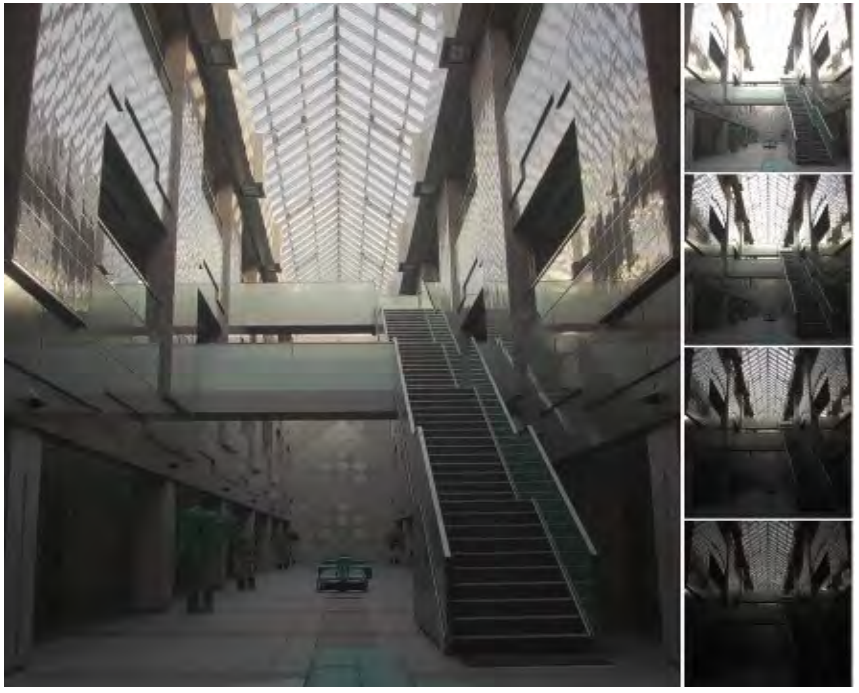
Realistic Image Synthesis

- Tone Mapping -

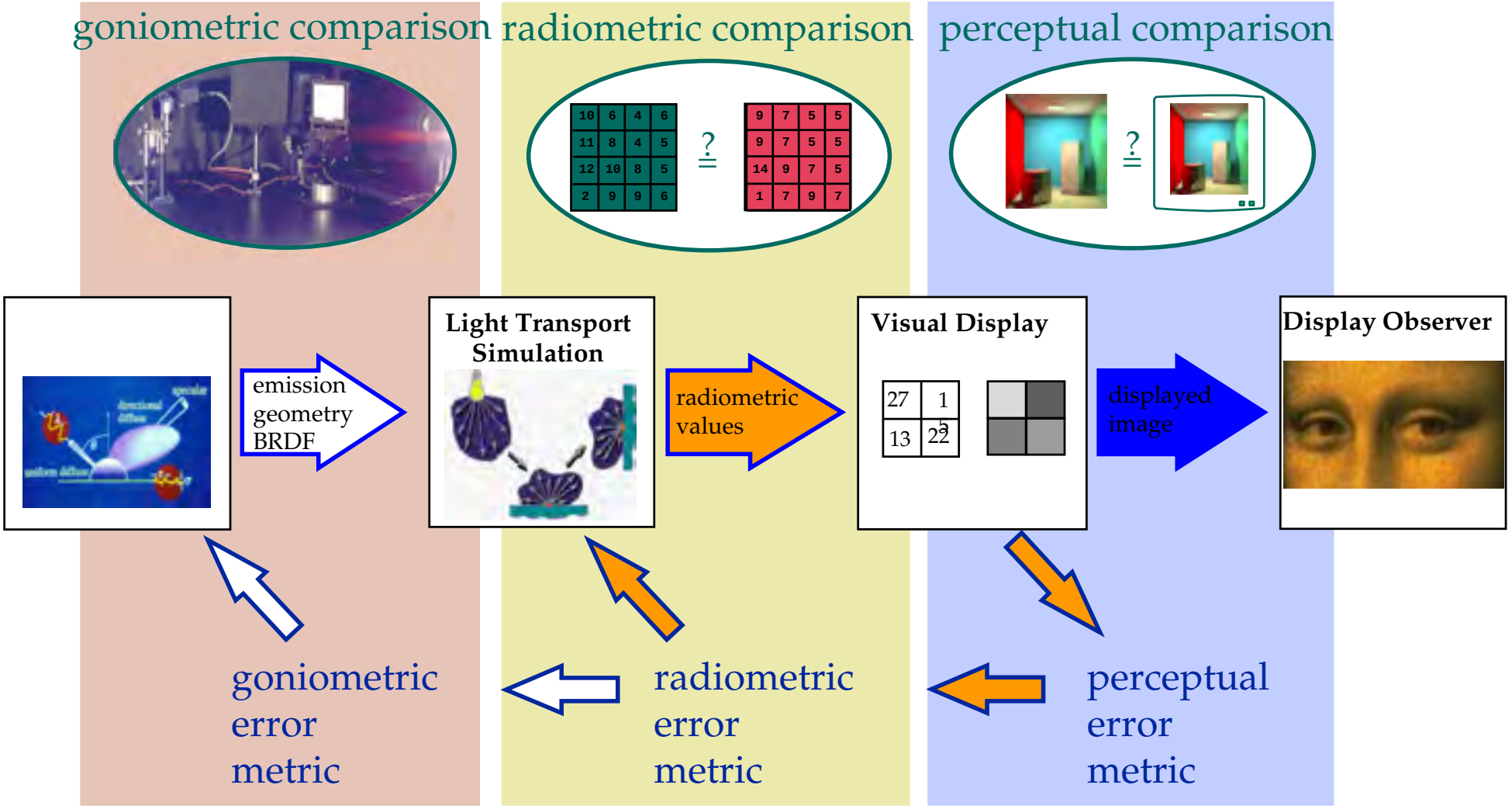
Karol Myszkowski

High-Dynamic Range Imagery

- **Many applications**
  - Lighting simulation and realistic rendering
  - Image-based lighting
  - High Dynamic Range photography
  - Multimedia: distributing HDR video streams



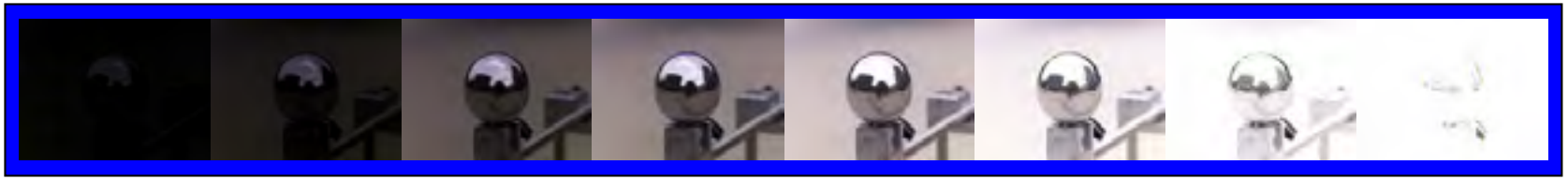
Realistic Image Synthesis



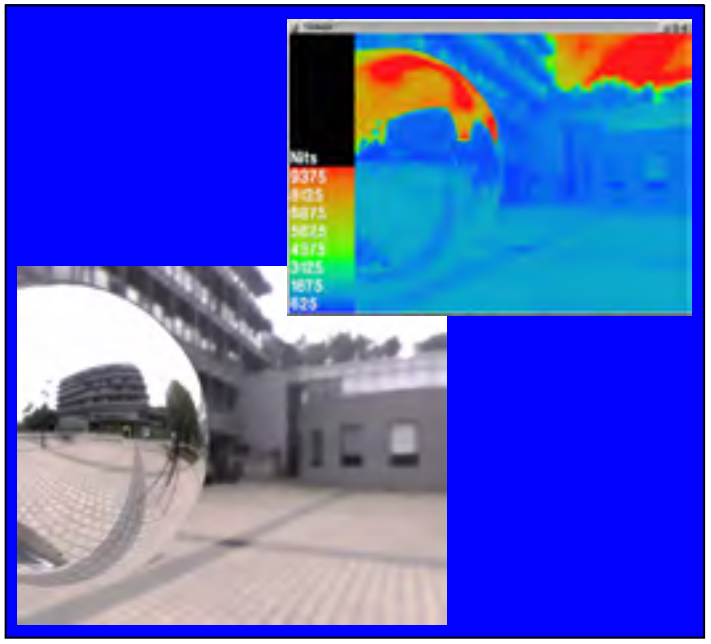
Greenberg et al. Siggraph'97. Cornell University

The Goal of Realistic Rendering

HDR Photographs + Rendering



1) Photographs of mirror sphere at varying exposure times



2) High-dynamic range environment map

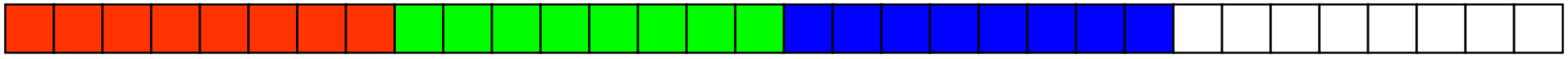
3) Use as light source in Monte Carlo radiosity algorithm

HDR Formats: RADIANCE Format (.pic, .hdr)

Greg Ward's "Real Pixels" format

- **4 bytes per pixel, 1 for each channel**

32 bits / pixel



Red Green Blue Exponent

(145, 215, 87, 149) =

(145, 215, 87) * 2^(149-128) =

(1190000, 1760000, 713000)

(145, 215, 87, 103) =

(145, 215, 87) * 2^(103-128) =

(0.00000432, 0.00000641, 0.00000259)

Ward, Greg. "Real Pixels," in Graphics Gems IV, edited by James Arvo, Academic Press, 1994

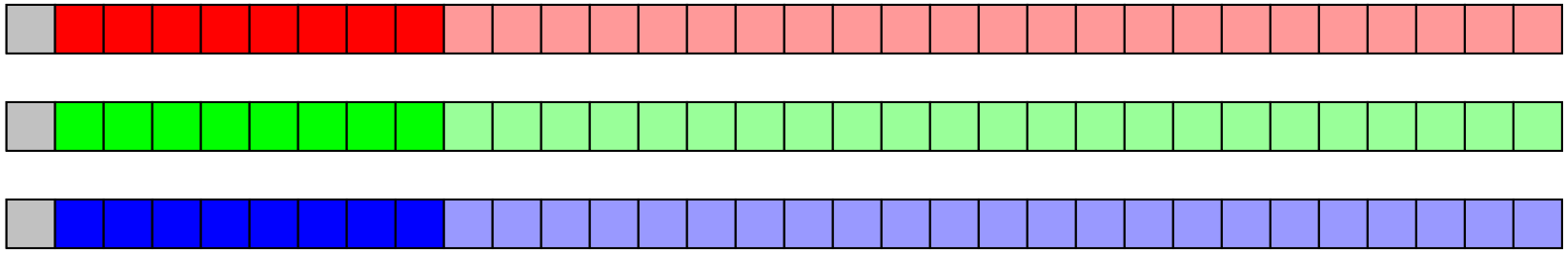
HDR Formats: RADIANCE Format (.pic, .hdr)

- **76 orders of magnitude in 1% steps**
- **Run-length-encoding (usually about 20% compression)**

– **Does not cover visible gamut**
– **Color quantization perceptually non-uniform**
– **Dynamic range at expense of accuracy**

HDR Formats: Portable FloatMap (.pfm)

- **12 bytes per pixel, 4 for each channel**



sign exponent mantissa

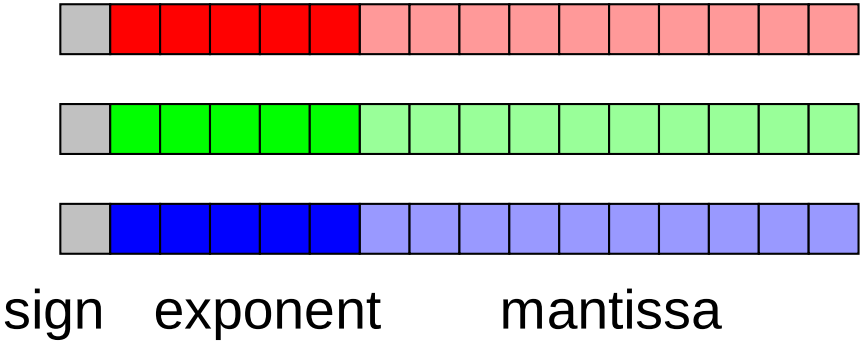
Text header similar to Jeff Poskanzer's .ppm image format:

```
PF
768 512
1
<binary image data>
```

Floating Point TIFF similar

HDR Formats: ILM's OpenEXR (.exr)

- **6 bytes per pixel, 2 for each channel, compressed**



- With 16-bit floating-point numbers
  - the representable dynamic range is significantly higher than the range of most image capture devices
  - 9.6 orders of magnitude in 0.1% steps (or 30 f-stops without loss of precision; 8-bit file formats have only 7-10 stops).
  - color resolution is 1024 steps per f-stop (only 20-70 steps per f-stop for most 8-bit file formats).
  - Several lossless compression options (RLE, ZIP), 2:1 typical
- Compatible with the "half" datatype in NVidia's Cg
  - Supported natively on GeForce FX and Quadro FX

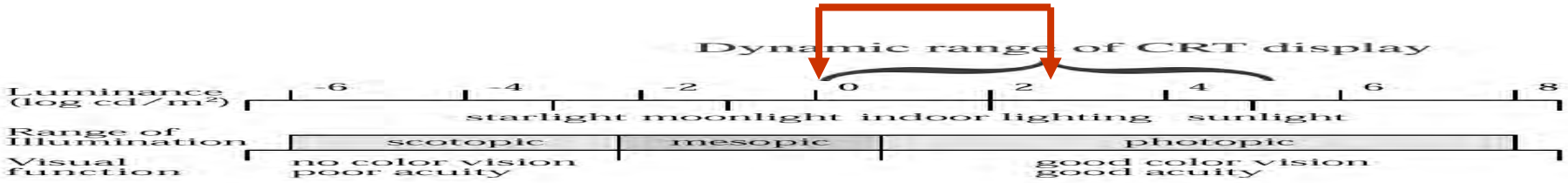
http://www.openexr.net/

Tone Mapping: Various Objectives

- **Get good perceptual match between the real-world and corresponding images**
- **Reproducing details**
- **Maximize reproducible contrast**
- **Just to get “nice-looking” images**

The Tone Mapping Problem

- **Technical requirement**
  - Match the dynamic range of image to the range available on a given display device



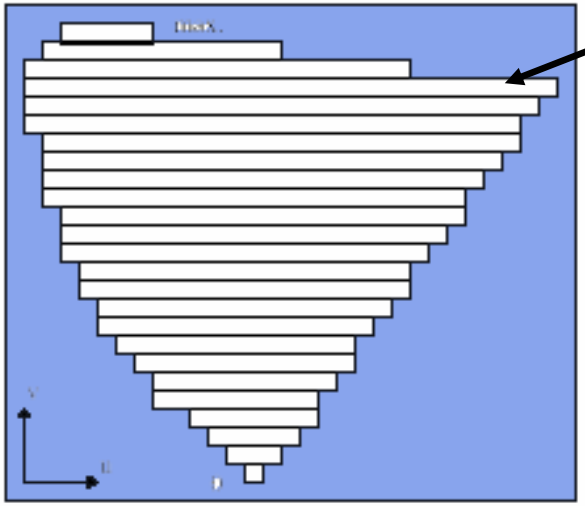
The range of luminances in the natural environment and associated visual parameters.

$$\text{Dynamic Range} = \frac{\text{Highest Scene Luminance}}{\text{Lowest Scene Luminance}}$$

  - Humans adjust comfortably to 8 orders of magnitude and can see simultaneously up to 4 orders
  - Typical CRT and LCD display images within a luminance range 1-700 cd/m^2
  - HDR display developed at Univ. of British Columbia in collaboration with Greg Ward was presented at Siggraph 2003
    - Min. luminance: 0.1 cd/m^2 Max. luminance: 3,000-10,000 cd/m^2

HDR Formats: Ward's LogLuv TIFF

based on human color perception



24 bits: 10 for log luminance
14 for chromaticity index

4.8 orders of magnitude in 1.1% steps

Just covers visible gamut and range

32 bits: 15 for log luminance
8 u chrominance
8 v chrominance
1 sign

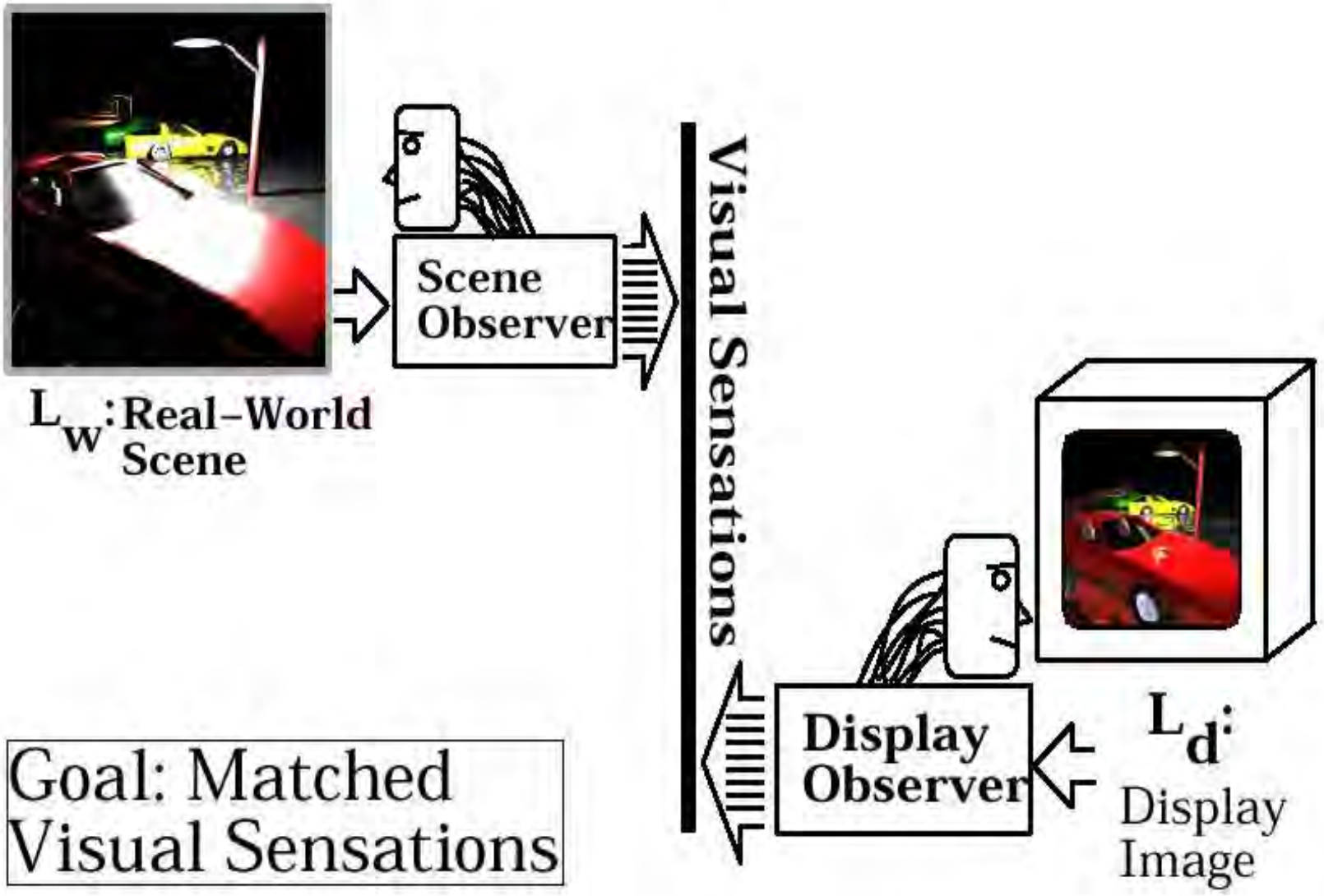
38 orders of magnitude in 0.3% steps

Color error: 0.0017 units in uv space

Larson, G.W., "Overcoming Gamut and Dynamic Range Limitations in Digital Images," Proceedings of the Sixth Color Imaging Conference, November 1998.

http://positron.cs.berkeley.edu/~gwlarson/pixformat/tiffluv.html

Visual Matching



Goal: Matched Visual Sensations

Common Approaches

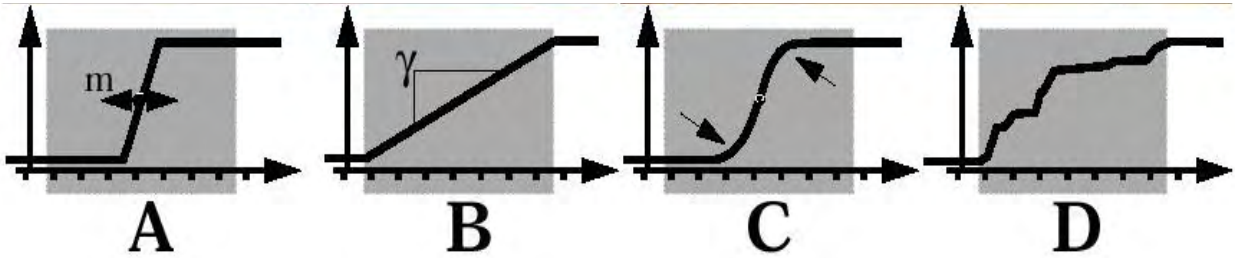
A **Average scene luminance mapped to the average monitor luminance**

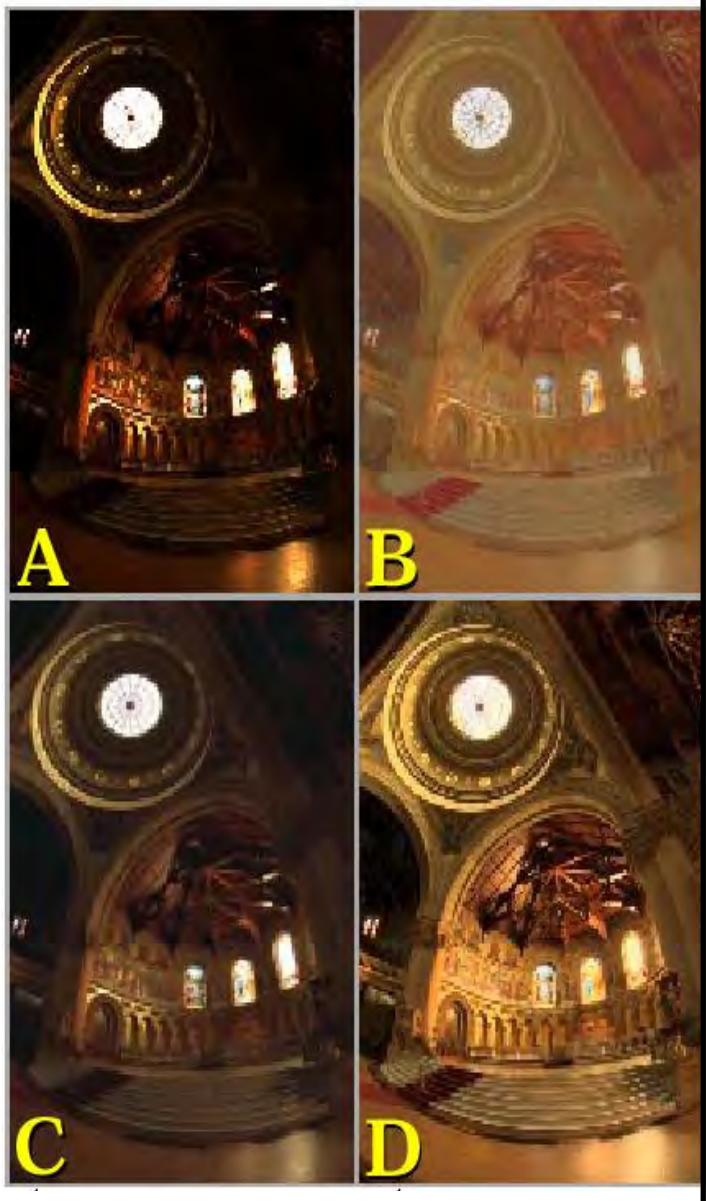
B **Maximum scene luminance mapped to the highest monitor luminance**

→ In all cases images will look the same independently whether the scene is illuminated by the moonlight or sunlight

C **S-shaped, common in photography**

D **histogram**





Multi-Exposure Desk

Linear Mapping

Visual Mapping

Various Classifications

- **Theoretical foundations**
  - Perception-based
  - Pure image processing techniques
- **Mapping function**
  - Global – the same for all pixels
  - Local – depends on local image contents
- **Temporal processing**
  - Static
  - Dynamic

Global vs. Local Operators

- **Spatially-uniform tone reproduction operators**
  - Adapatation is the same (**global**) for the whole image. Thus, the mapping function is the same for the whole image as well.
  - Mapping function is monotonic, i.e. for increasing luminance values in the scene non-decreasing luminance values of the display device will be assigned
  - Key issue: shape of the function

$$L_d(x,y) = mL_w(x,y)$$

- **Spatially-non-uniform tone reproduction operators**
  - Adaptation is **local**ized. Thus, the mapping function might be different for various image regions
  - Key issue: size of local neighborhood used for the adaptation computation

$$L_d(x,y) = m(x,y)L_w(x,y)$$

Global Methods

- **Perception-based**
  - Tumblin and Rushmeier (1993,1999)
    - Brightness matching
  - Ward (1994), Ferwerda et al. (1996)
    - Contrast matching (a linear function is used)
  - Ward et al. (1997)
    - Adjusting image histogram to avoid exceeding display contrast in respect to the real-world scene
  - Drago et al. (2003)
- **Efficiency-driven**
  - Schlick (1994)
    - Rational functions

Comparison

Ferwerda et al. **Tumblin (1999)** **Ward et al.** **Schlick**

Tumblin & Rushmeier (1)

- **Brightness Matching**
  - Brightness preservation based on a mathematical model of human vision
    - Stevens & Stevens function
    - Suphrathreshold vision
  - Keep a constant relationship between the display brightness and scene brightness.
    - Brightness for the observer of the display and the real-world scene are equated: visual impressions from observing the scene and display must be the same.

Tumblin & Rushmeier.Tone reproduction for computer generated images.

IEEE Computer Graphics and Applications. 1993

Tumblin & Rushmeier (2)

$$1\,\text{micro-lambert} = \frac{1}{100 \cdot \pi}\frac{cd}{m^2}$$

- **Stevens & Stevens function**
  - Brightness (B) – measured in brils
    - 1bril is the sensation of brightness from a fully adapted eye viewing a 5 degree target of 1 micro-lambert for one second.

$$B = 10^{\beta} L^{\alpha}$$

$$\alpha = 0.4\log_{10}(L_a) + 2.92$$

$$\beta = -0.4(\log_{10}(L_a))^2 + (-2.584\log_{10}(L_a)) + 2.0208$$

- L_a the luminance of the adaptation level
- L luminance, B brightness in brils

Tumblin & Rushmeier (3)

- **The visual impressions from observing the scene and display must be the same!**
  - Brightness for the observers of the display (subscript *d*) and the real-world scene (subscript *w*) are equated

$$L_d = L_w^{\alpha_w/\alpha_d} 10^{[(\beta_w - \beta_d)/\alpha_d]}$$

it is assumed that the real world adaptation level $L_{a(w)}$ is

$$\log_{10}(L_{a(w)}) = E[\log_{10}(L_w)] + 0.84$$

where is E is the statistical average over the image, and

$$L_{a(d)} = L_{d,\max} \approx 100 cd/m^2$$

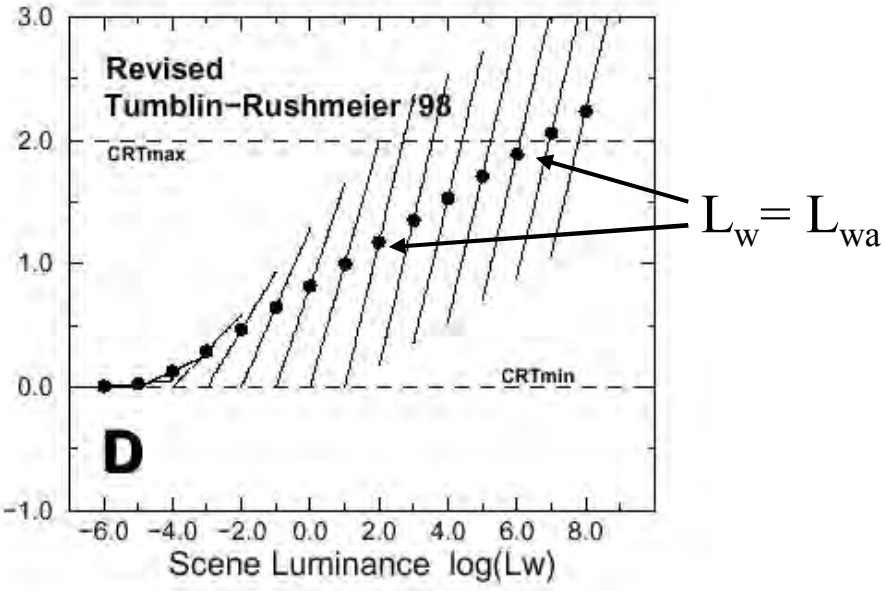
Then the recalculation of L_d to the display units n $(0 < n < 1)$,

for the display with the gamma – correction γ can be performed as

$$\mathrm{n} = \left[(\mathrm{L_d} / L_{d,\max}) - (1/C_{\max})\right]^{1/\gamma} \qquad C_{\max} \approx 35 \text{ max contrast for CRTs}$$

Tumblin & Rushmeier (4)

- **Bright scenes exaggerate contrast unrealistically**



Ward (1)

Threshold vision model:

Accordingly to Blackwell the luminance difference ΔL that is just noticeable at an adaptation level L_a (measured in cd/m^2) can be expressed as:

$$\Delta L = 0.054(1.219 + L_a^{0.4})^{2.5}$$

Match between JNDs for the display and real world can be obtained when $\Delta L_d = m \Delta L_w$

Thus, all real-world luminance are mapped to display luminances by:

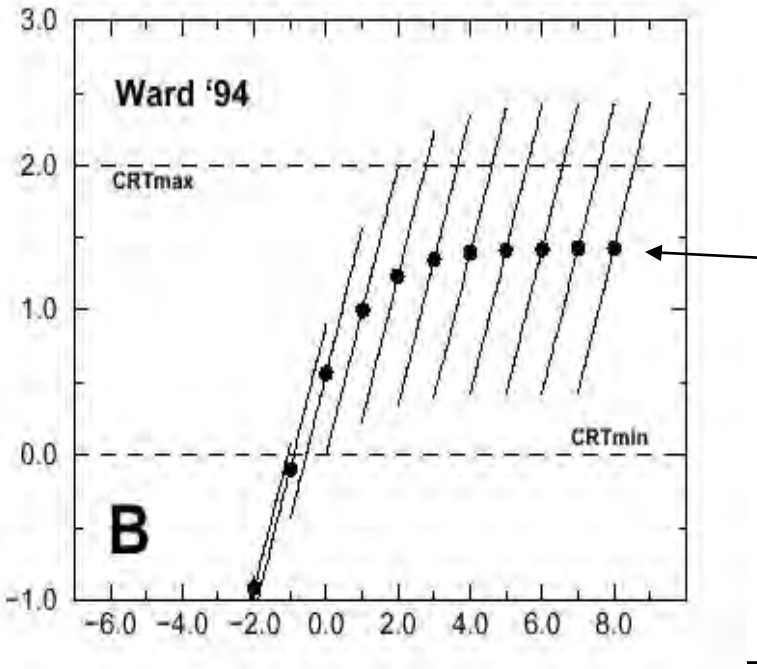
$L_d = mL_w$, where m is given by:

$$m = \left[\frac{1.219 + L_{a(d)}^{0.4}}{1.219 + L_{a(w)}^{0.4}} \right]^{2.5}$$

Ward assumes that $L_{a(d)} = L_{d\max}/2$, and $L_{a(w)}$ is computed locally for the scene region that is around the observer fixation area.

Ward (2)

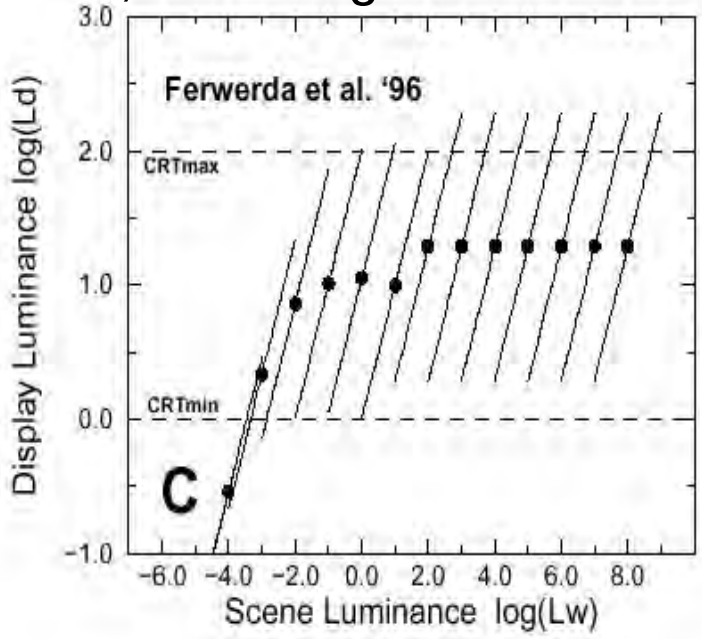
- **Dark scenes displayed always as dark images, and contrast is never inversed.**
- **Scenes with L_w < 0.01 cd/m^2 are mapped to black**
  - Rod-mediated vision not modeled
- **Scenes with L_{wa} > 100 cd/m^2 are normalized (i.e., displayed in the same way)**



$L_w = L_{wa}$

Ferwerda et al. (1)

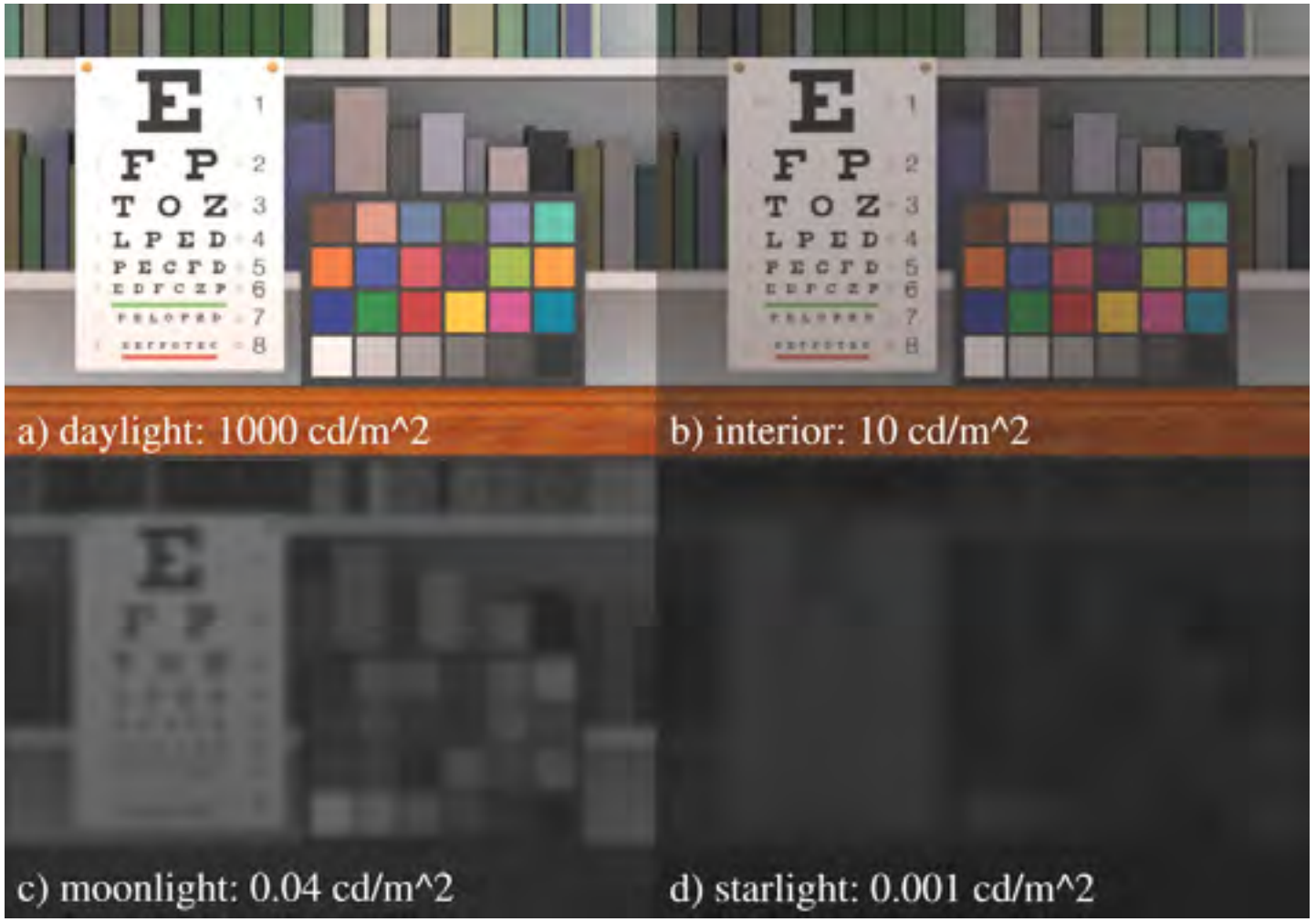
- Extended the dark response of Ward's method down to 10^{-4} cd/m^2.
- Proper modeling luminance sensitivity, color sensitivity, and spatial acuity with decreasing light.
- Display luminance is not monotonically increasing function of L_{wa} near 1 cd/m^2. As for Ward's method scenes with L_{wa} > 100 cd/m^2 are strictly normalized, and image contrast is not modified.



James Ferwerda, Sumant Pattanaik, Peter Shirley, and Donald P.Greenberg.

A Model of Visual Adaptation for Realistic Image Synthesis . SIGGRAPH 96

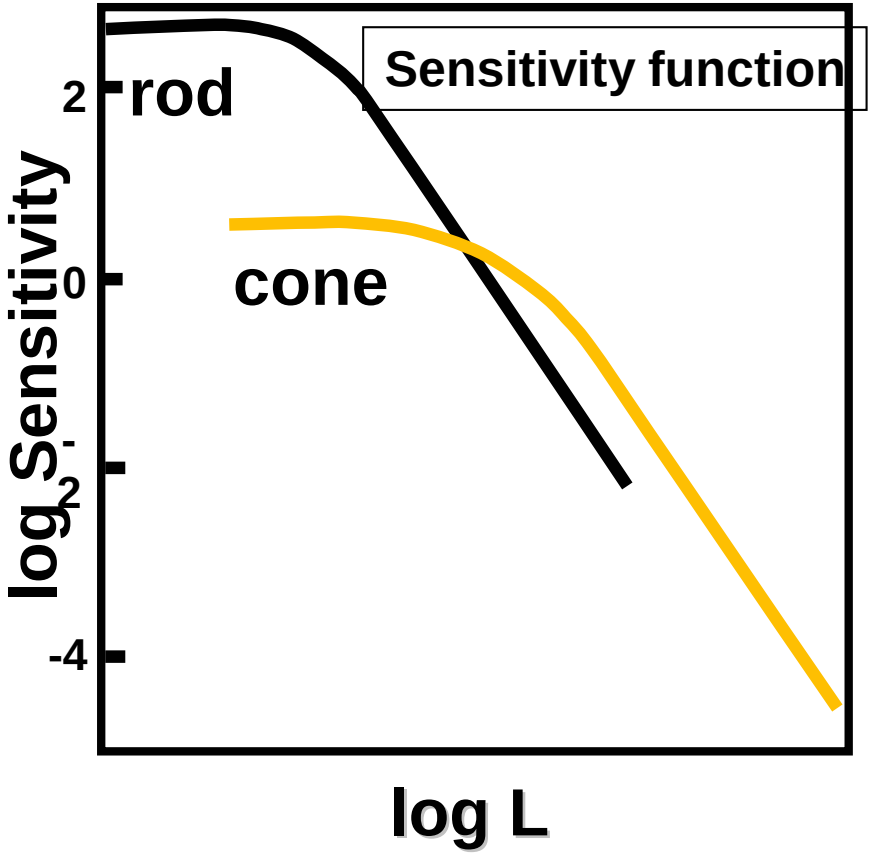
Ferwerda et al. (2)



Visibility of a Snellen chart and a Macbeth Colorchecker for various levels of adaptation luminance

Ferwerda et al. (3)

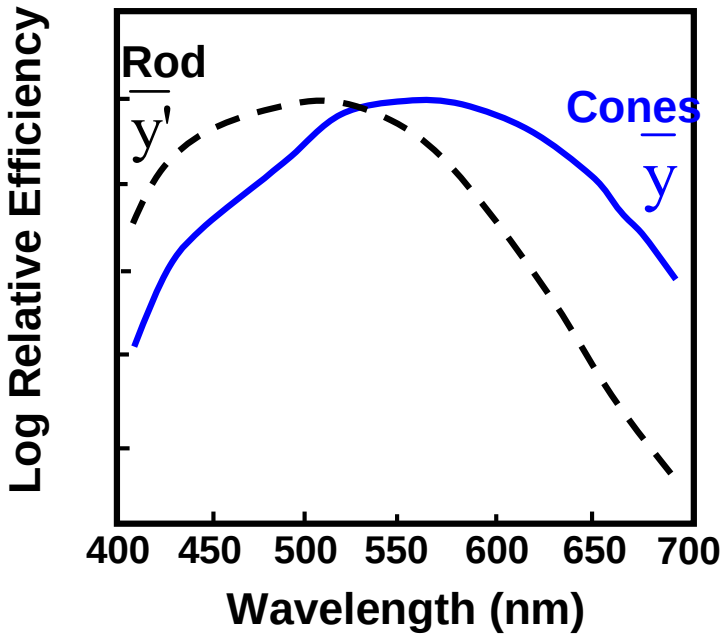
- ***Threshold Model of Adaptation***
- ***Sensitivity as a gain control mechanism***



$$[X, Y, Z]_{Cone} \times Sensitivity_{Cone} + [X, Y, Z]_{Rod} \times Sensitivity_{Rod} = [X, Y, Z]_{Total}$$

Luminance, Chrominance Values

Spectral efficiency functions



$$X = 683 \frac{\text{lm}}{\text{watt}} \int_{380nm}^{700nm} L_s(\lambda)\, \bar{x}(\lambda)\, d\lambda$$

$$Y = 683 \frac{\text{lm}}{\text{watt}} \int_{380nm}^{700nm} L_s(\lambda)\, \bar{y}(\lambda)\, d\lambda$$

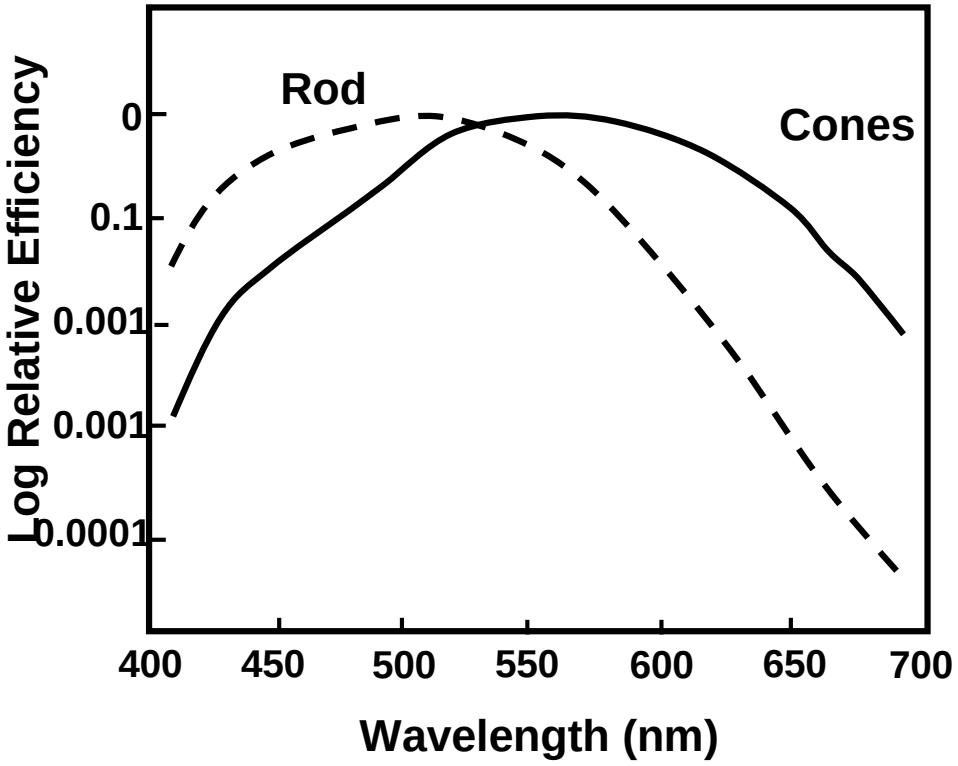
$$Z = 683 \frac{\text{lm}}{\text{watt}} \int_{380nm}^{700nm} L_s(\lambda)\, \bar{z}(\lambda)\, d\lambda$$

For Cones

For rods

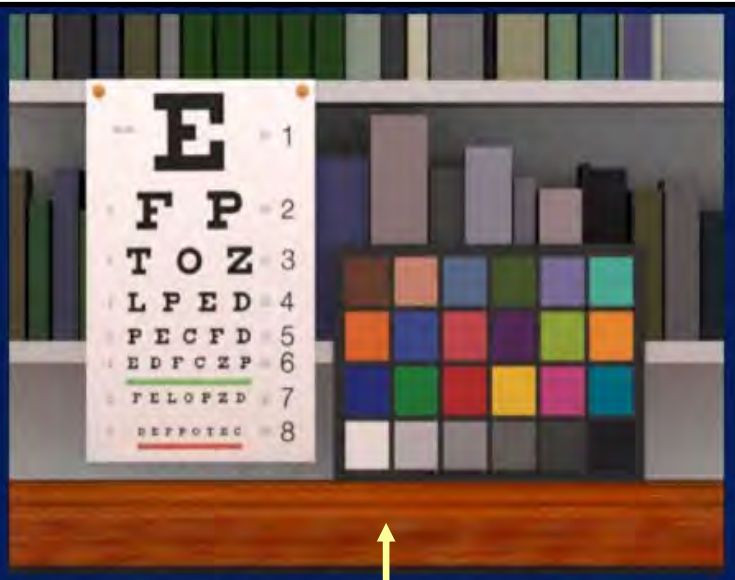
$$X' = Y' = Z' = 1700 \frac{\text{lm}}{\text{watt}} \int_{380nm}^{700nm} L_s(\lambda)\, \bar{y}'(\lambda)\, d\lambda$$

Ferwerda et al. (5): Purkinje Shift



Simulating daylight vision

(1000 cd/m^2)



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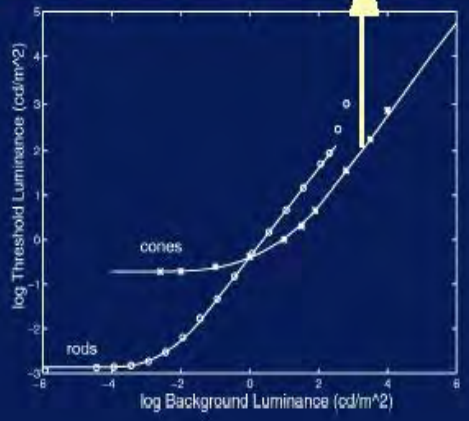
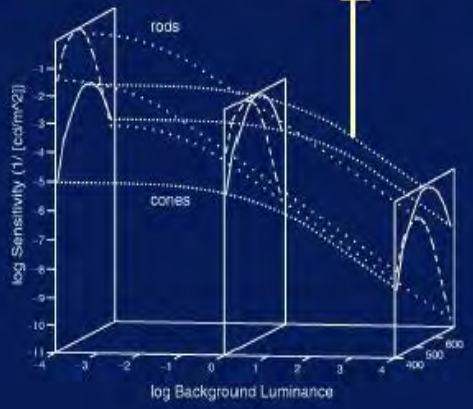
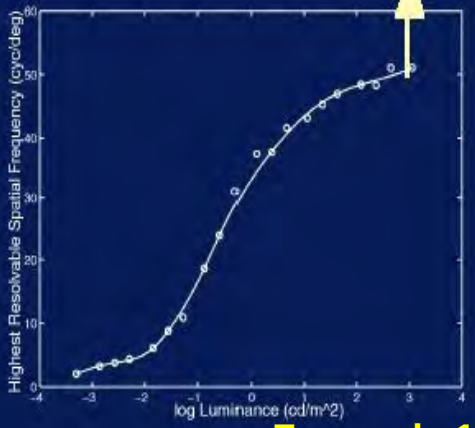


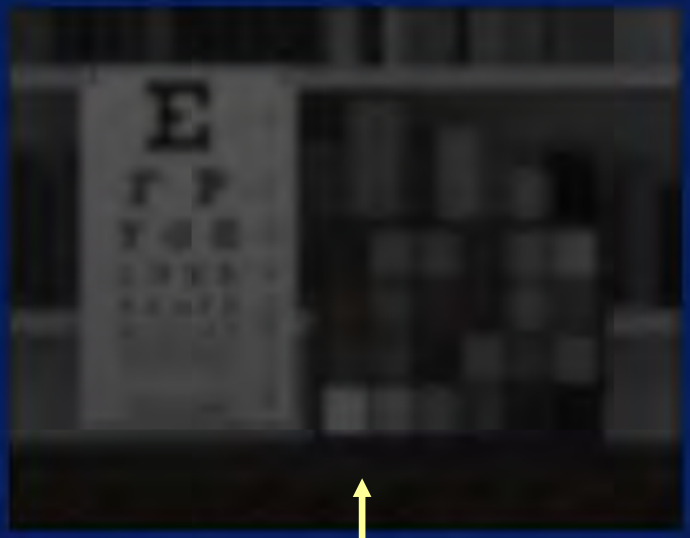




Ferwerda 1998

Simulating night vision

(0.04 cd/m^2)



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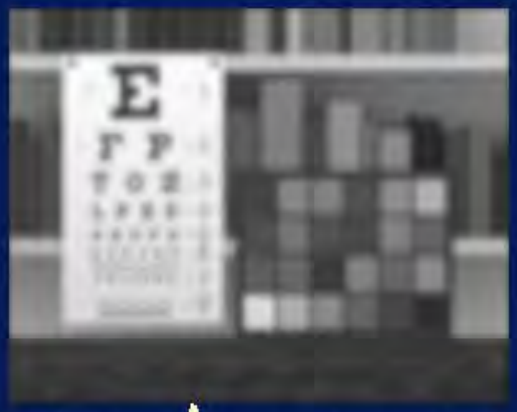
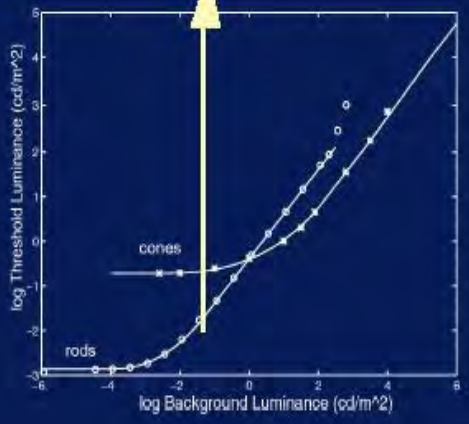
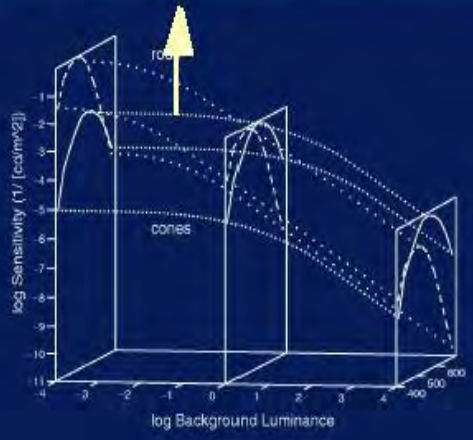
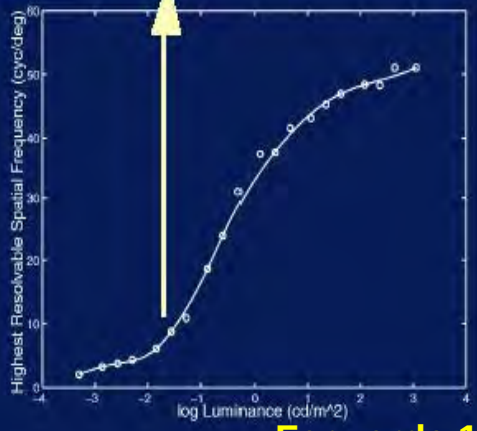




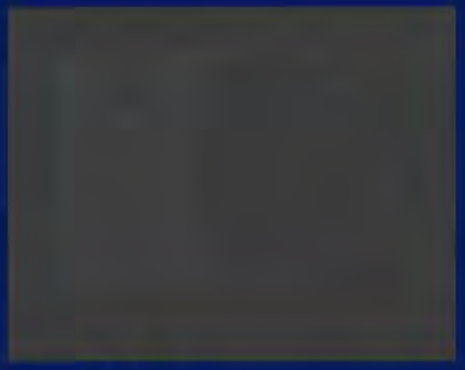




Ferwerda 1998

Dark adaptation

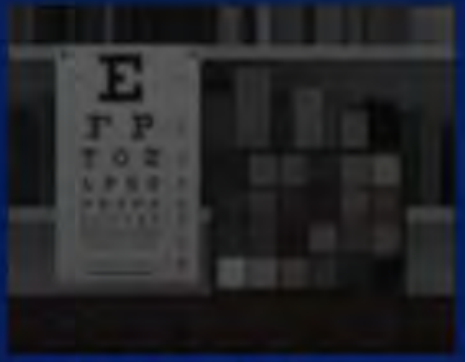
t= 0 s
lum= 1412 cd/m^2



t= 25 s
lum= 0.1 cd/m^2

t= 50 s
lum= 0.1 cd/m^2

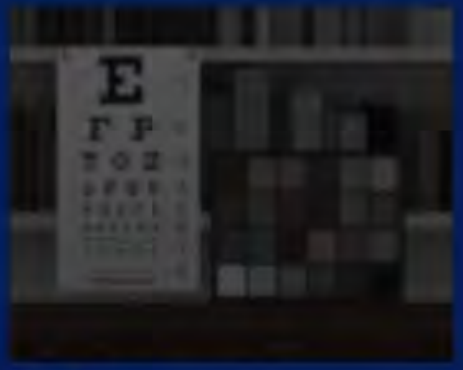
t= 1 min. 40 s
lum= 0.1 cd/m^2



t= 3 min. 20 s
lum= 0.1 cd/m^2

Ferwerda 1998

Light adaptation



t= 0 s
lum= 0.1 cd/m²

t= 1 s
lum= 5800 cd/m²

t= 10 s
lum= 5800 cd/m²

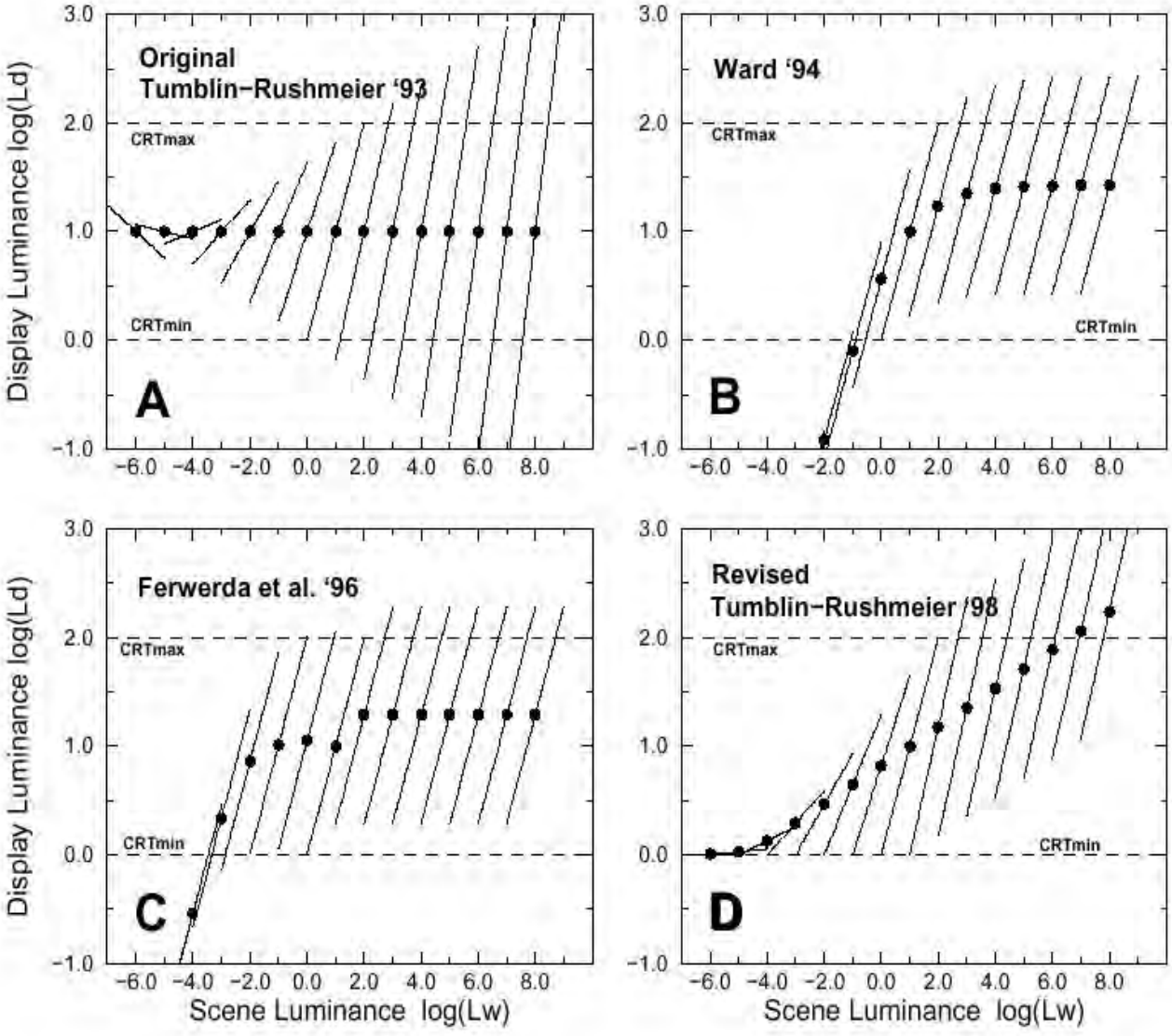
t= 25 s
lum= 5800 cd/m²

t= 1 min. 15 s
lum= 5800 cd/m²

Ferwerda 1998

Ferwerda et al. (6)

Global Methods: Comparison



Jack Tumblin, Ph.D. thesis

Ward-Larson et al. (1)

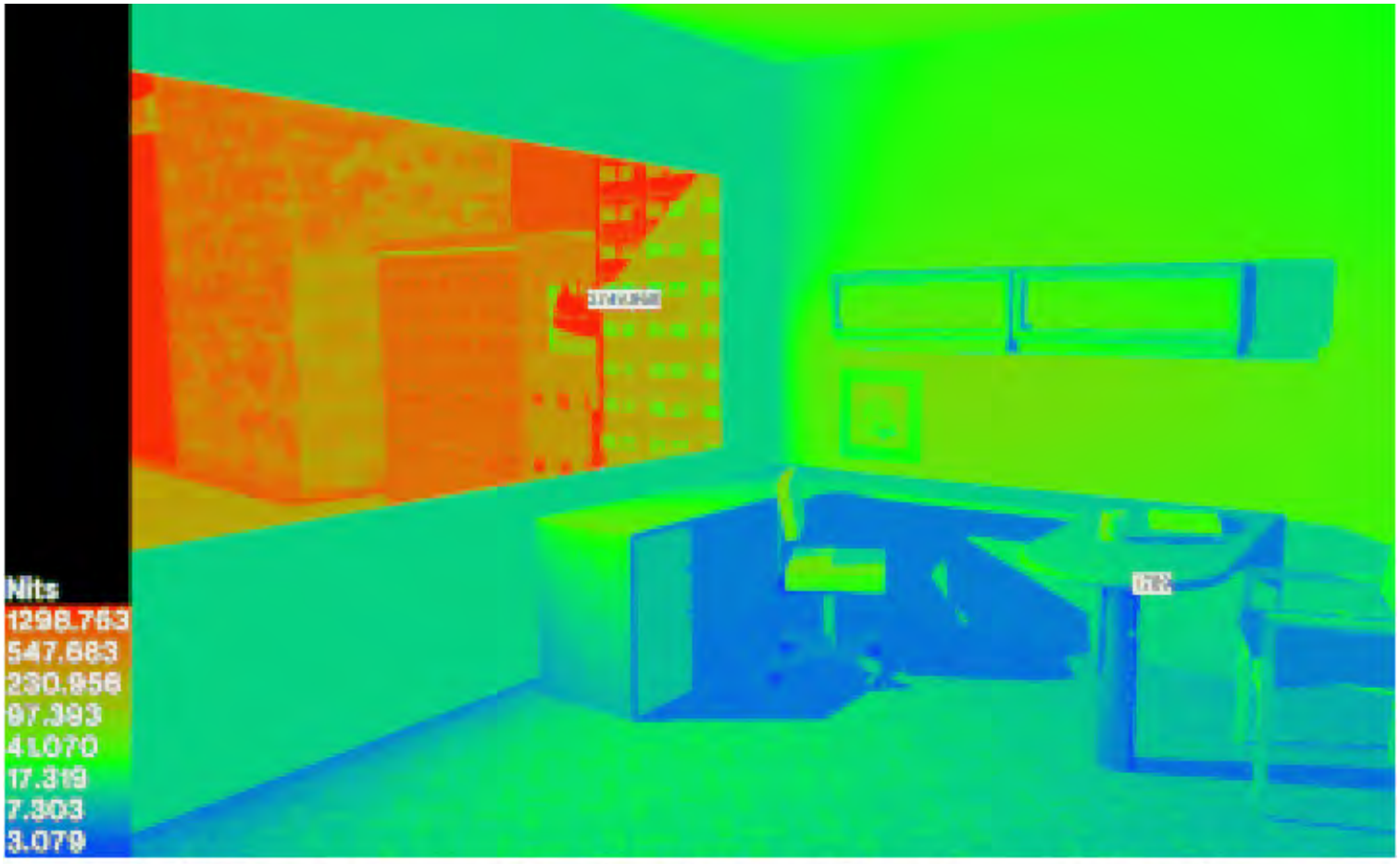
- Adaptation luminance is computed locally in the image for 1° field of view, and clusters of similar adaptation levels are found. Histogram of luminances and cumulative distribution function of all local adaptation luminances are built.
- Image histogram is adjusted to minimise the visible contrast distortions:
  - High contrasts are reduced to match display capabilities.
  - Contrasts exceeding human visibility threshold are preserved.
- Model of locally adapted glare, color sensitivity, and acuity is included.

Greg Ward, Holly Rushmeier, and Christine Piatko

A Visibility Matching Tone Reproduction Operator for High Dynamic Range Scenes.

IEEE Transactions on Visualization and Comp. Graphics 1997

Ward-Larson et al. (2)



A false color image showing the world luminance values for a window office in candelas per meter squared (cd/m^2 or Nits).

Greg Ward

Ward-Larson et al. (3)

A linear mapping of the luminances that overexposes the view through the window.

Greg Ward

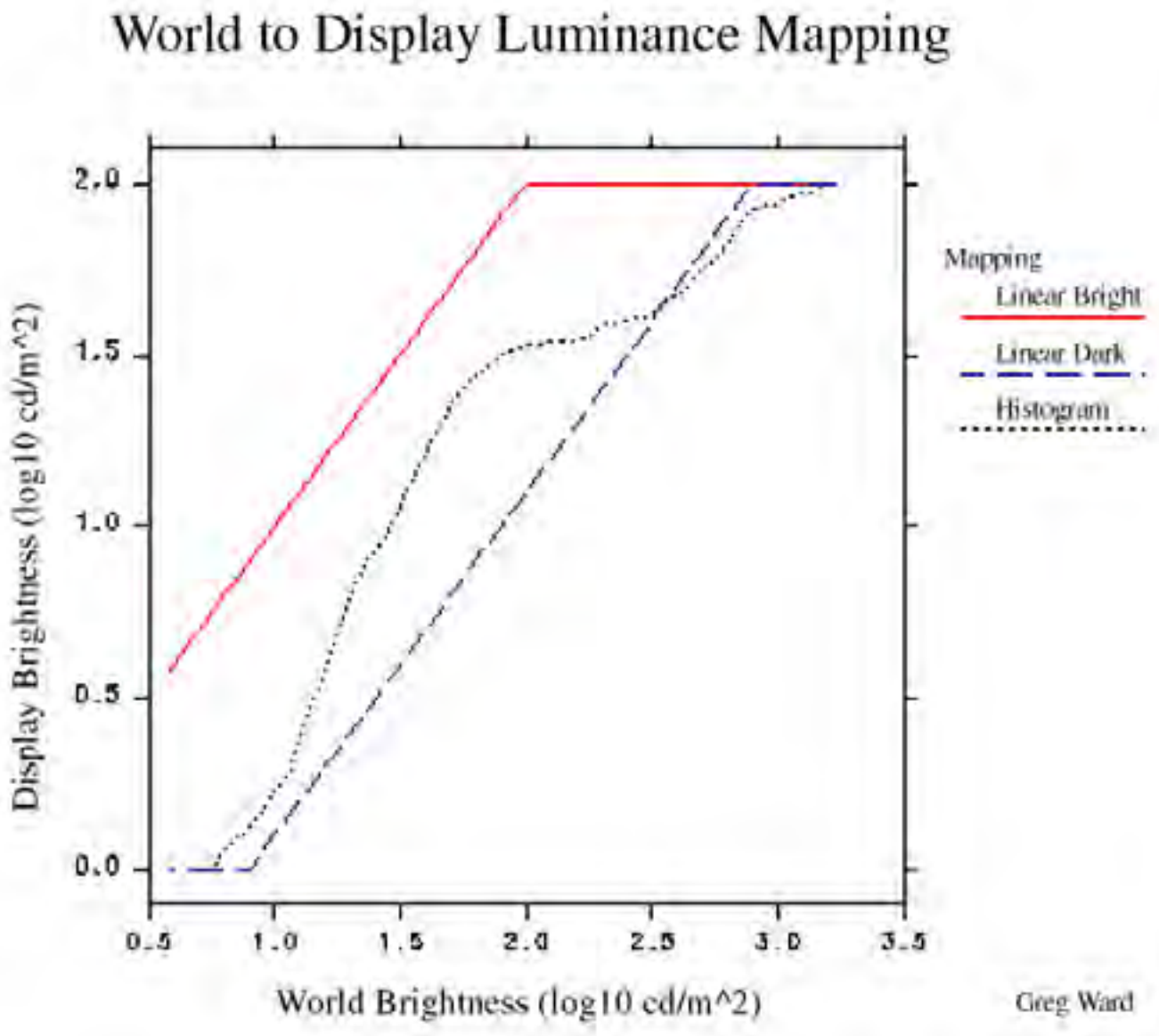
A linear mapping of the luminances that underexposes the view of the interior.

Greg Ward

The luminances mapped to preserve the visibility of both indoor and outdoor features.

Greg Ward Histogram adjustment

Ward-Larson et al. (4)

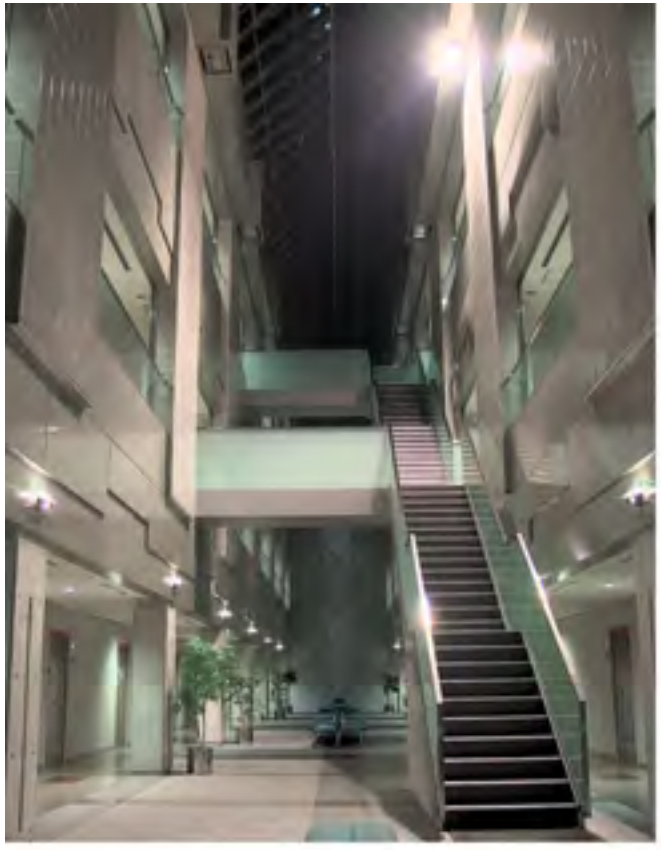


Ward-Larson et al. (5)

Histogram Adjustment Procedure

```
  procedure match_visibility()
1 - compute 1° foveal sample image
    compute veil image
    add veil to foveal adaptation image
    add veil to image
    blur image locally based on visual acuity function
    apply color sensitivity function to image
    generate histogram of effective adaptation image
2 - adjust histogram to contrast sensitivity function
3 - apply histogram adjustment to image
4 - translate CIE results to display RGB values
    end
```

Ward-Larson et al. (6)



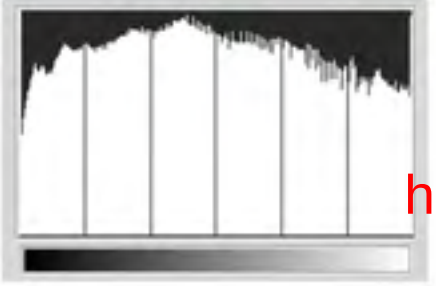
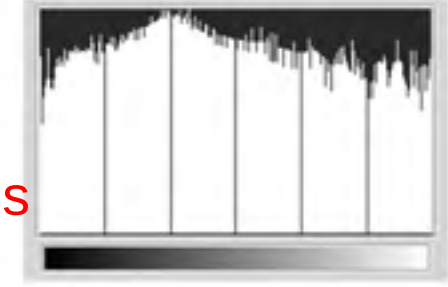
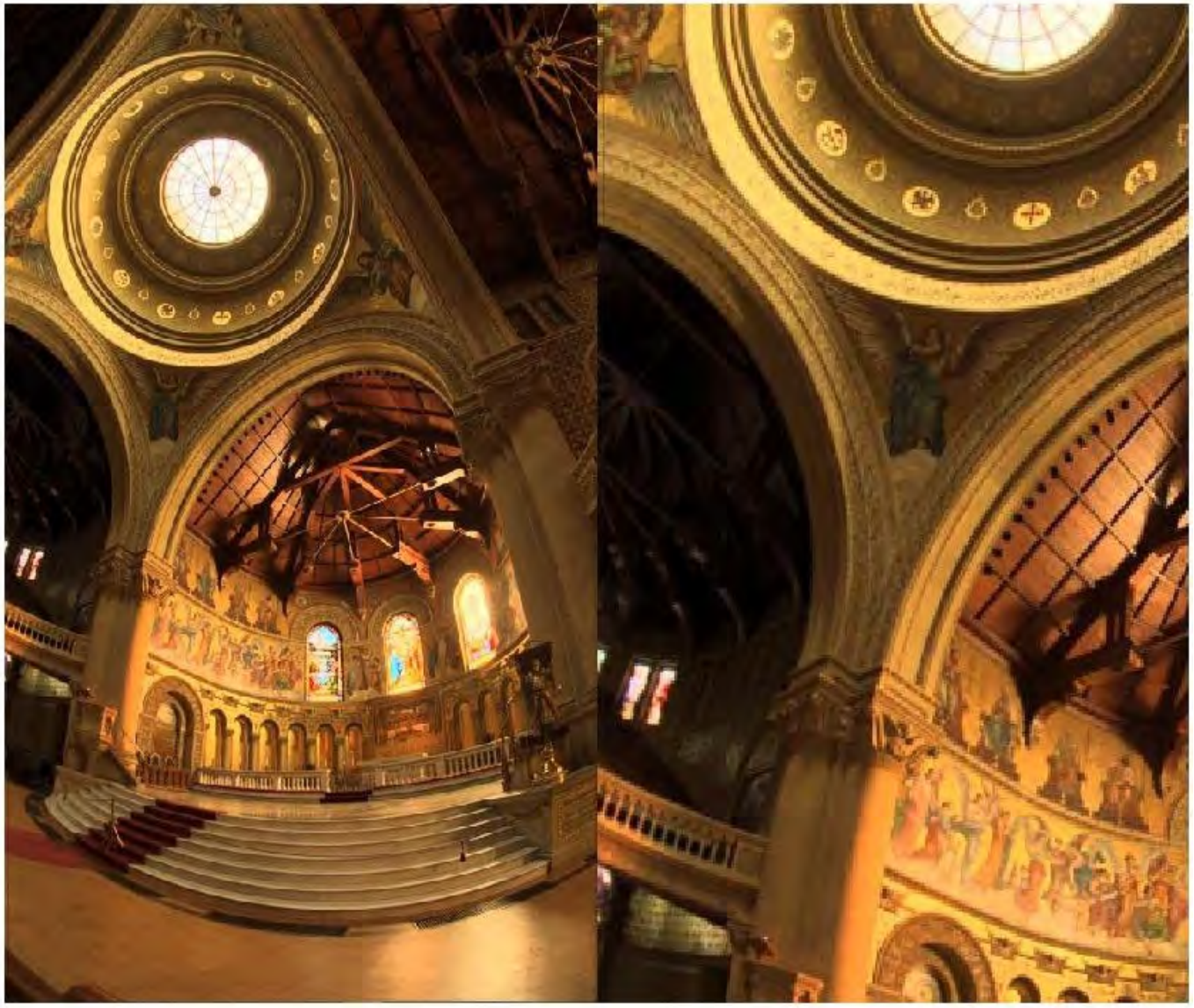


image histograms



Ward-Larson et al. (7)



Ward-Larson et al. (8) - Problems

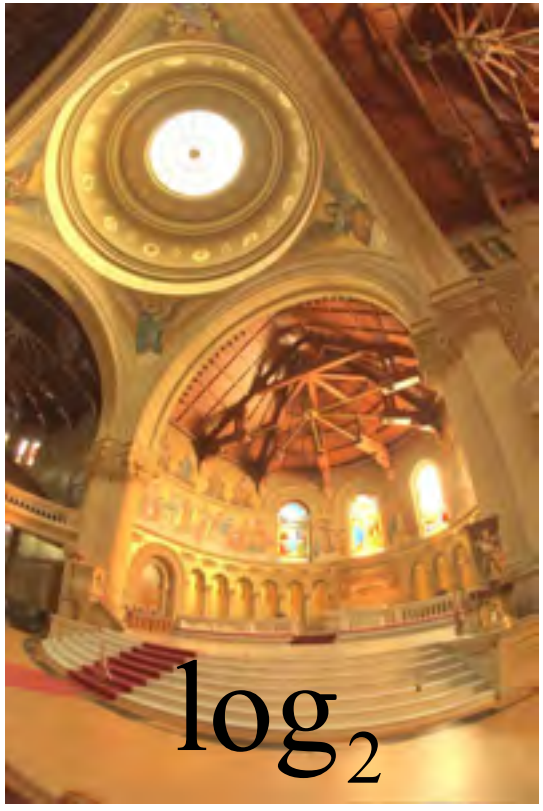
- **No position dependence – a pixel intensity is equally affected by the nearby and distant pixels.**
- **Monotonically increasing mapping from scene intensity to display intensity. Artists do not do that.**
- **Reducing contrasts of pixels belonging to sparsely populated region in the scene's histogram, and vice versa. As the result the small scene contrast can be displayed as much larger than the large scene contrasts.**

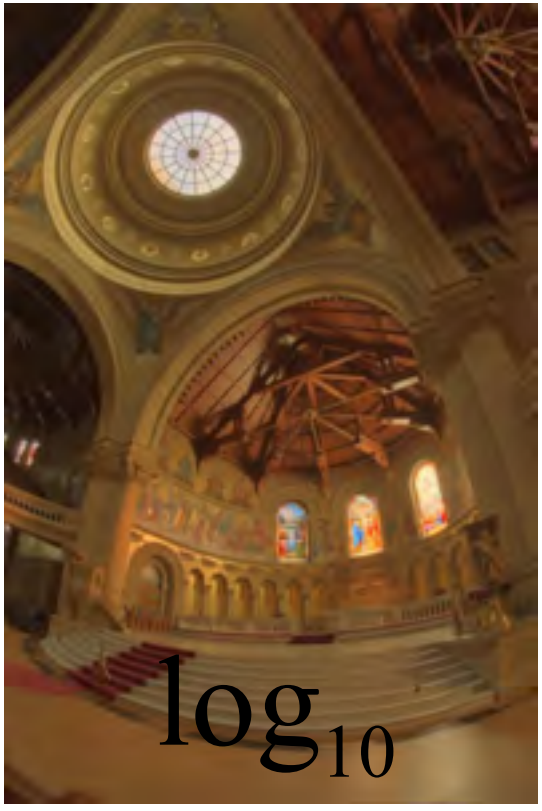
Ward-Larson et al. (9) –

Application Example

Estimating display and console devices visibility at the air traffic control tower.

Fixed Base Logarithm Mapping

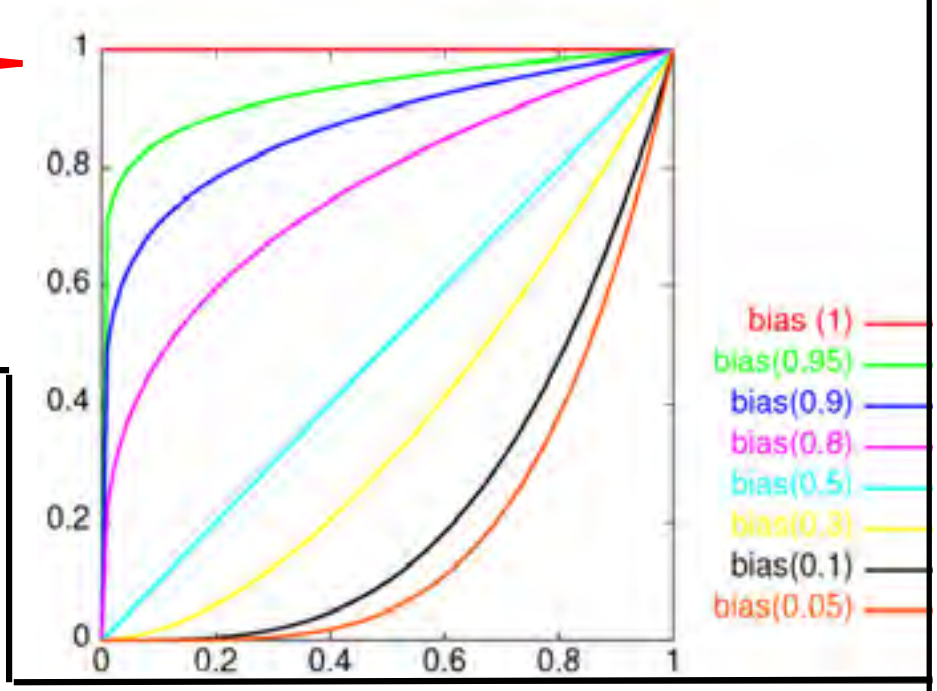




The contrast and brightness difference is evident, but none of these images provides a satisfying rendition.

Logmap Equation

$$\text{Bias function} \quad bias(x) = x^{\frac{\log a}{\log 0.5}}$$



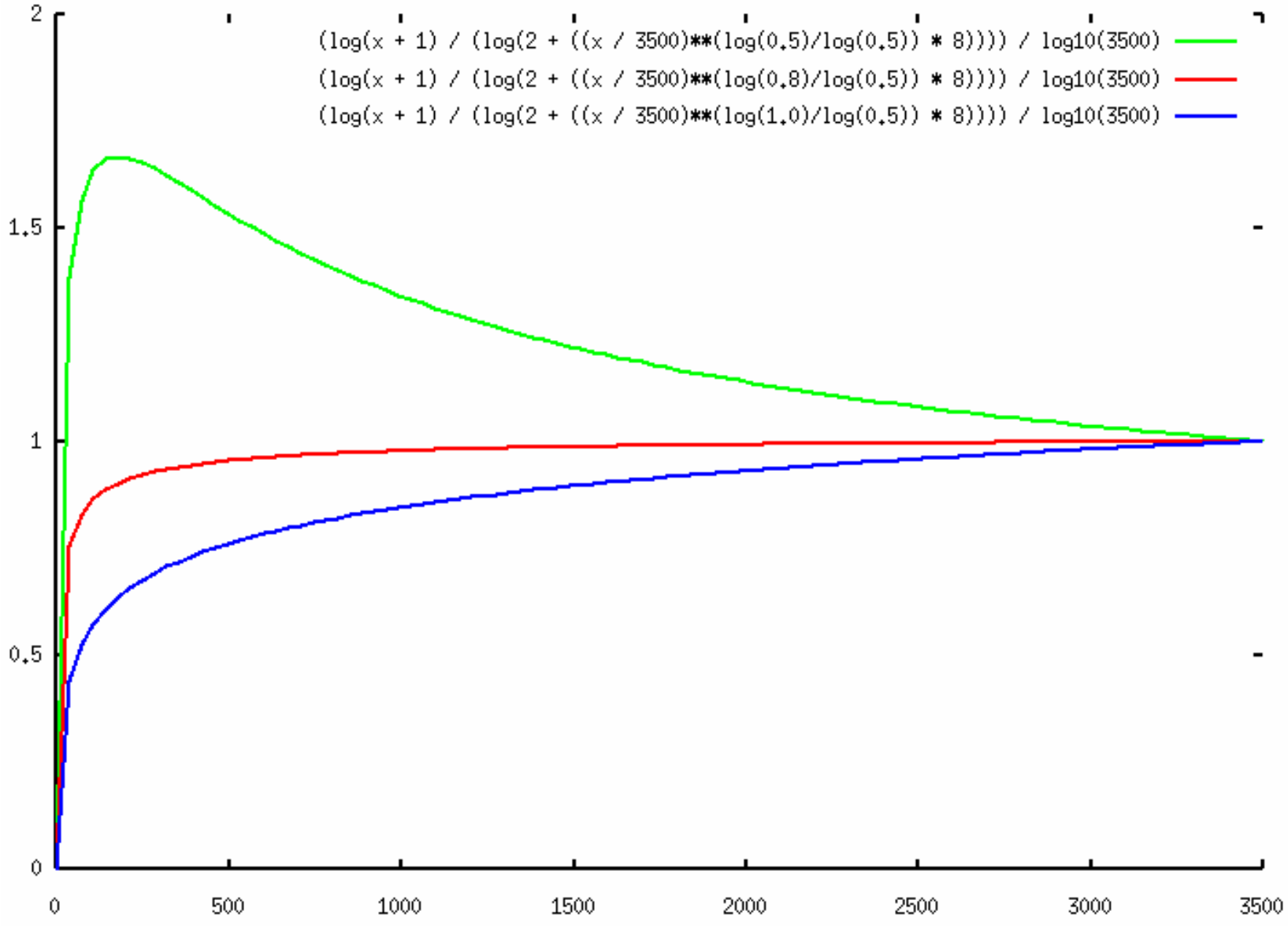
$$\text{Base change}: \ \log_{base}(x) = \frac{\log(x)}{\log(base)}$$

$$sceneLum = \frac{L_w}{L_{w\text{adapt}}} \qquad sceneMaxLum = \frac{L_{w\max}}{L_{w\text{adapt}}}$$

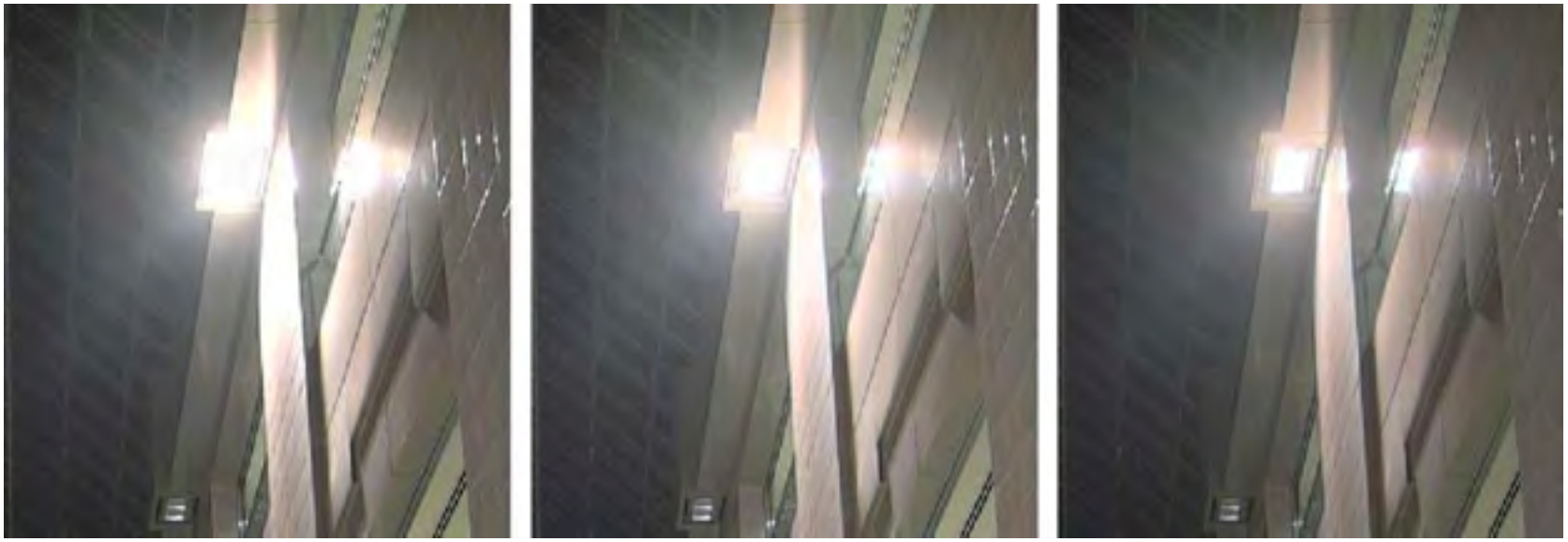
$$imageLum = \frac{L_{d\max}}{\log_{10}(sceneMaxLum+1)} \cdot \frac{\log(sceneLum+1)}{\log\left(2+8\cdot\boxed{\left(\frac{sceneLum}{sceneMaxLum}\right)^{\frac{\log(base)}{\log(0.5)}}}\right)}$$

Bias function

Logmap Equation



Close-up of a Light Source

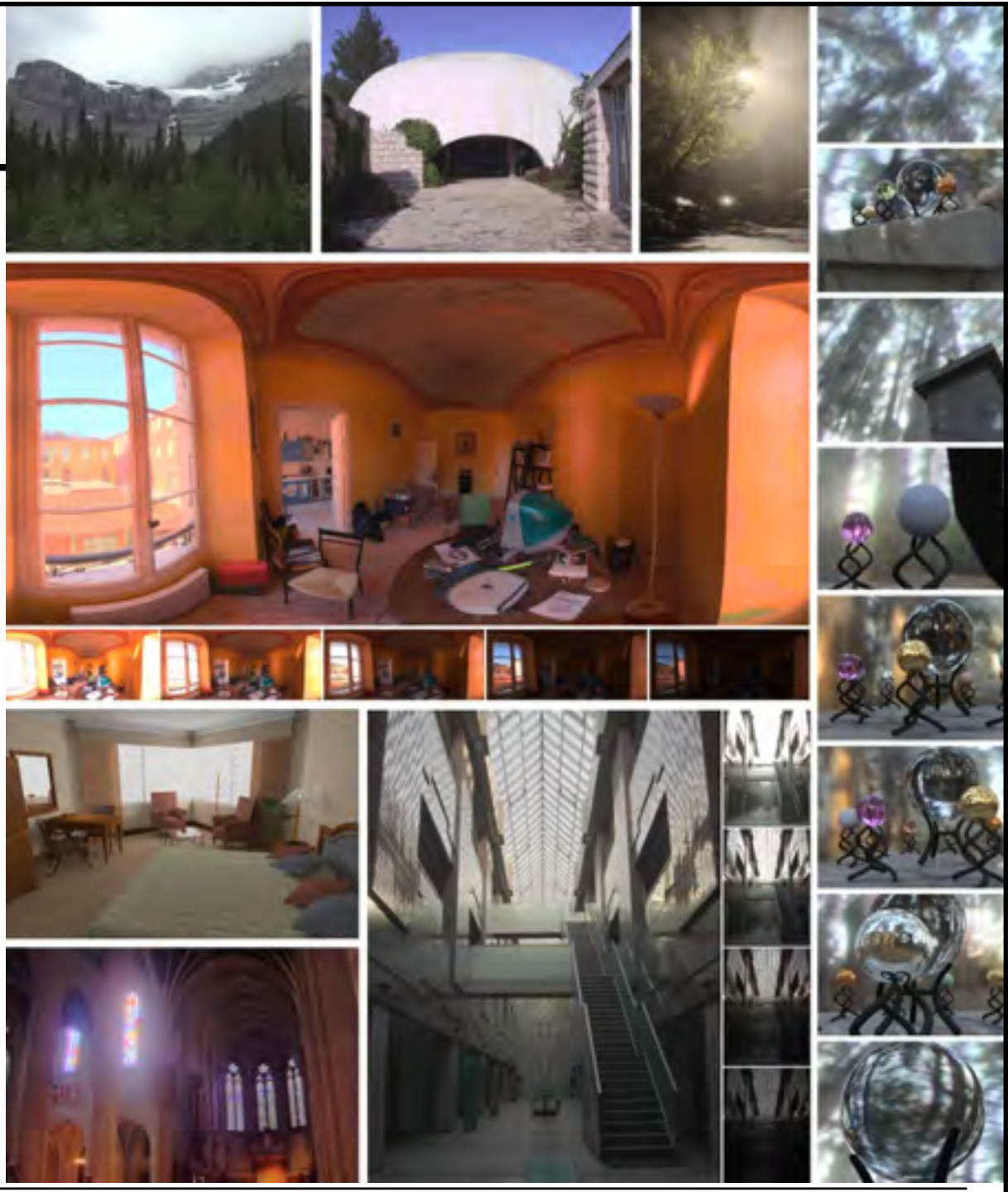


Bias = 0.5 Bias = 0.7 Bias = 0.9

- These images illustrate how high luminance values are clamped to the maximum displayable values using different bias parameter values.
- The scene dynamic range is 11,751,307:1.

Results:

Adaptive Logarithmic Mapping



Early Local Methods

Prone to halo artifacts

- **Local content dependent scaling function**
  - Shirley et al. (1993)
- **Rational polynomial function**
  - Schlick (1994)
- **Retinex**
  - Frankle and McCann (1983), Rahman, Jobson et al. (1996-97)
- **Multiscale model of adaptation and spatial vision**
  - Pattanaik et al. (1998)
  - **The most comprehensive model of Human Visual System (HVS) used in CG**

Shirley et al.

- General perceptual principles:
  - Adaptation is localized to a given image region
  - Luminance variations with relatively low spatial frequency are less perceivable than the higher frequency variations (image details).
- The apparent dynamic range of the display can be extended by introducing low frequency spatial variations in the scaling factor calculated from localized estimates of adaptation.

$$L_d(i,j) = \frac{L_w(i,j)}{kL_{blur}(i,j)}$$

L_{blurr} is obtained through low-pass filtration of the image.

The wider filter support the lower spatial frequency of the scaling factor for L_w.

Shirley et al.

– Note the halo effect (dark band) in the proximity of bright regions (light sources) and edges of high contrast.

Schlick

- **Global operator aimed at rendering realistic looking images in every lighting conditions.**
  - Rational rather than logarithmic tone reproduction which is applied uniformly to all pixels:

$$n = \frac{p \cdot L}{p \cdot L - L + L_{max}}$$

  - Photometric measurements of the display device are not required.
    - Only three parameters needed: highest and lowest luminance, and just noticeable difference (JND).
  - The function preserves contrasts for dark image regions and asymptotically compresses image highlights that clipping on the display can be avoided.

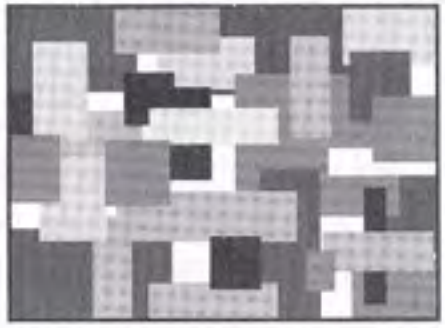
Schlick. Photorealistic Rendering Techniques. Eurographics 94

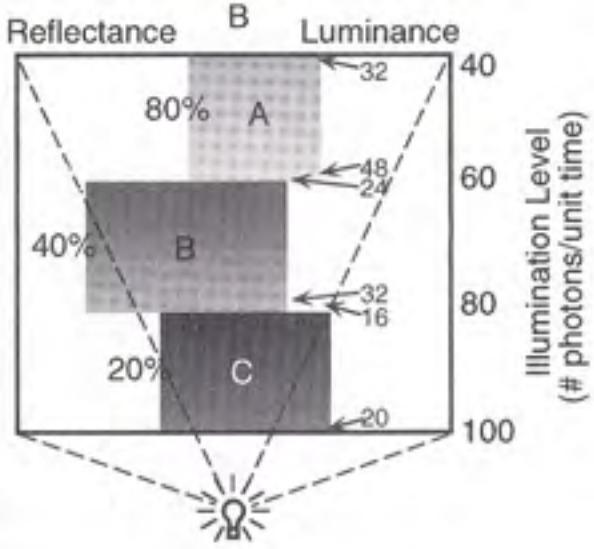
Schlick

Retinex

- **Process the human sensory response to lightness**
- **Maximize the range of luminance**
- **Solve the color constancy problem**
- **Algorithm: ratio-product-reset-average iteration following a square spiral path**

- **Black-white Mondrian under linearly changed illumination**





$$\frac{48}{24} \times \frac{32}{16} = \frac{1536}{384} = \frac{4}{1}$$

Luminance Edge Calculation of A to C

Jonathan Frankle, John McCann

Method and Apparatus for Lightness Imaging. 1983

Retinex

Frankle-McCann Retinex algorithm

- **Ratio-product-reset-average iteration**
  - ***NP(x,y)*** new pixel value is obtained from the original image ***R(x,y)*** and previous iteration image ***OP(x,y)*** as follows:

$$\log NP(x,y) = \frac{(\log OP(xs,ys) + \log R(x,y) - \log R(xs,ys)) + \log OP(x,y)}{2}$$

  - Reset test $\log L = \log OP(xs,ys) + \log R(x,y) - \log R(xs,ys)$

$$\text{if } (\log L > \log L_{\max}^{scene}) \quad \text{then} \quad L = L_{\max}^{scene}$$

  - In the first iteration $OP(xs,ys) = L_{\max}^{scene}$
- **In each iteration (the number of iterations predefined by the user)**
  - the distance D between pixels (x,y) and (xs,ys) is halved
  - the direction for pixel comparison is rotated 90° clockwise
- **Main problem: Suppressing halo effects**

Retinex

Retinex variation of the Stanford Memorial church.

The three color channels were computed separately.

Modern Local Methods

Spatially non-uniform tone reproduction operators:

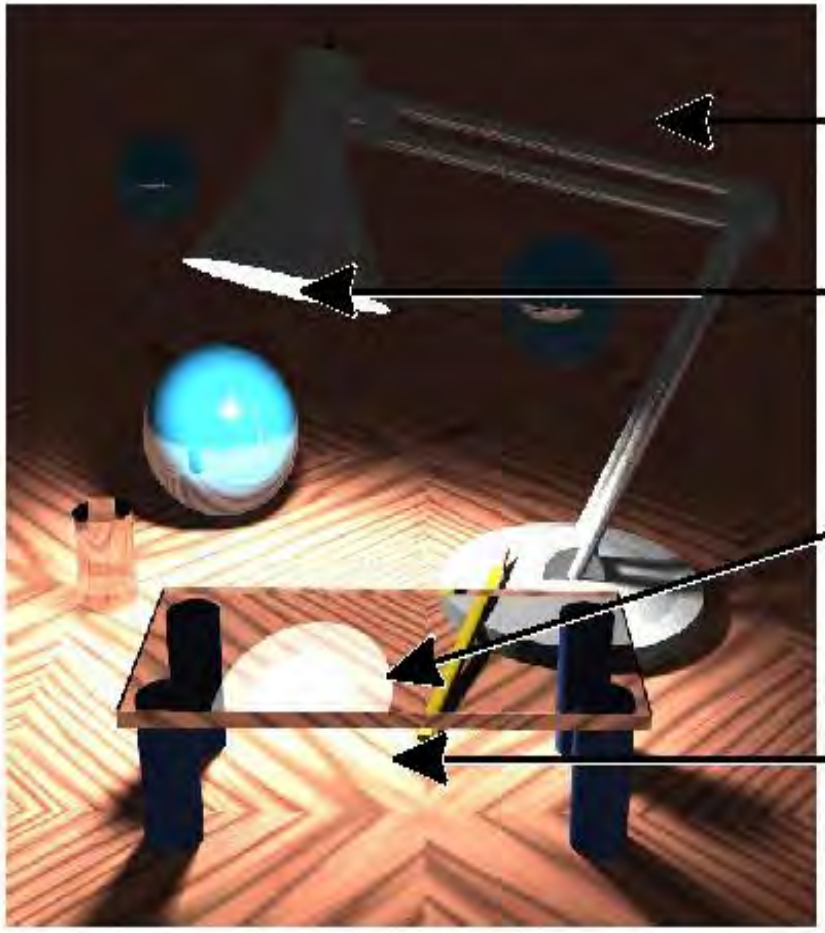
- **Layering Method, Foveal Method, and LCIS**
  - Tumblin (1999)
- **Bilateral Filtering, Trilateral Filtering**
  - Durnad & Dorsey (2002), ? & Tumblin (2003)
- **Gradient Domain HDR Compression**
  - Fattal et al. (2002)
- **Photographic Tone Reproduction**
  - Reinhard et al. (2002)
  - A spatially uniform variation: Photoreceptor Inspired Tone Mapping
    - Reinhard & Devlin (2004)
- **Time-Dependent Visual Adaptation**
  - Pattanaik et al. (2000)

Tumblin – Layering Method (1)

- Human Visual System supposedly constructs separate but simultaneous mental images of scene properties at once.
- Sensitivity to scene reflectance (refer to the lightness constancy property) is much higher than scene illumination.
- Separation of the input scene into the large features (illumination) and small details (reflectance).
  - Compression is performed only for large features of the scene.

Tumblin – Layering Method (2)

- Example scene



Deep shadow:
0.4 cd/m^2 –>(50, 30, 23)

Lightbulb:
175,000 cd/m^2 –>(255, 255, 255)

Shroud reflection:
40,000 cd/m^2 –>(240, 240, 240)

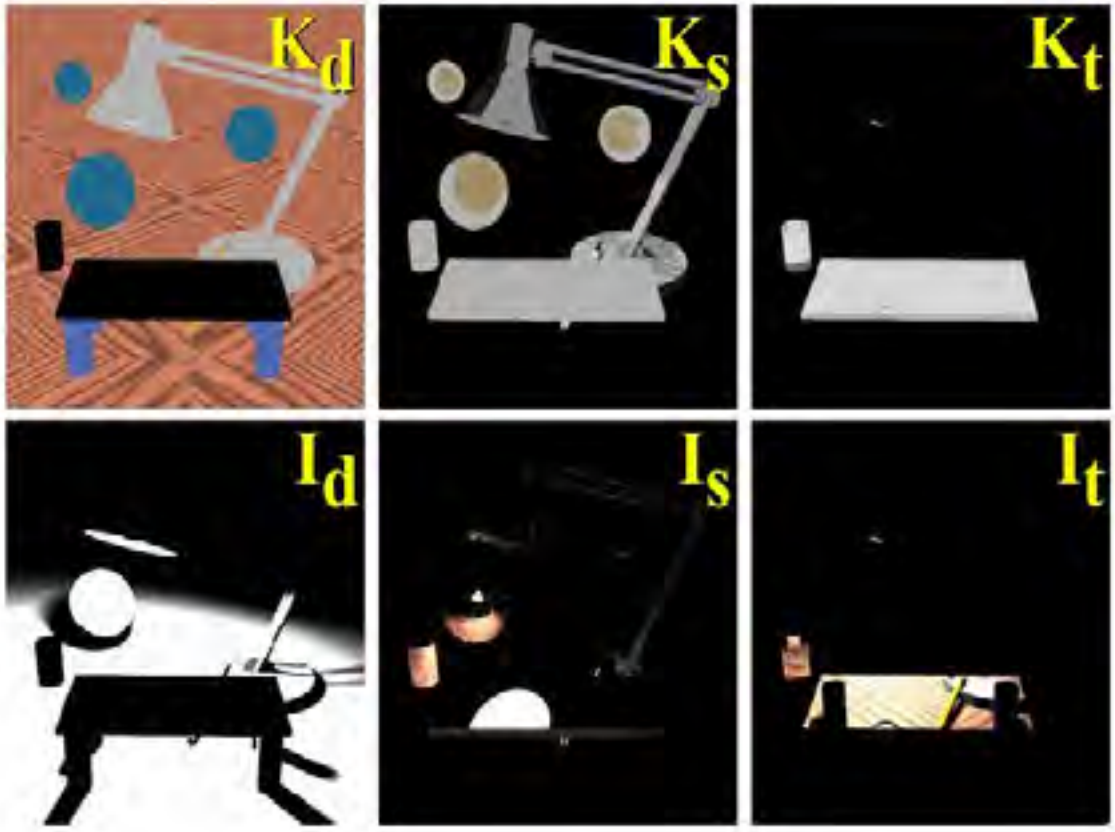
Bright wood:
1,600 cd/m^2 –>(250, 199, 154)

Jack Tumblin, Ph.D. thesis

Tumblin – Layering Method (3)

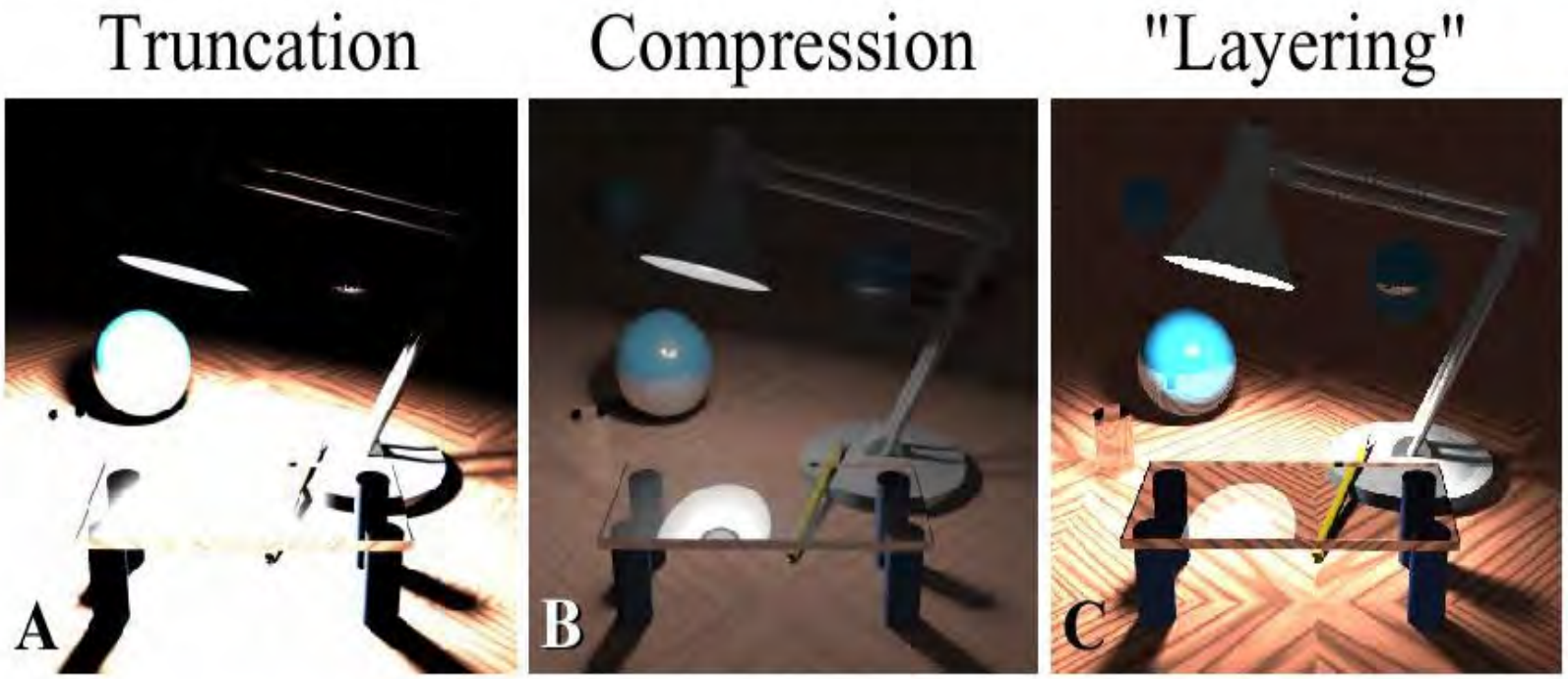
- **Layer separations:**

$$Scene(x,y) = K_d(x,y)I_d(x,y) + K_s(x,y)I_s(x,y) + K_t(x,y)I_t(x,y)$$



Jack Tumblin, Ph.D. thesis

Tumblin – Layering Method (4)



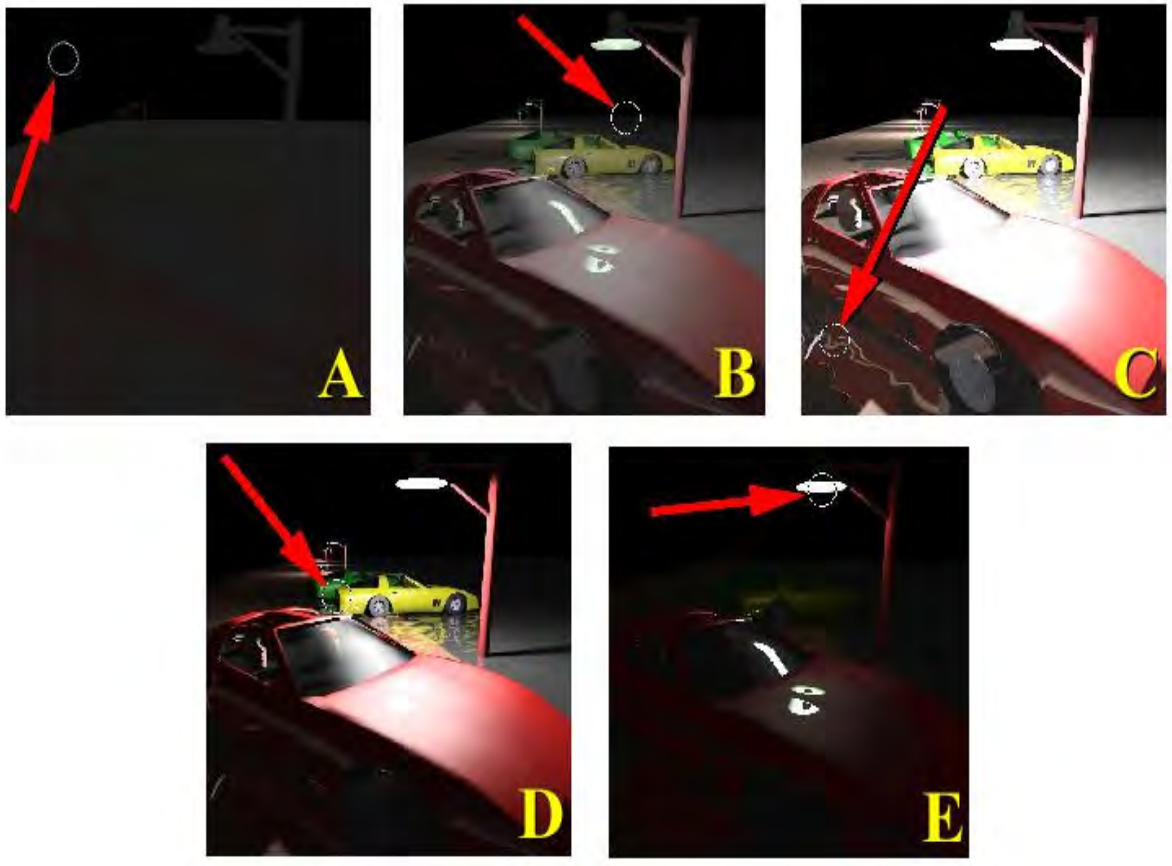
- **Algorithm**
  - Estimate adaptation for every layer
  - Separate compression of every illumination layer (S-shaped compressive function)
  - Combine all layers to form the displayed image

Layer separation is possible only for synthetic images

Jack Tumblin, Ph.D. thesis

Tumblin – Foveal Method (1)

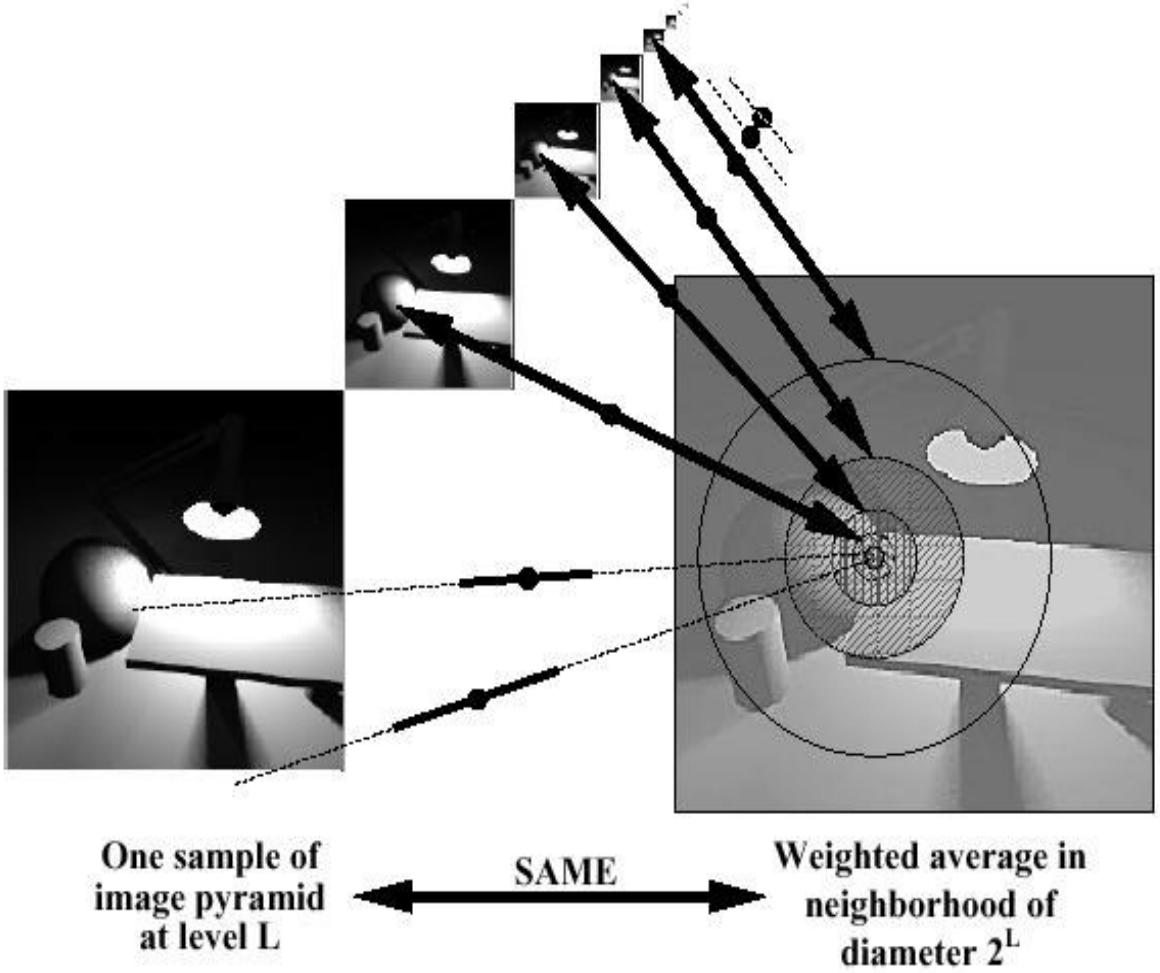
- **Interactive program to imitate adaptation in the user direction of gaze pointed on the image by the mouse click.**



Jack Tumblin, Ph.D. thesis

Tumblin – Foveal Method (2)

- **Image pyramid is used for fast computation of L_{wa} as a weighted sum of neighborhood pixel values.**



Jack Tumblin, Ph.D. thesis

Low Curvature Image Simplifier (1)

- Based on an anisotropic diffusion procedure
- Suitable both for synthetic and natural scenes
- Like the foveal and layering methods, LCIS performs separation of the input scene into the large features and small details, and compression is done only for large features of the scene.
  - Large features of a scene are defined as large, simple, low-curvature regions separated by sharp, ridge-like boundaries.
  - A diffusion-like process finds and sharpens major boundaries in the scene, and smoothes away the details between these boundaries.
  - Fine details are found as the difference between the original and its large features.

– **Result: emphasis on local details but excessive global contrast compression**

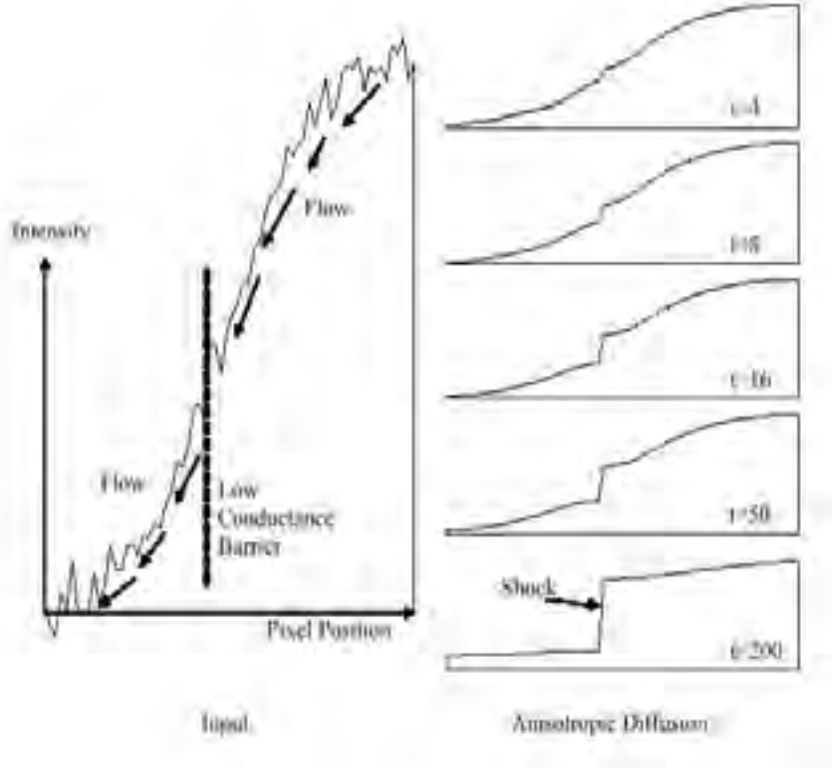
Low Curvature Image Simplifier (2)

- **Anisotropic diffusion method is used for boundary finding and intra-region smoothing method. Mathematically it is a gradual, time-dependent evolution of an image towards a piece-wise constant approximation.**

$$I_s^{t+1} = I_s^t + \frac{\lambda}{4} \sum_{p \in neighborhood_4(s)} g(I_p^t - I_s^t)(I_p^t - I_s^t)$$

edge stopping functions *g(x)*

$$g(x) = \frac{1}{1 + \frac{x^2}{\sigma^2}} \quad \text{or} \quad g(x) = e^{-\frac{x^2}{\sigma^2}}$$

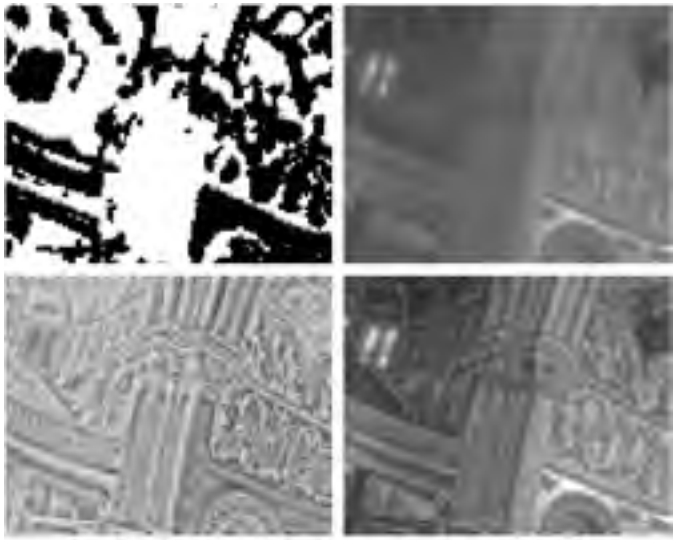


Low Curvature Image Simplifier (3)

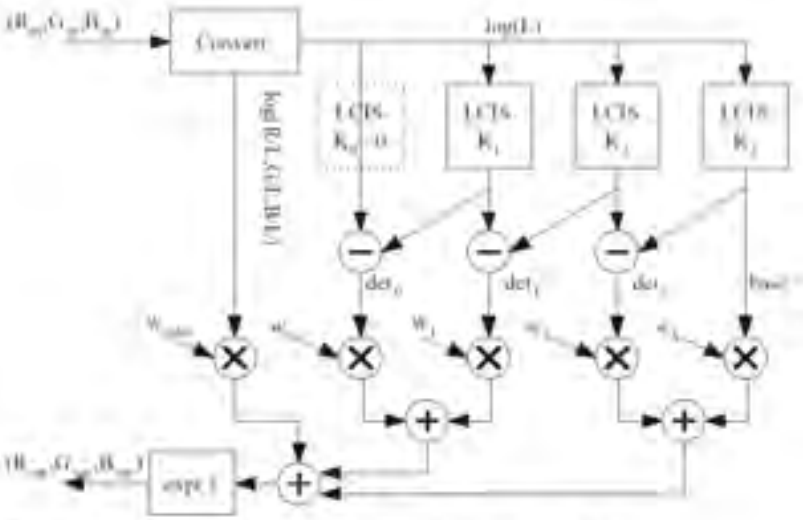
Jack Tumblin, Greg Turk

LCIS: A boundary hierarchy for detail-preserving contrast reduction. SIGGRAPH 99

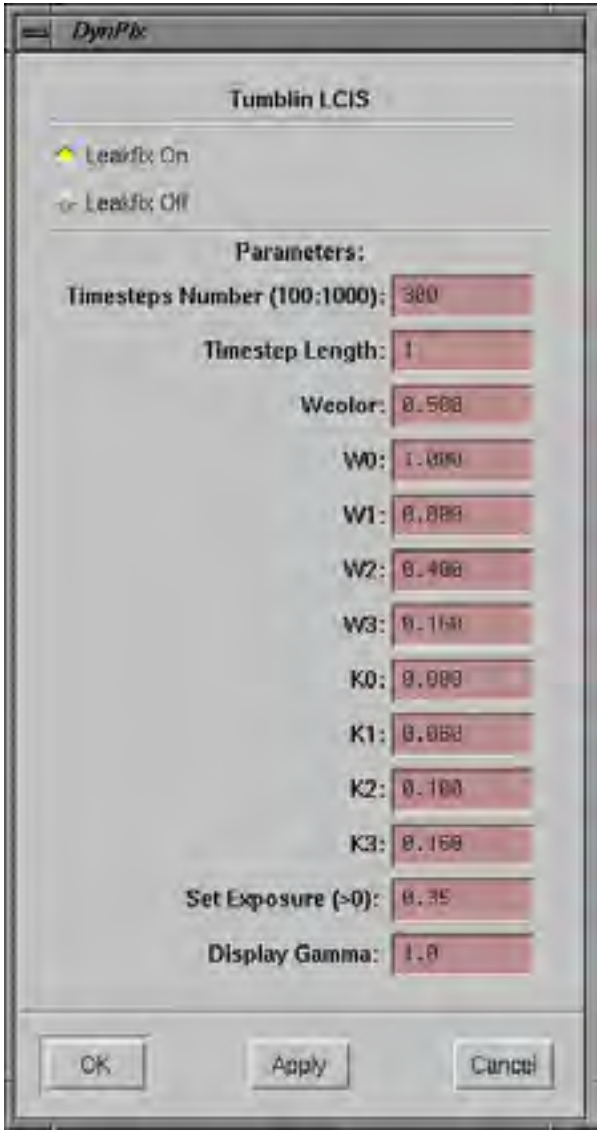
Low Curvature Image Simplifier (4)



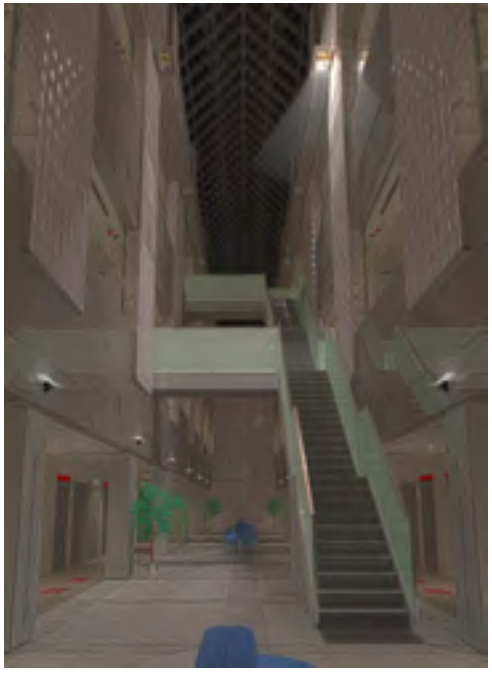
Images from an LCIS hierarchy reveal its methods

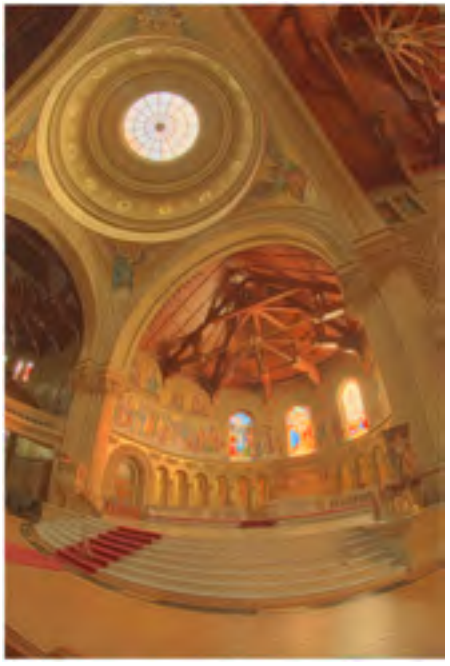


Detail-preserving contrast reduction method using an LCIS hierarchy



Low Curvature Image Simplifier (5)





Low Curvature Image Simplifier (6)

Gamma Compression Results

Bilateral Filtering of HDR Images

Local operator (spatially variant)

Idea:

1. **Decouple image into two layers**
   - **base** – high dynamic range illumination layer
   - **detail** – low dynamic range texture layer
2. **Compress base layer and combine with detail layer**

Durand et al. – “Fast Bilateral Filtering for the Display of High Dynamic Range Images”, SIGGRAPH 2002 Conference Proceedings

Decomposition: Base & Detail Layers

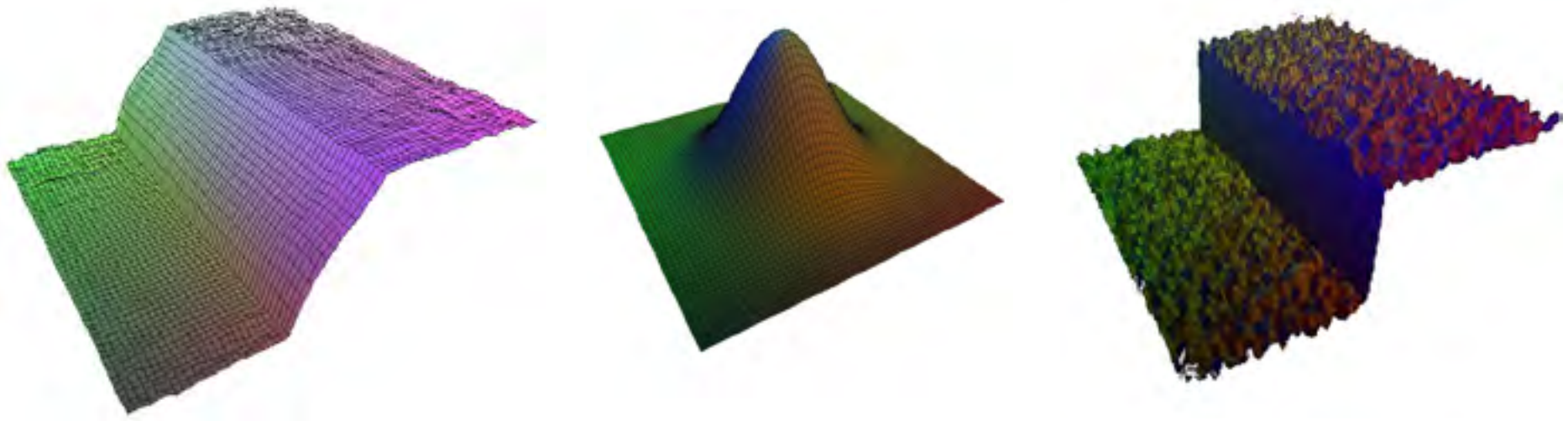
Base

Detail

Gaussian Filtering

Proposed by Chiu at al. 1993

Blurring across the edges results in halo artifacts.

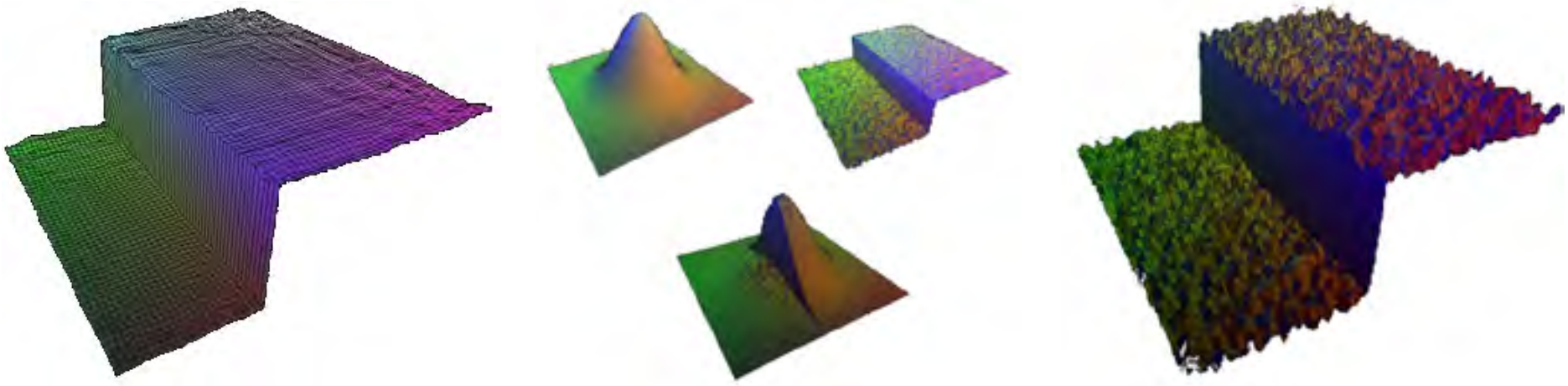


$$J = f \otimes I$$

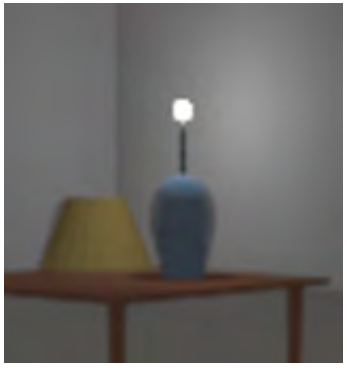
f spatial kernel with large σ_s

Bilateral Filtering

Edge preserving filter – no halo artifacts.



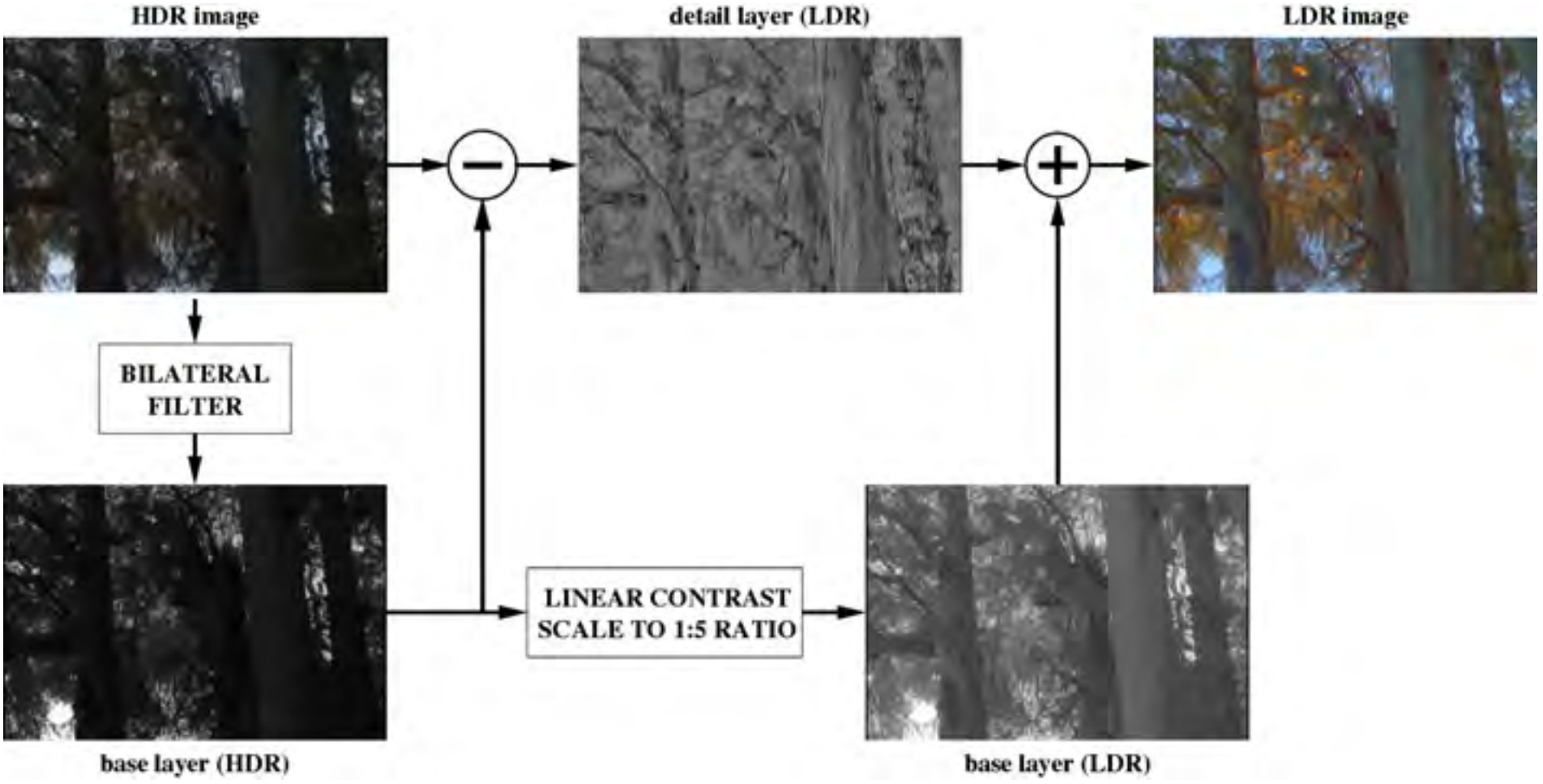
$$J = (f \times g) \otimes I$$



f spatial kernel with large σ_s

g range kernel with very small σ_r

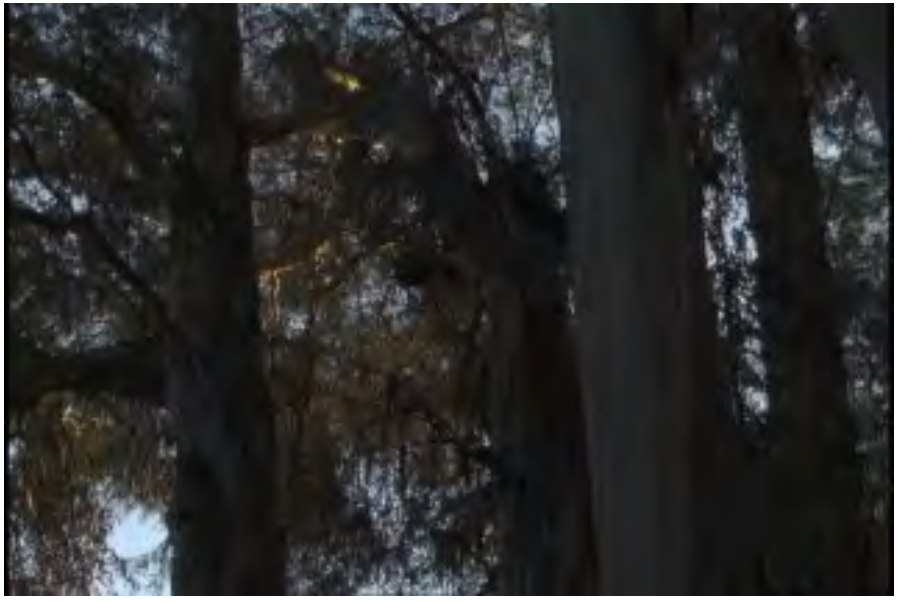
Bilateral Filtering – Tone Mapping



Luminance calculations in log-space (brightness approximation)

Bilateral Filtering – Results

normalization



bilateral filtering

Good contrast compression with well preserved details

Bilateral Filtering – Improvements

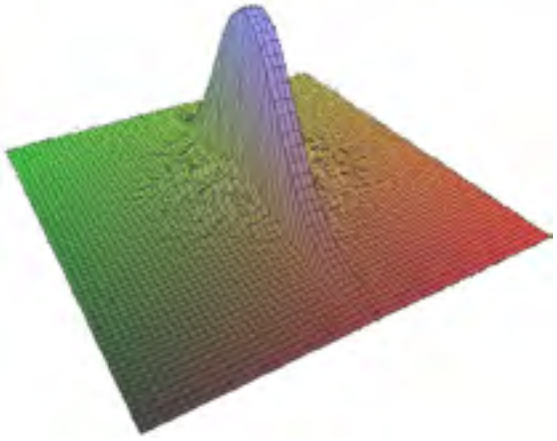
1. **Speed-up**

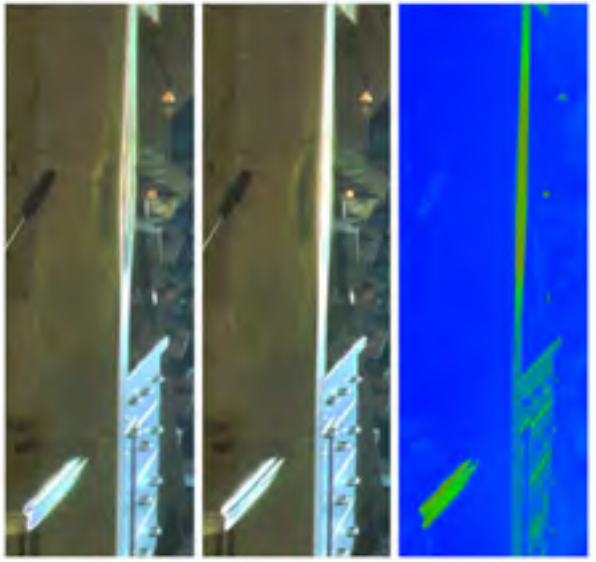
   Piecewise-linear bilateral filtering

2. **Uncertainity correction**

   Not enough similar pixels to decouple large-scale and small-scale features – halo artifacts at specular highlights.

   Solution: interpolation between HDR & LDR image.

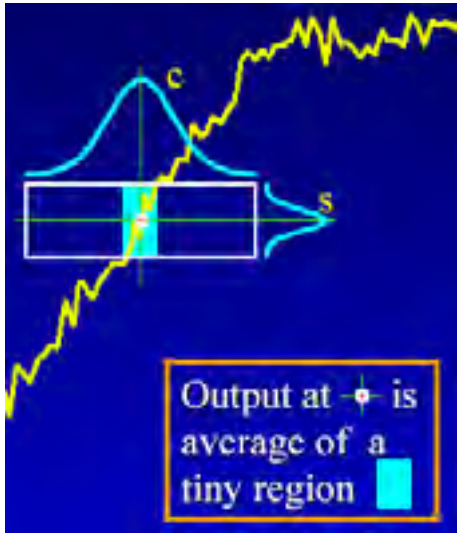


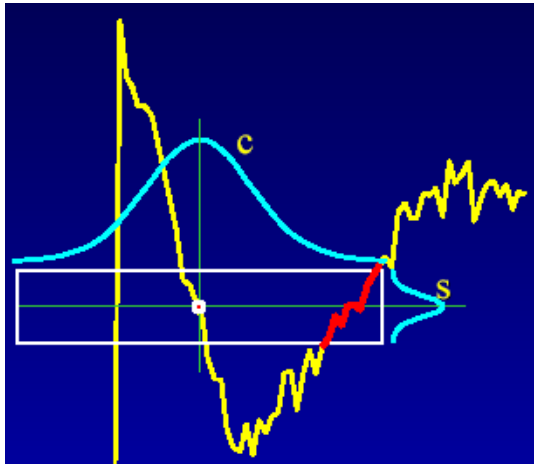


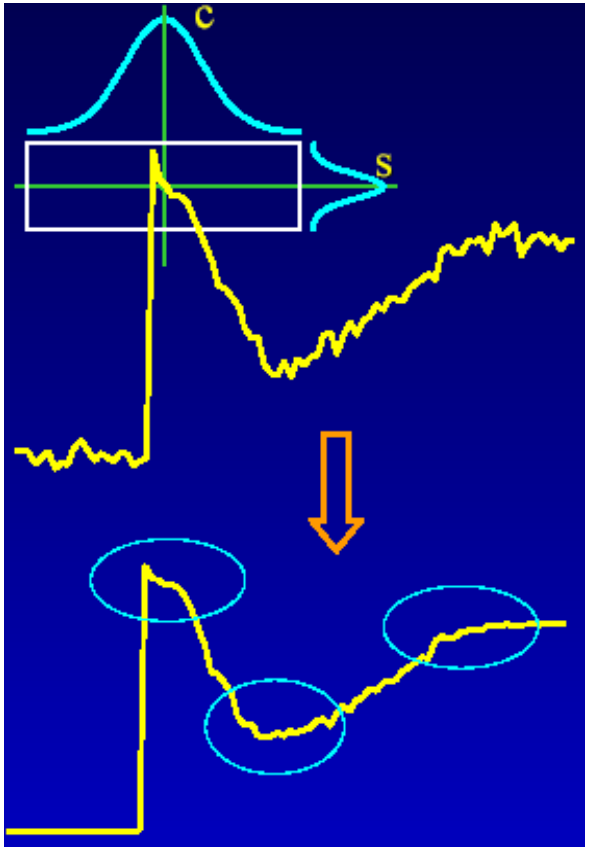
without with uncertainty fix uncertainty

Bilateral Filtering – Weak Aspects

1. **Poor smoothing in high gradient regions**
2. **Blends together disjoint regions**
3. **Smoothes and blunts cliffs, valleys & ridges**







Trilateral Filtering

1. **<u>Tilt</u> the filter window**

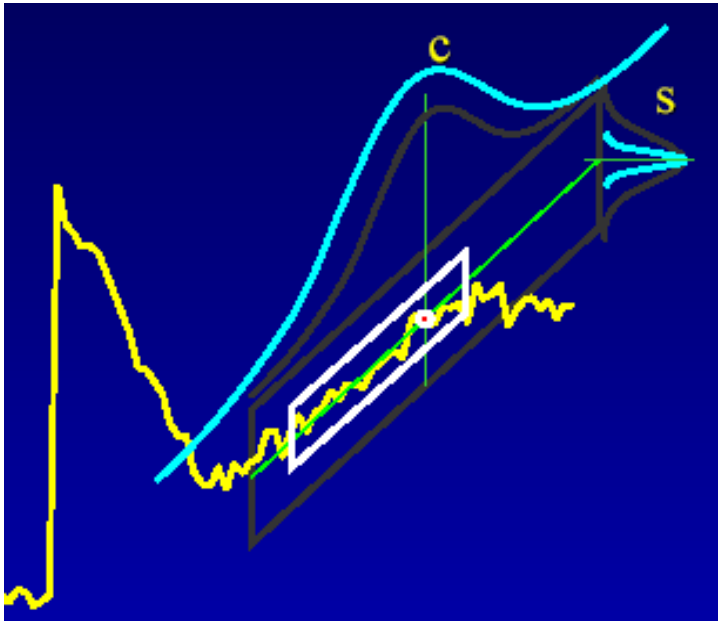
   according to bilaterally smoothed gradients

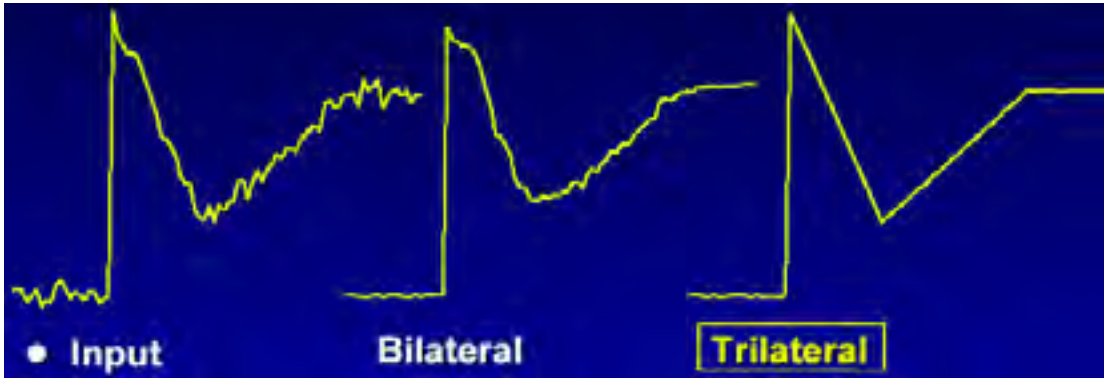
2. **<u>Limit</u> the filter window**

   to connected regions of similar smoothed gradients

3. **<u>Adjust</u> parameters**

   From measurements of the windowed signal





Tumblin et al. – “The Trilateral Filter for High Contrast Images and Meshes”, Eurographics Symposium on Rendering 2003

Gradient Domain HDR Compression

Local operator (spatially variant)

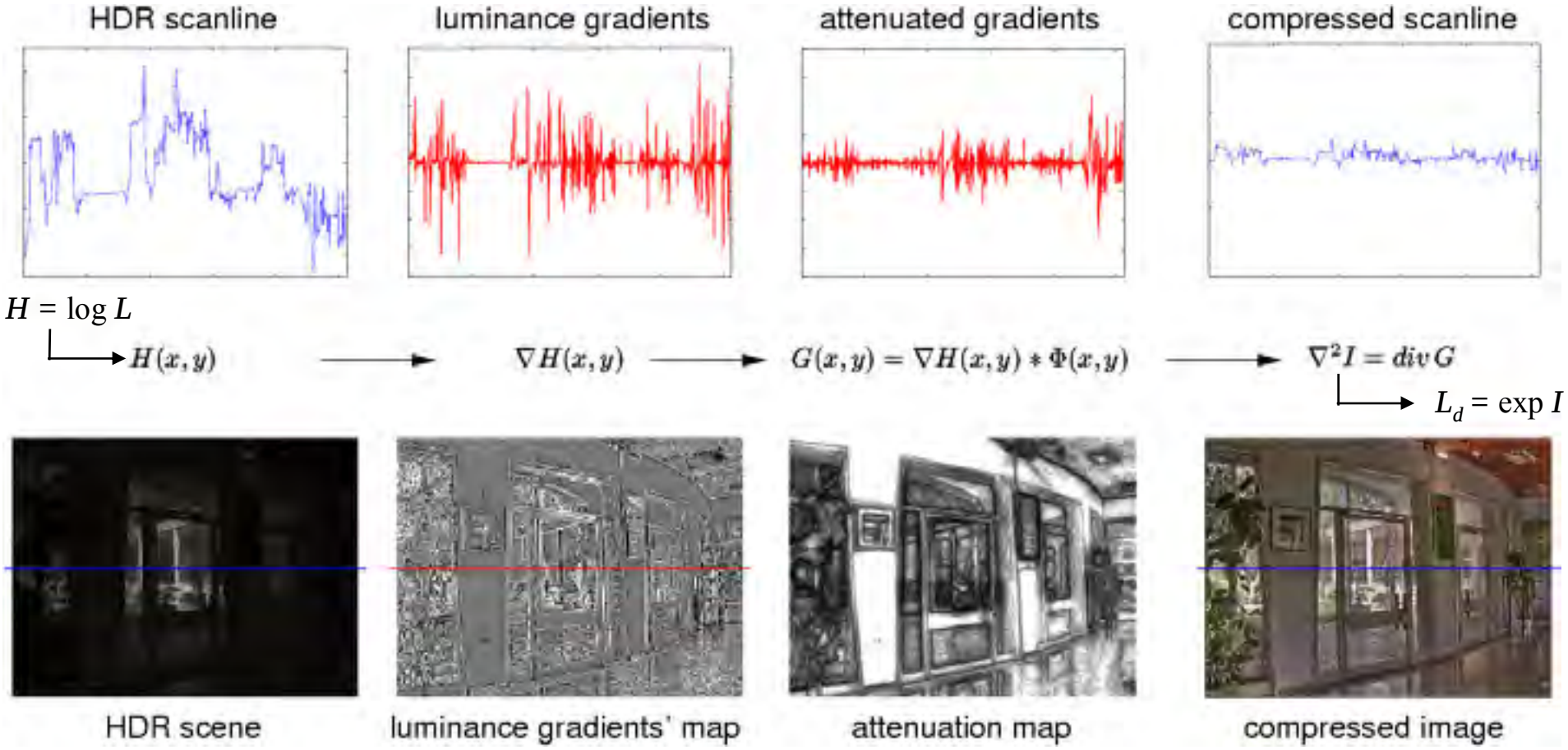
Idea:

1. **Identify large gradients of luminance at different scales**
2. **Attenuate gradients, penalizing larger gradients more than smaller ones**

Thus reduce high dynamic range by compressing drastic luminance changes, while preserving fine details.

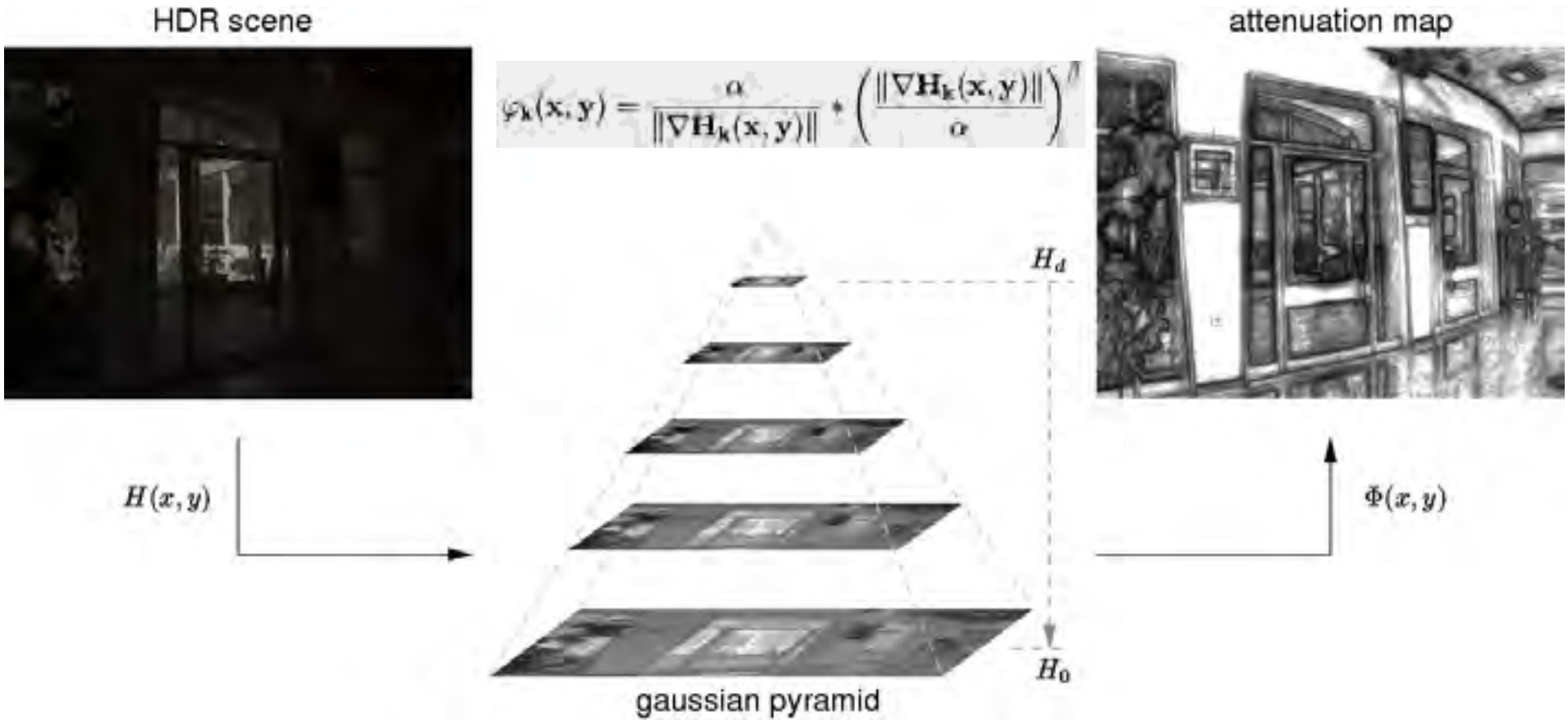
Fattal et al. – “Gradient Domain High Dynamic Range Compression” SIGGRAPH 2002 Conference Proceedings

Gradient Compression Algorithm



1. **Take logarithm for each pixel**
2. **Calculate gradients map of image**
3. **Calculate attenuation map**
4. **Attenuate gradients**
5. **Solve Poisson equation to recover image**
6. **Exponentiate**

Attenuation Map



1. **Create Gaussian pyramid**
2. **Locate gradients on levels**
3. **Calculate attenuation on levels - φ_k**
4. **Propagate levels to full resolution**

Gradient Integration Problem

1. **Boundary conditions**

   Neumann boundary condition – the derivative in direction normal to the boundary is zero

$$\nabla I \cdot \mathrm{n} = 0$$

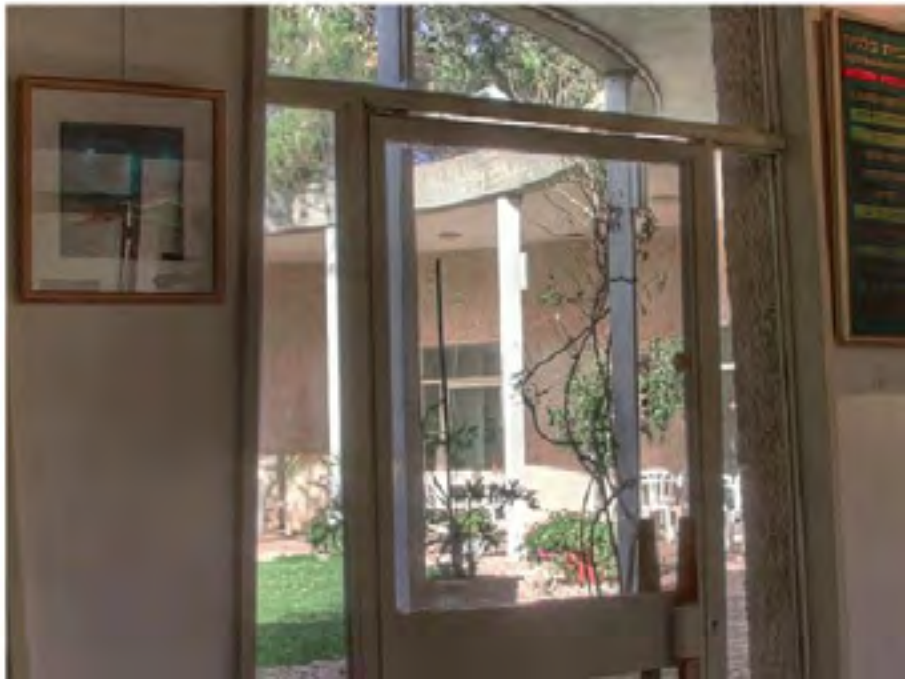
   Implementation: repeat the pixels on the edges of an image

2. **Integration of gradients**
   - Approximation of gradients with linear differences
   - Iterative methods solving a set of sparse linear equations
   - Various algorithms with different stability and efficiency
   - Suggested method – **full-multigrid algorithm**

Global vs. Local Compression

Adaptive Logarithmic Mapping

Gradient Domain Compression



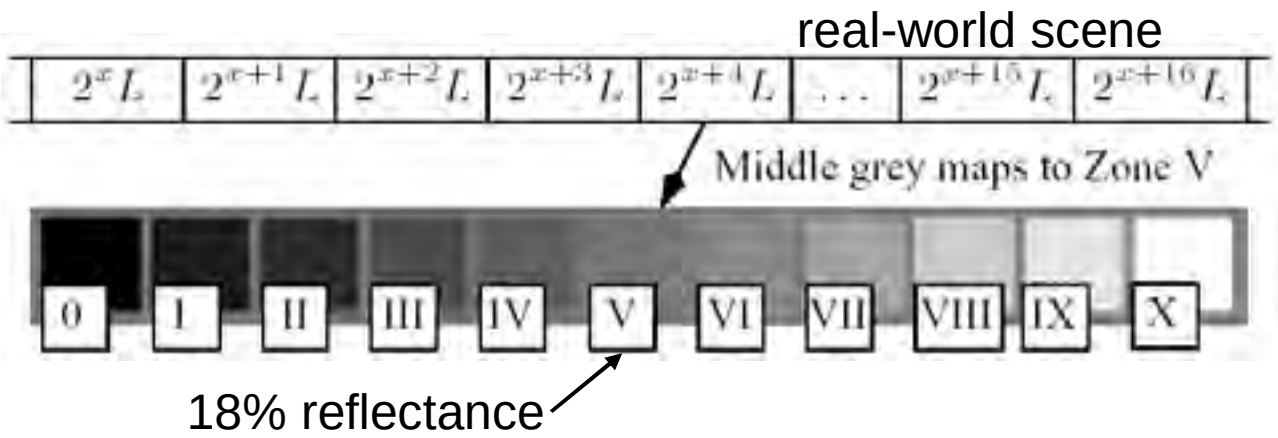
- **Loss of overall contrast**
- **Loss of texture details**
- **Short execution time**
- **Simple hardware implementation**

- **Impression of high contrast**
- **Good preservation of fine details**
- **Solving Poisson equation takes time**
- **Complicated hardware implementation**

Photographic Tone Reproduction

Local operator (spatially variant)

1. **Print zones**



2. **Key values**

3. **Dodging & burning technique**

Reinhard et al. – “Photographic Tone Reproduction for Digital Images” Proceedings of SIGGRAPH 2002

Tone Reproduction Algorithm

Algorithm:

1. **Initial luminance mapping (global normalization)**

$$L(x,y) = \frac{aL_w(x,y)}{\overline{L}_w(x,y)} \qquad L_d(x,y) = \frac{L(x,y)}{1+L(x,y)}$$

2. **For every pixel, find size of local adaptation zone using center surround function**

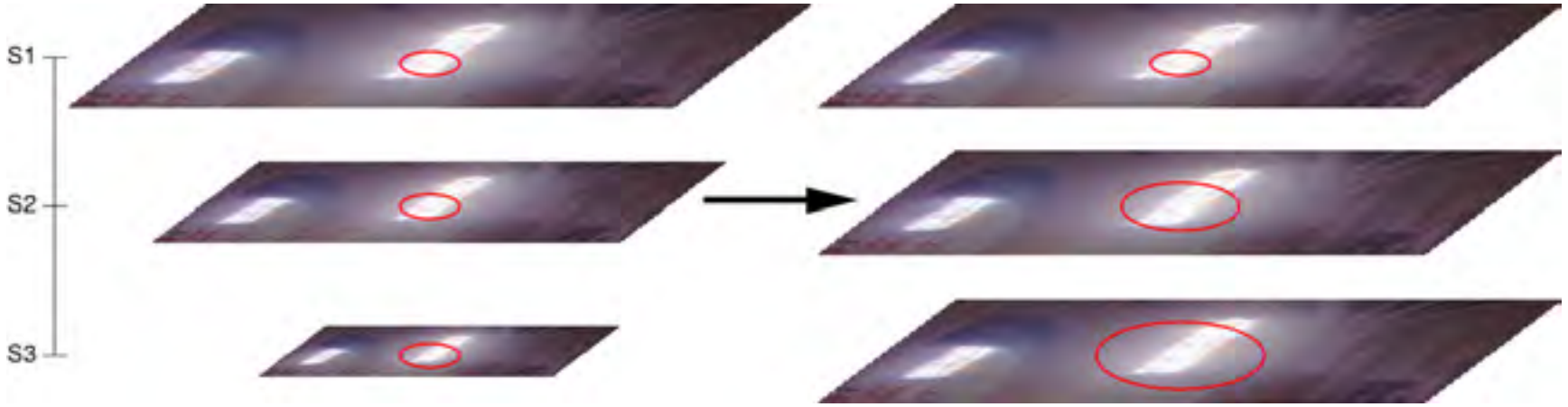
3. **Luminance mapped with sigmoid response function according to local adaptation value**

$$L_d(x,y) = \frac{L(x,y)}{1+V(x,y,s_m(x,y))}$$

Pyramid of Local Adaptation Zones

Gaussian Pyramid - set of images, each level is half a resolution of a previous level, down-sampled using Gaussian kernel.

Local Adaptation Zone doubles its area at each lower level of pyramid.



$V(x,y,s_m)$ centre surround function for pixel (x,y) at given local adaptation zone s_m

Automatic Dodging & Burning

1. Local adaptation zones

for every pixel, find the largest zone scale s_m, which does not cause high variation of local luminance *V* between scales

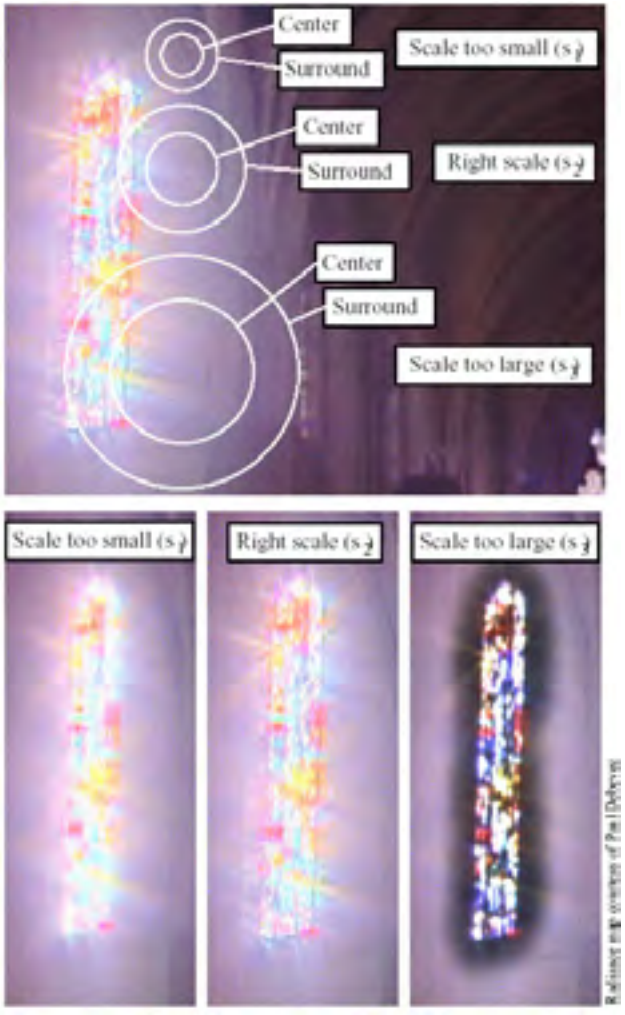
$$\|V(x,y,s_m) - V(x,y,s_{m-1})\| < \epsilon$$

2. Display luminance function

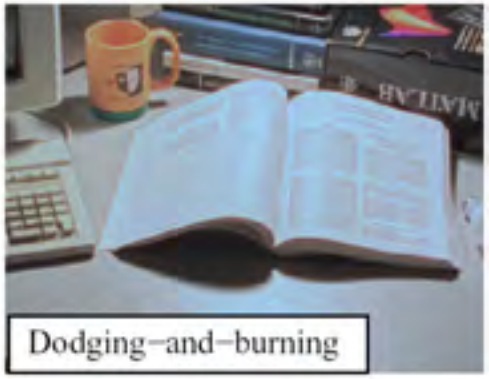
$$L_d(x,y) = \frac{L(x,y)}{1 + V(x,y,s_m(x,y))}$$

dodge luminance of pixels in bright regions is significantly decreased

burn pixels in dark regions are compressed less, so their relative intensity increases



Tone Reproduction Results



Automatic dodging-and-burning technique is more effective in preserving local details (notice the print in the book).

Photoreceptor Inspired Tone Mapping

Global operator (spatially invariant)

Idea:

1. **Sigmoid response function**

$$V = \frac{I}{I + \sigma(I_a)} V_{\max} \qquad \sigma(I_a) = (f\, I_a)^m$$

2. **Adaptation to single pixels**

$$I_a(x, y) = I(x, y)$$

3. **Chromatic adaptation (von Kries model)**

   Algorithm operates separately on RGB intensities and not luminance values.

Reinhard et al. – “Dynamic Range Reduction inspired by Photoreceptor Physiology”, IEEE TVCG 2004

Photoreceptor – Results

logarithmic mapping

photoreceptor inspired mapping

- **Details of stained glass are well depicted.**
- **Colors in the image are not oversaturated due to von Kries chromatic adaptation.**

Time-Dependent Visual Adaptation

Global operator (spatially invariant)

Idea:

1. **Model of Human Visual System – separate <u>rods</u> and <u>cones</u> response**
2. **Time-dependent terms to model visual adaptation**

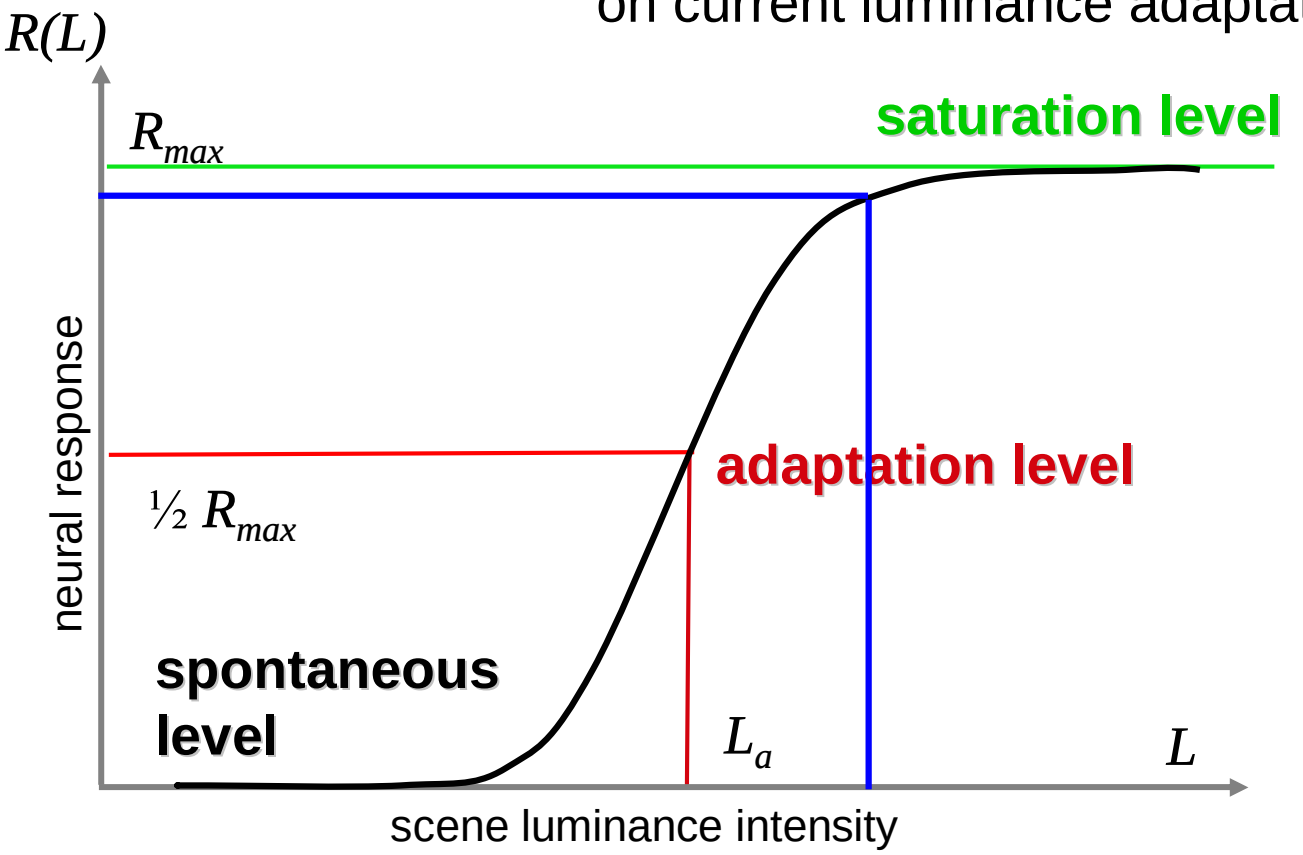
Physically based and accurate results.

Pattanaik et al. – “Time-Dependent Visual Adaptation For Fast Realistic Image Display”, ACM Proceedings 2000

Rods & Cones Responses

Sigmoid response: $R(L) = \dfrac{L^n}{L^n + \sigma_{L_a}^n} R_{\max} \qquad n \approx 0.74$

$\boldsymbol{\sigma_{La}}$ half-saturation constant dependent on current luminance adaptation level



Adaptation Processes

1. **Adaptation to dark/light**

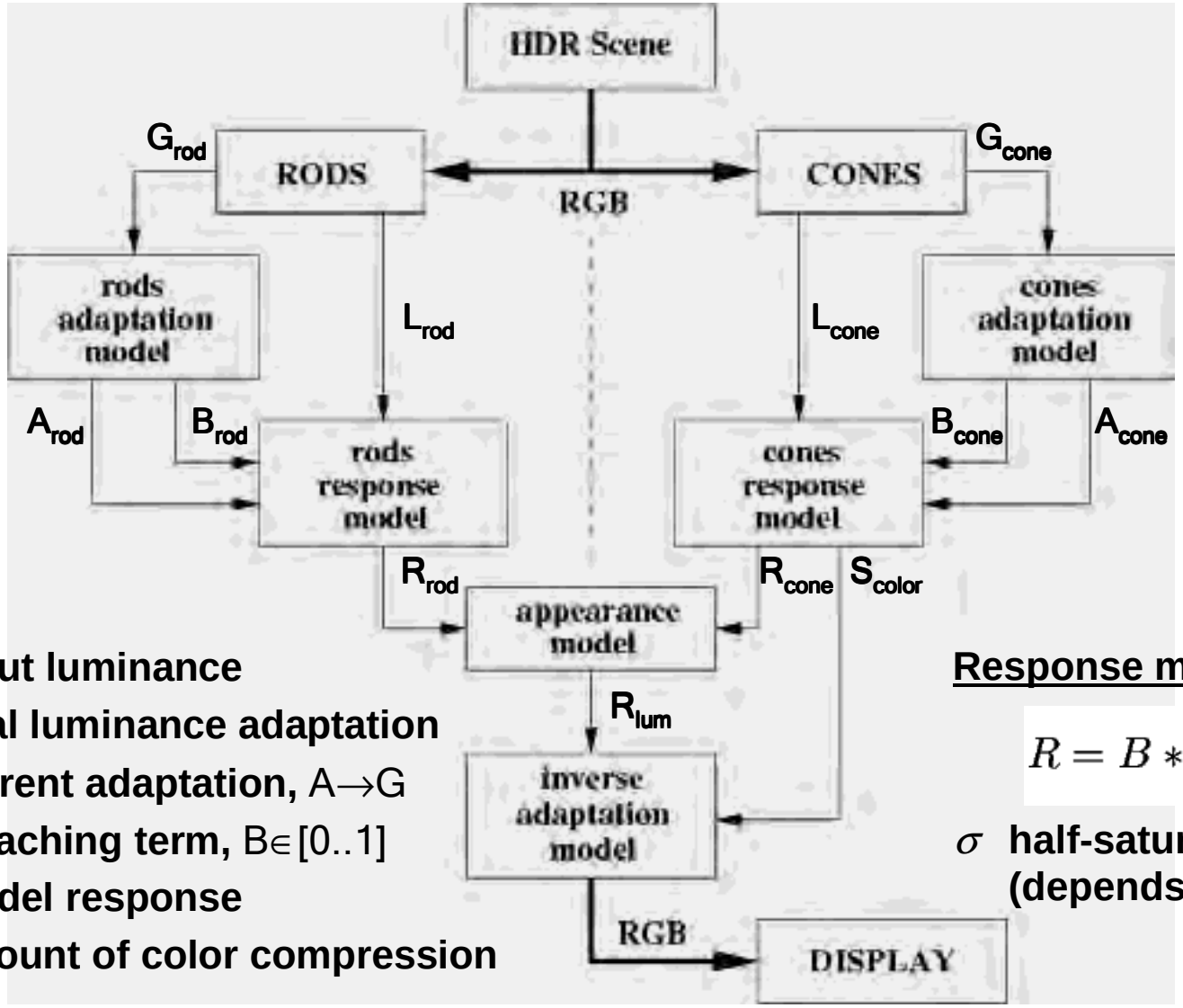
   decrease (increase) of visual sensitivity upon increases (decreases) in the overall level of illumination

2. **Photo-pigment bleaching**

   Two competing processes in photoreceptors caused by high luminance of light falling on retina:

   - **pigment depletion** – decrease in area of active receptor fields to limit the detected light intensity
   - **pigment regeneration** – chemical process of pigment recovery allowing for increase in sensitivity

Visual System Model



$L_{rod/cone}$	**input luminance**
$G_{rod/cone}$	**goal luminance adaptation**
$A_{rod/cone}$	**current adaptation,** $A \rightarrow G$
$B_{rod/cone}$	**bleaching term,** $B \in [0..1]$
$R_{rod/cone}$	**model response**
S_{color}	**amount of color compression**

Response model:

$$R = B * \frac{L^n}{L^n + \sigma^n}$$

σ **half-saturation constant (depends on** A**)**

Dynamic Aspect of Visual Adaptation

1. Luminance adaptation – short term

changes in goal luminance adaptation ***G*** are smoothed with exponential filters; adaptation time for rods $\mathbf{t_{rod}}$**=150[ms]**, cones $\mathbf{t_{cone}}$**=80[ms]**.

$$A_{cone,t} = (A_{cone,t-1} - G_{cone}) * (1 - e^{-T/t_{0,cone}}) \quad t_{0,cone} = 80[\mathrm{ms}]$$

2. Pigment kinetics – long term

Time-dependent bleaching term ***B*** is affected by process of **pigment depletion *J*** and **pigment regeneration *K***: ***ΔB = K- J***

depletion depends on current goal adaptation ***G*** and bleaching term ***B,***

regeneration depends only on current bleaching term ***B.***

time constant for rods $\boldsymbol{\tau_{rod}}$**=400[s]**, cones $\boldsymbol{\tau_{cone}}$**=110[s]**.

$$J_{cone,t} = T * \frac{B_{cone,t-1}}{2.2 \times 10^8} * G_{cone} \quad K_{cone,t} = T * \frac{1 - B_{cone,t-1}}{\tau_{cone}} \quad \tau_{cone} = 110[\mathrm{s}]$$

Inverse Appearance Model

1. **Purpose**

   For calculated response values, $\boldsymbol{R_{cone}}$ and $\boldsymbol{R_{rod}}$, find proper **RGB** values so, that the image displayed on screen produces <u>the same response</u> values in visual system under given <u>observation conditions</u>.

2. **Inverse response model**

$$L = \sigma_{display} \left(\frac{R}{1-R} \right)^{\frac{1}{n}}$$

3. **Reference black and reference white mapping**

   Image is <u>linearly scaled</u> so that the <u>black/white values</u> in the image correspond to <u>black/white intensities</u> of target display screen under given observation conditions.

   This is according to the Tumblin&Rushmeier(93) model of tone reproduction.

Time-Dependent Visual Adaptation

1. Light adaptation

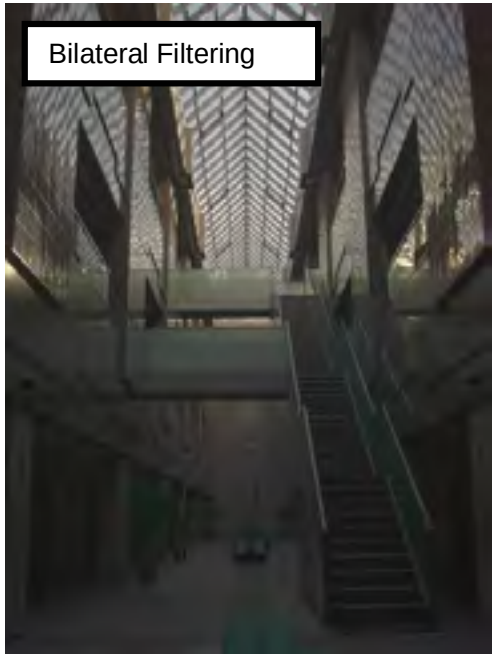
steady state | 0[s] – light on | 0.5[s] | 1[s] | 2.6[s] – fully adapted

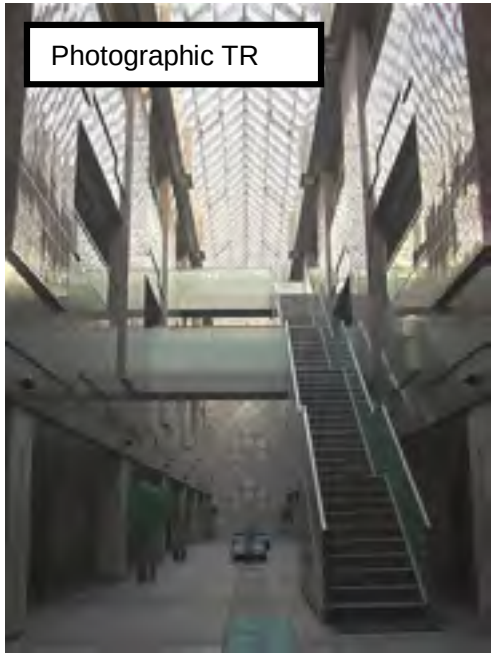
2. Dark adaptation

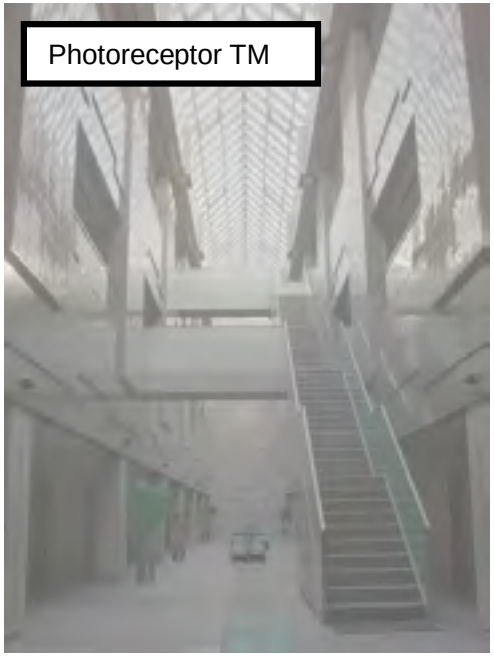
steady state | 0[s] – light off | 2[s] | 20[s] | 300[s]

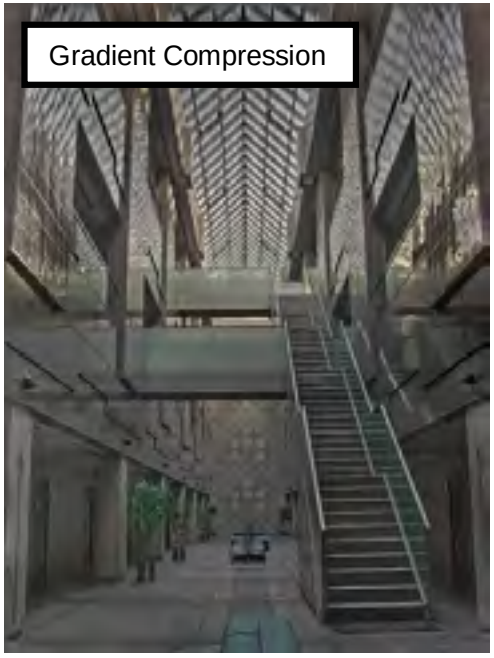
Example Results #1

Example Results #2

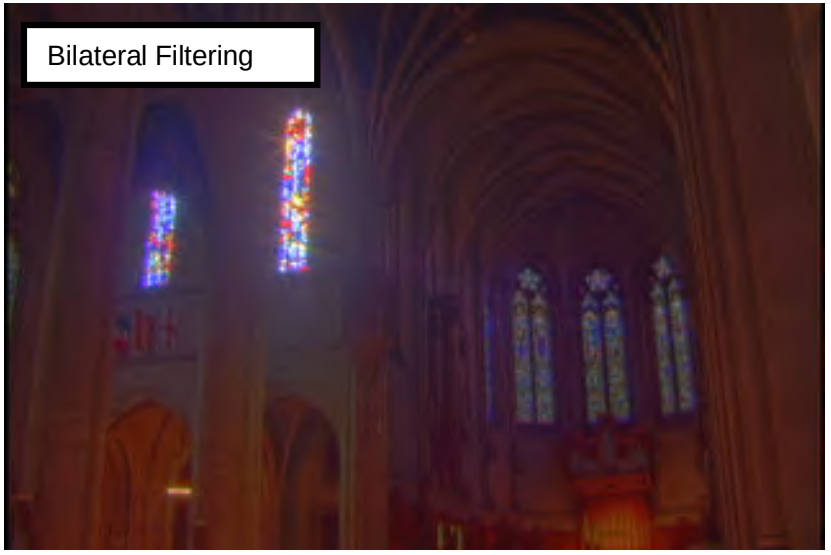






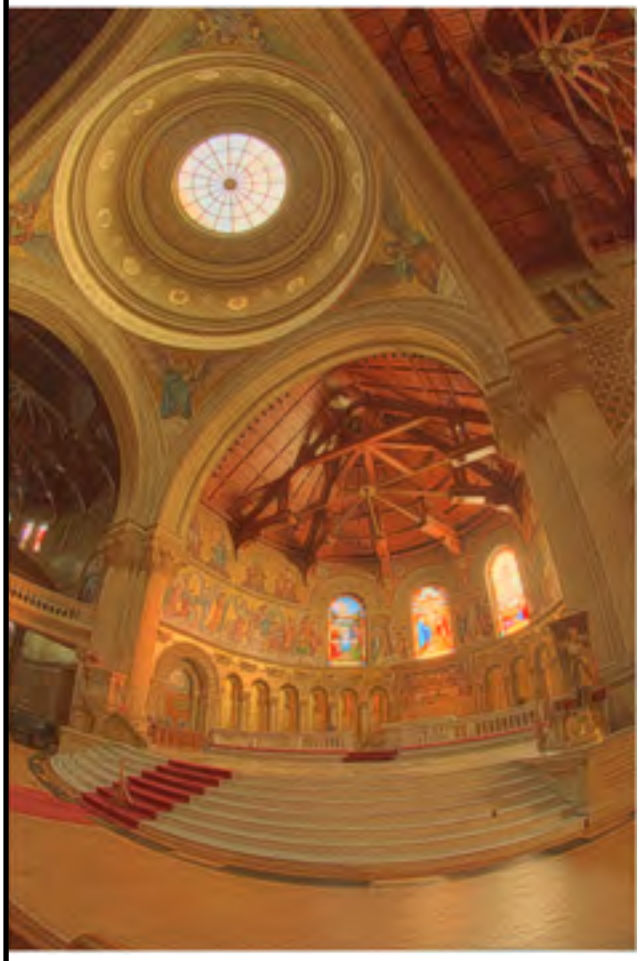


Example Results #3

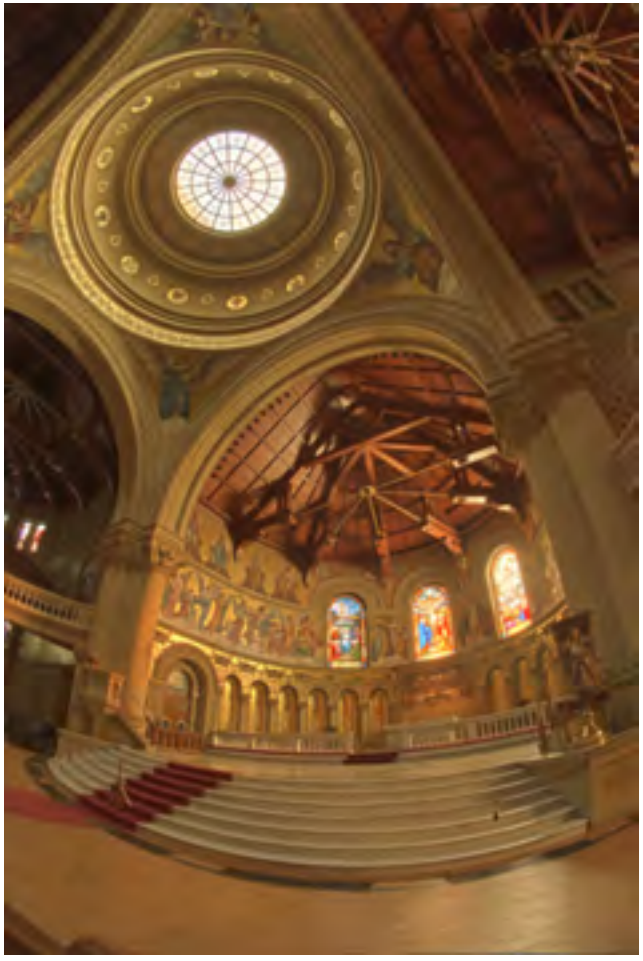


Example Results #4a

Tumblin and Turk



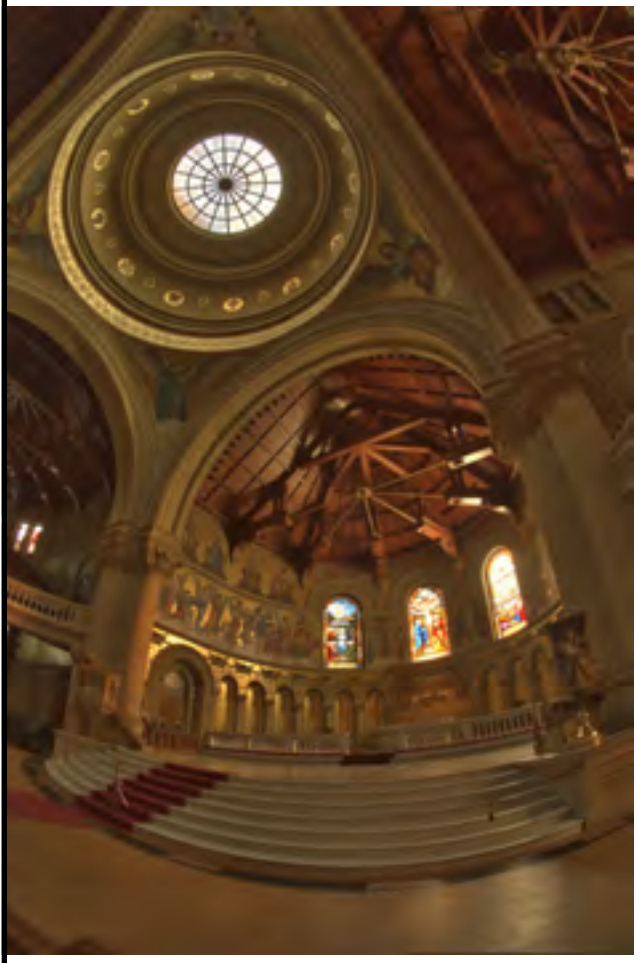
Ashikhmin



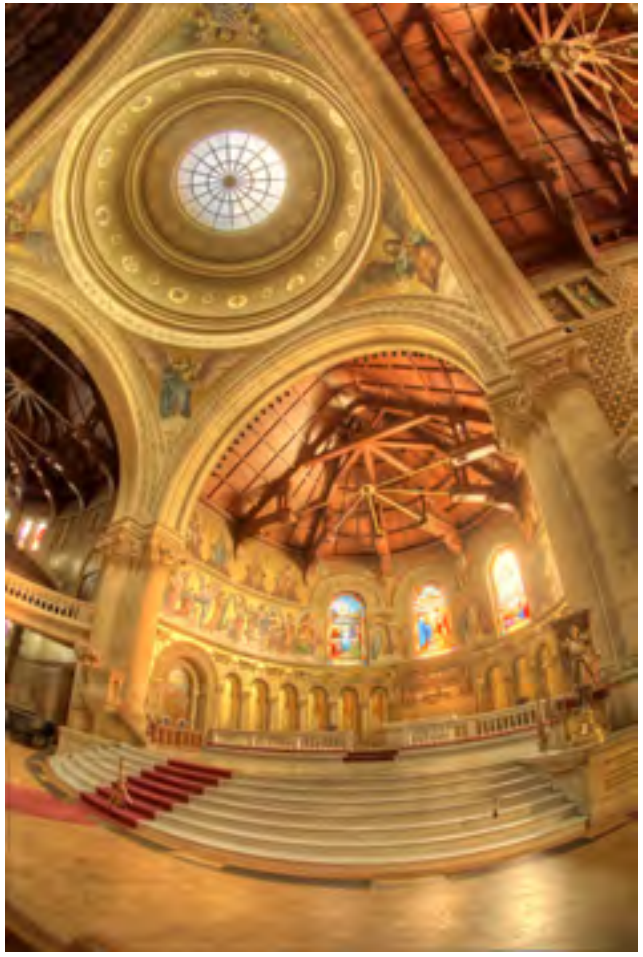
Retinex

Example Results #4b

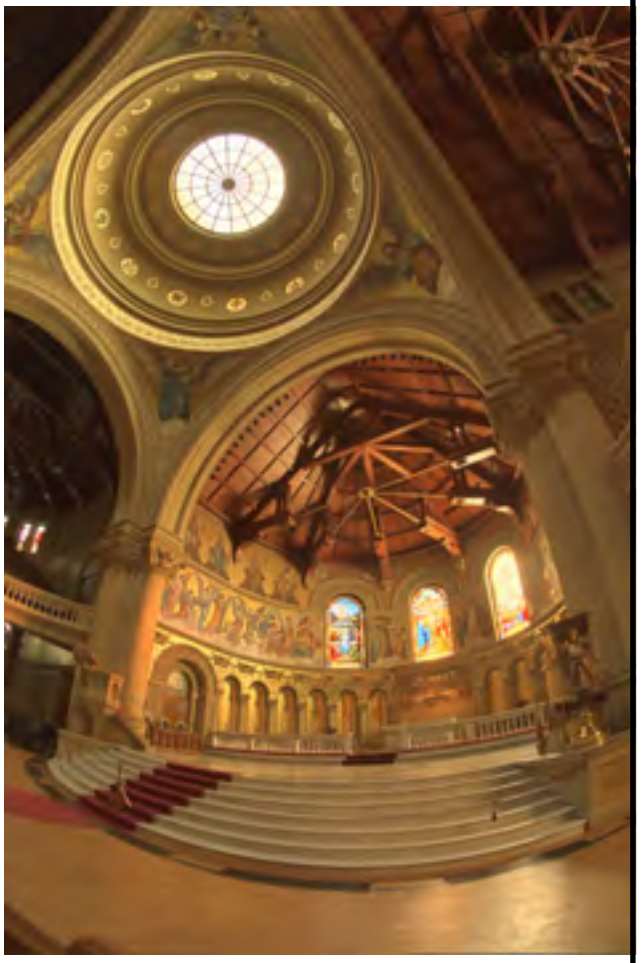
Durand and Dorsey



Fattal et al.



Reinhard et al.



Ashikhmin

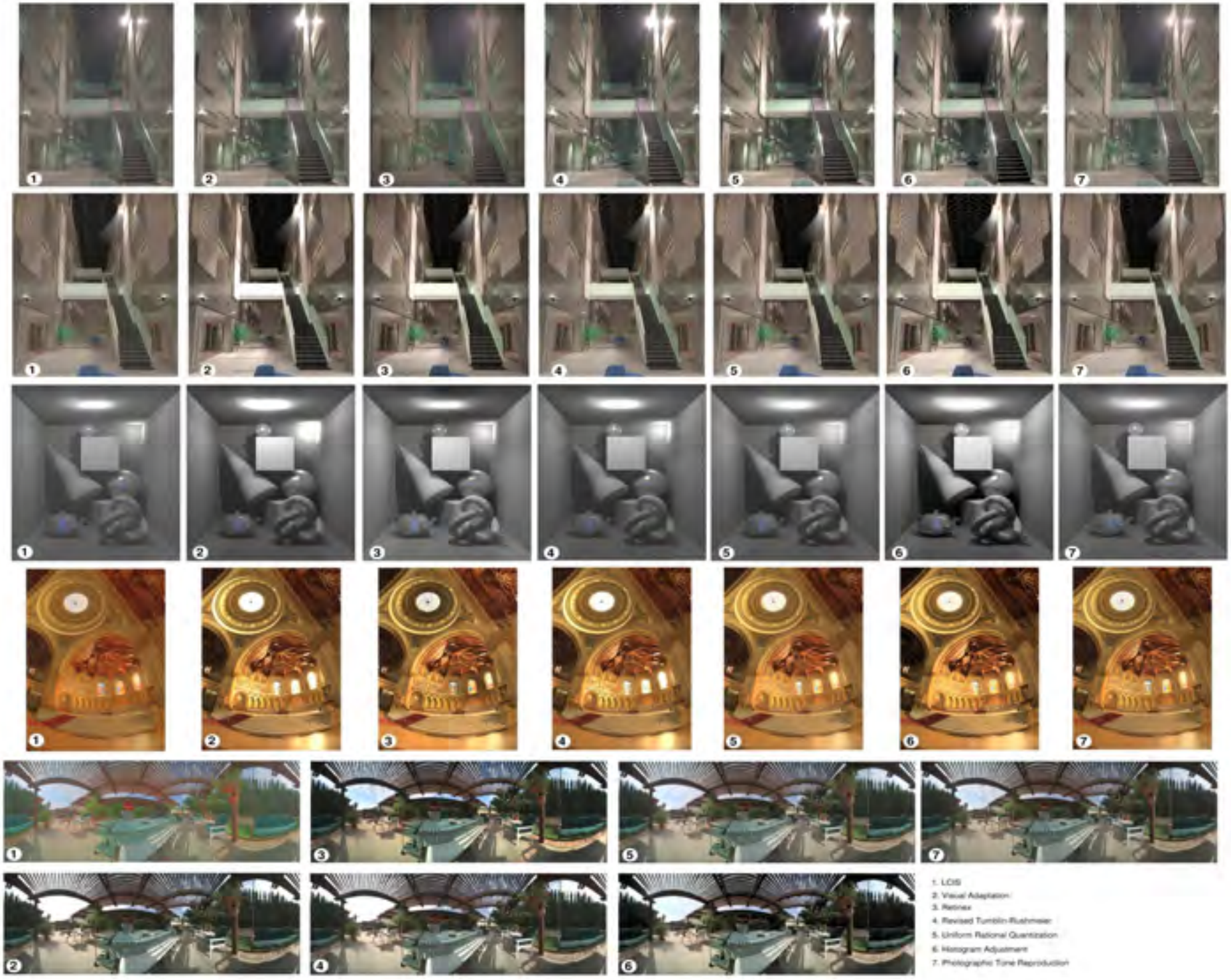
Durand and Dorsey

Fattal et al.

Reinhard et al.

Psychophysical Experiment

- Perceptual evaluation of subject preference by pairwise comparison of tone mapped images
- Seven tone mapping algorithms examined:
  - Tumblin and Rushmeier (1993),
  - Ferwerda et al. (1996),
  - Ward et al. (1997),
  - Schlick (1994),
  - Retinex - based on Funt and Ciurea (2001) implementation
  - Reinhard et al. (2002) – photographic method
  - Tumblin and Turk (1999) - LCIS
- Four scenes considered


1. LCIS
2. Visual Adaptation
3. Retinex
4. Revised Tumblin-Rushmeier
5. Uniform Rational Quantization
6. Histogram Adjustment
7. Photographic Tone Reproduction

F

Multi-Dimensional Scaling

	Atl	Chi	Den	Hou	LA	Mia	NYC	SF	Sea	DC
Atlanta	0									
Chicago	587	0								
Denver	1212	920	0							
Houston	701	940	879	0						
LA	1936	1745	831	1374	0					
Miami	604	1188	1726	968	2339	0				
NYC	748	713	1631	1420	2451	1092	0			
SF	2139	1858	949	1645	347	2594	2571	0		
Seattle	2182	1737	1021	1891	959	2734	2406	678	0	
DC	543	597	1494	1220	2300	923	205	2442	2329	0

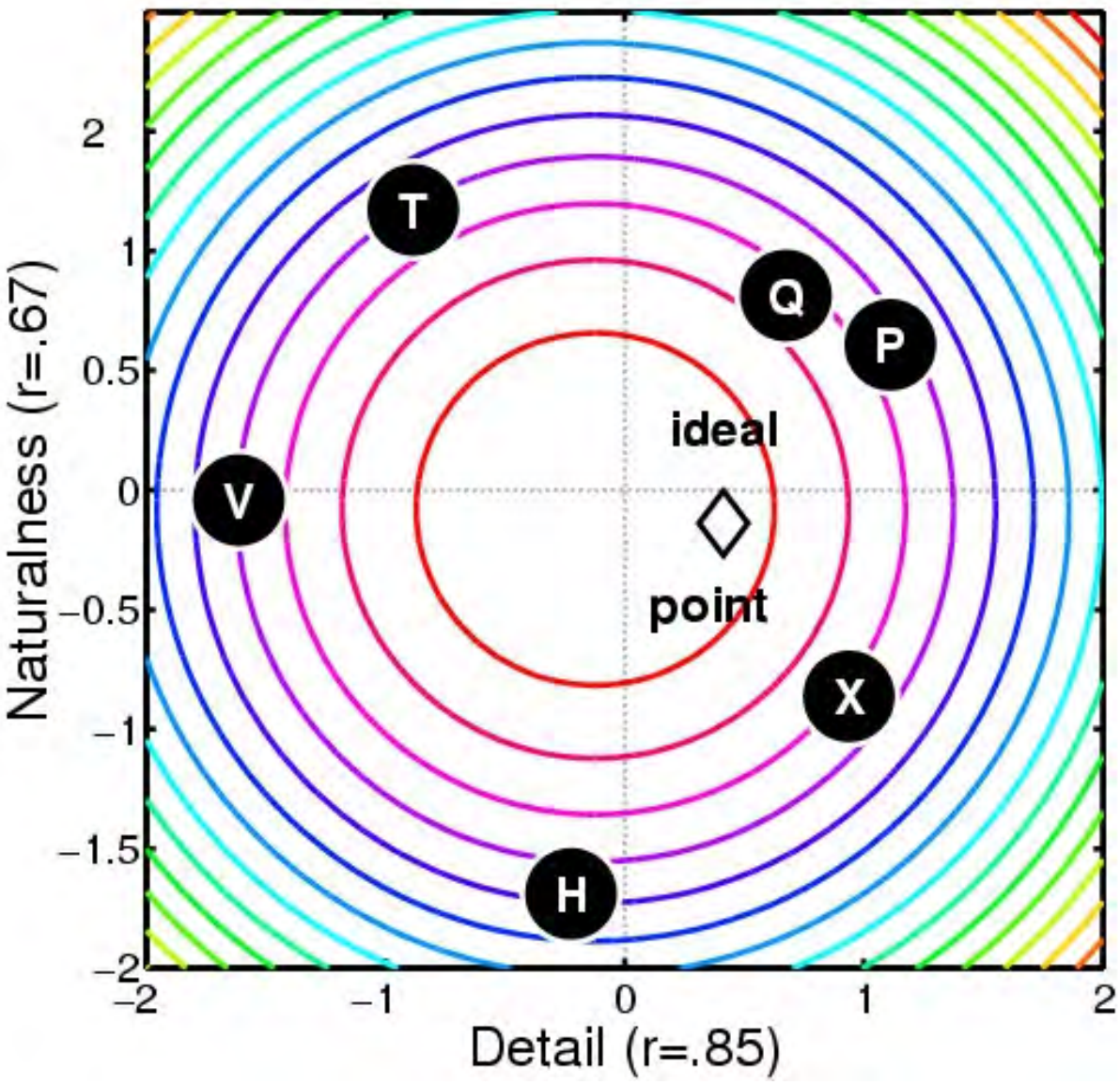
Proximity matrix of distances between U.S. cities

MDS reconstruction of the U.S. map

Statistical Data Processing

- 11 subjects participated
- Dissimilarity ratings for pairwise comparisons of images submitted to Individual Differences Scaling (INDSCAL) analysis
- Stimulus Space configures the stimuli such that Euclidian distances between the stimuli match the obtained dissimilarity judgments
- Axes labeled based upon correlation of the dimensional coordinates with independently generated attribute ratings (naturalness, detail and contrast reproduction)
- “Ideal” preference point obtained through Preference Mapping (PREFMAP) analysis

Subject Preferences



- ***T***: Tumblin & R.
- ***V***: Ferwerda et al.
- ***H***: Ward et al.
- ***Q***: Schlick
- ***X***: Retinex
- ***P***: Reinhard et al.

Conclusions

- It seems that there is no a single tone reproduction method that works well for all scenes. The development of such a method seems to be at present unattainable given the current status of computational models of human visual response.
- A good tone mapping operators should do more than matching brightness or contrast.
- Solution: choose careful tone reproduction methods which work well for a given task and adjust their parameters to get best possible results.

Acknowledgements

- **I would like to thank Karol Myszkowski, Frederic Drago and Grzegorz Krawczyk for help in preparing some slides used during this lecture.**