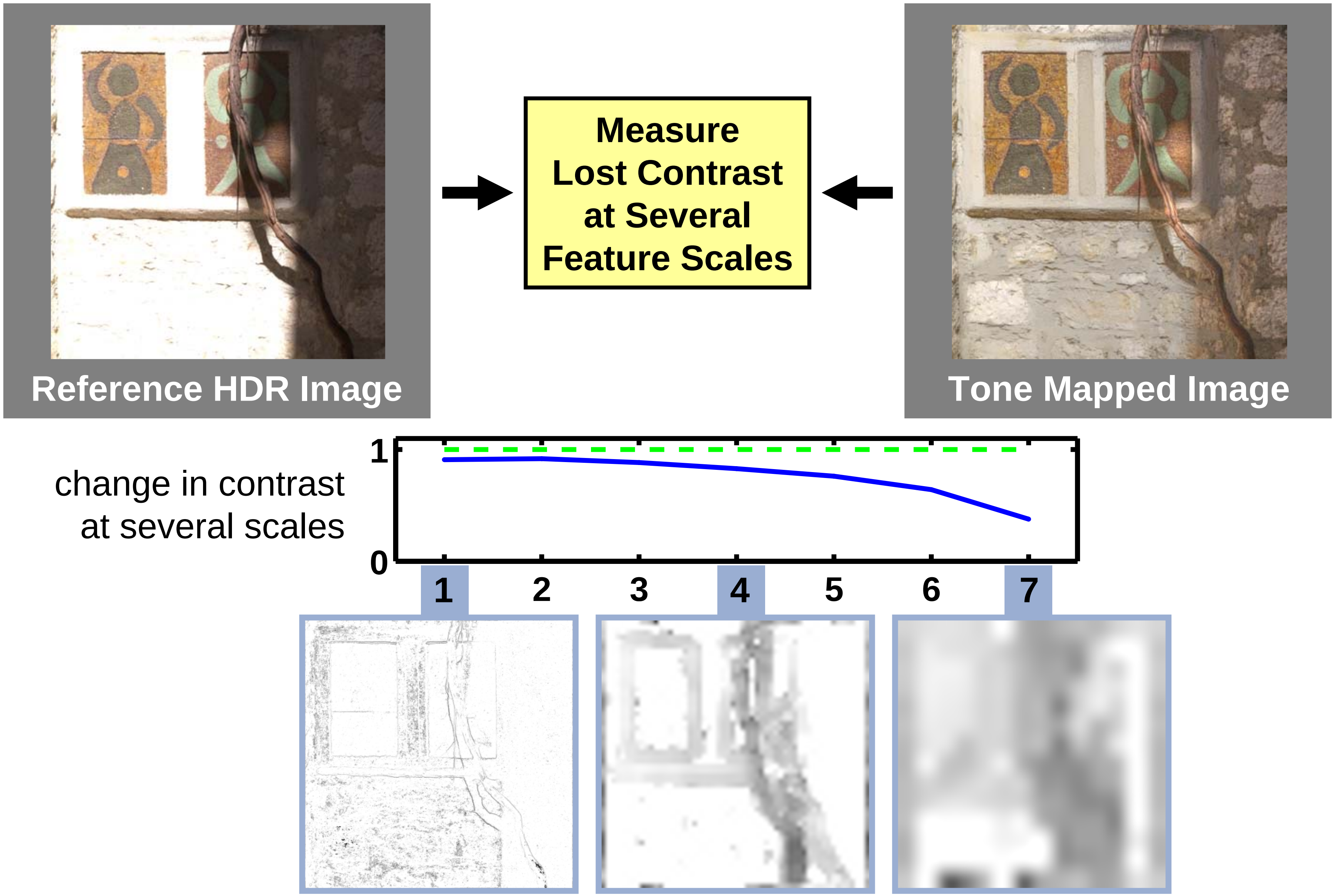
- Profile from low-pass filtered reference
- Size and amplitude adjusted manually
- This is **unsharp masking**

Construction of Simple Profile (2/2)

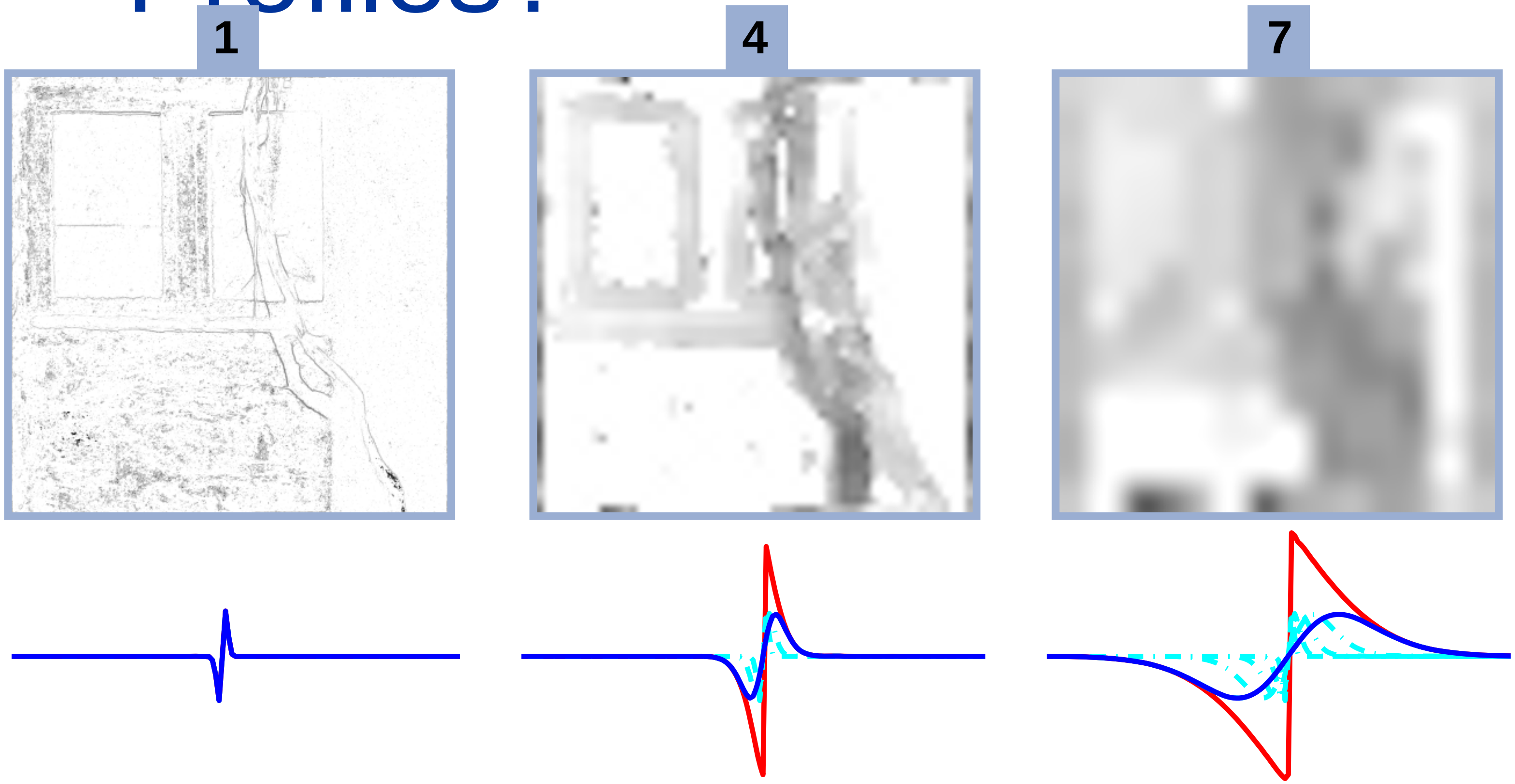


Well preserved signal is exaggerated by **unsharp masking**

Where to Insert Profiles?

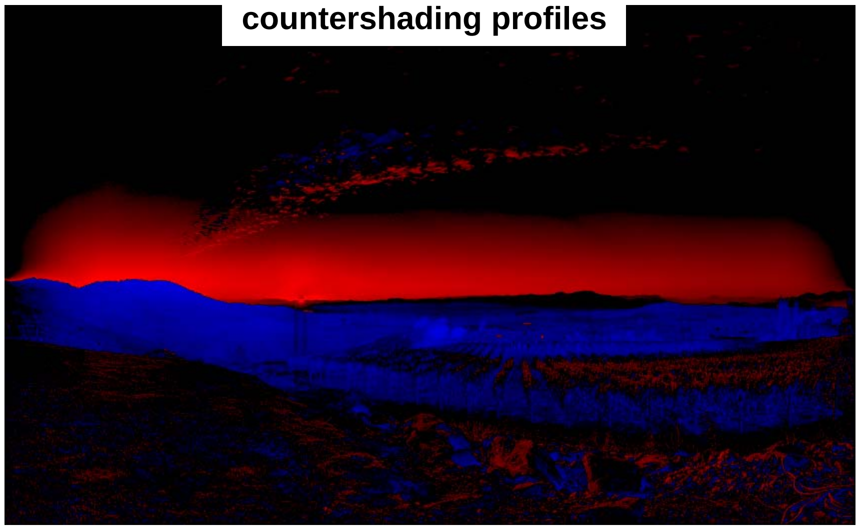


How to Construct Profiles?

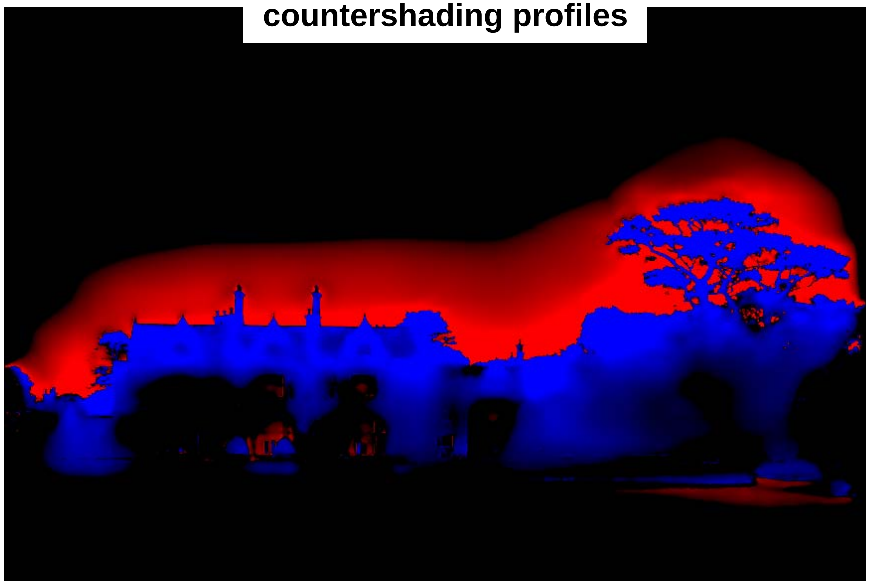


1. Scale of contrast measure defines the profile size
2. Contrast ratio at each scale defines the sub-band amplitude (blue)
3. Contrast for larger scales appears also on smaller scales
   - the full profile is always reconstructed (red)

Subtle Correction of Details



Improved Separation



C-shading vs. Unsharp Mask

tone mapping

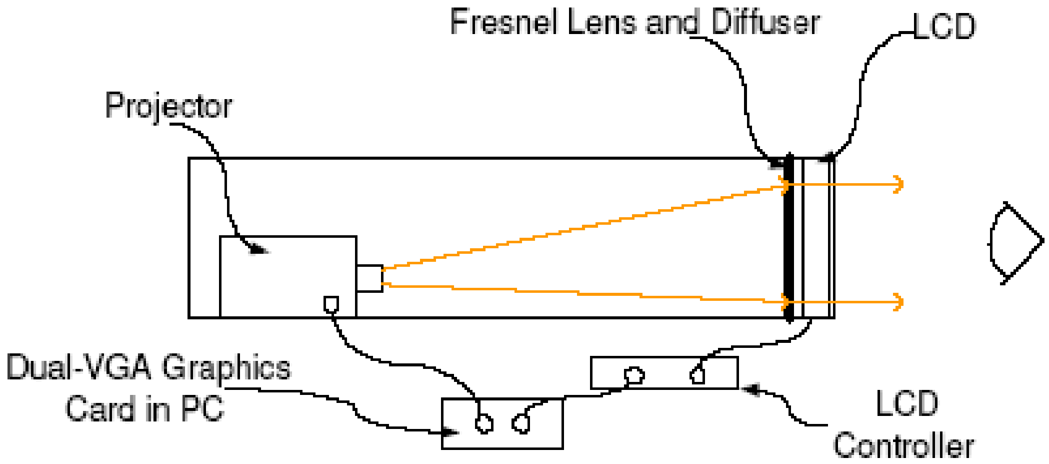
Alternative: HDR Display

- **Human Visual System**
  - Sensitive to contrast, insensitive to absolute luminance difference
  - Mach bands: reduced resolution at discontinuities
  - “Very high contrast, although important on a global scale, cannot be perceived by humans at high spatial frequencies”

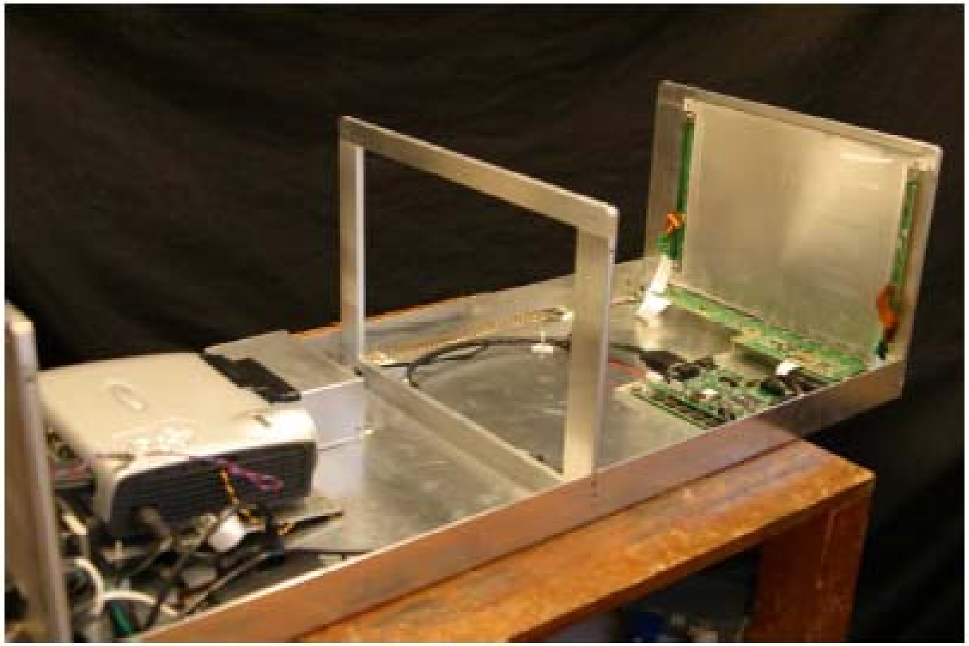
- **Idea [Heidrich et al., Siggraph 2004]**
  - High-resolution transparency filter to modulate high-intensity (low-resolution) image from a second display

  - Transparency filter: LCD screen
  - High intensity image: video projector, array of superluminous LEDs
  - dynamic range: >50,000:1
  - maximum intensity: 2700 cd/m^2, 8500 cd/m^2

Setup

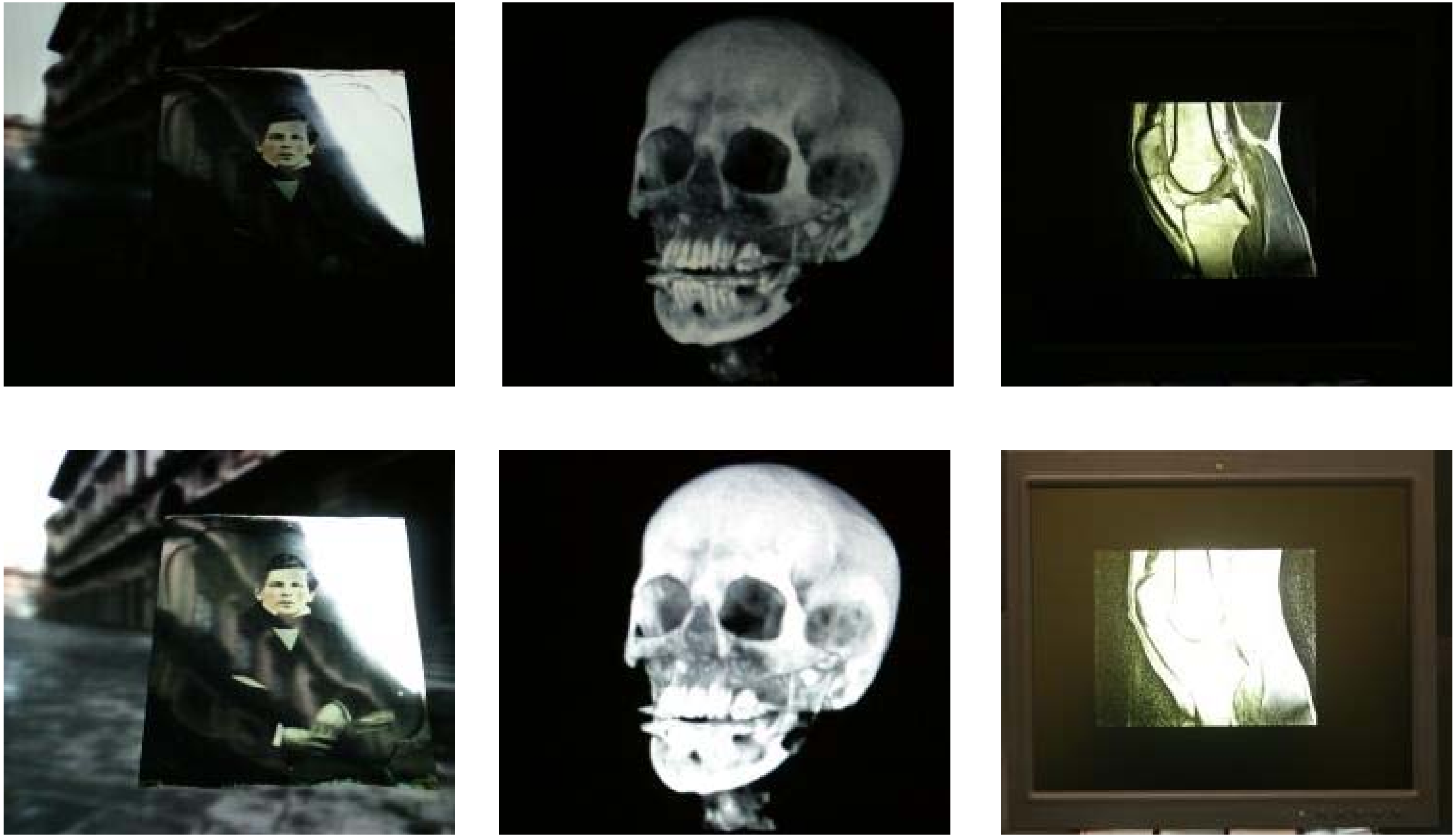


Fresnel Lens and Diffuser
LCD
Projector
Dual-VGA Graphics
Card in PC
LCD
Controller



Of-Screen Captured Photographs

- **4 aperture stops difference**



Wrap-up

- **HDR acquisition**
- **Tone mapping necessary due to dynamic range**
- **Reduction of dynamic range**
- **Histogram equalization**
- **Just noticeable difference**
- **HDR Display**