Realistic Image Synthesis

- Tone Mapping -

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

- Tone Mapping -

Roman Durikovic

High-Dynamic Range Imagery

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Realistic Image Synthesis

The Goal of Realistic Rendering

Greenberg et al. Siggraph’97. Cornell University

Ferwerda 1998
Realistic Image Synthesis

The Goal of Realistic Rendering
Realistic Image Synthesis – Tone Mapping

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

<table>
<thead>
<tr>
<th>Red</th>
<th>Green</th>
<th>Blue</th>
<th>Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>32 bits / pixel</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[
\begin{align*}
(145, 215, 87, 149) &= (145, 215, 87, 103) = \\
(145, 215, 87) &\times 2^{(149-128)} = (145, 215, 87) &\times 2^{(103-128)} = \\
(1190000, 1760000, 713000) &= (0.00000432, 0.00000641, 0.00000259)
\end{align*}
\]

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### 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

```
<table>
<thead>
<tr>
<th>sign</th>
<th>exponent</th>
<th>mantissa</th>
</tr>
</thead>
</table>
```

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

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

Floating Point TIFF similar
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  ![Binary Image Data]

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  ```
  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
  - sign exponent mantissa
  - 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/

HDR Formats: Ward’s LogLuv TIFF

based on human color perception

- 24 bits: 10 for log luminance
  - 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


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

Realistic Image Synthesis – Tone Mapping

Greg Ward
Realistic Image Synthesis – Tone Mapping

**The Tone Mapping Problem**

**Technical requirement**
- Match the dynamic range of image to the range available on a given display device
- 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/m²
- HDR display developed at Univ. of British Columbia in collaboration with Greg Ward was presented at Siggraph 2003
  - Min. luminance: 0.1 cd/m²  Max. luminance: 3,000-10,000 cd/m²

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

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
Realistic Image Synthesis – Tone Mapping

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HDR Formats: Ward’s LogLuv TIFF

**based on human color perception**

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Visual Matching

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
Visual Matching

Goal: Matched Visual Sensations

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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
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Global vs. Local Operators

- **Spatially-uniform tone reproduction operators**
  - Adaptation 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
    \[ L_d(x, y) = mL_u(x, y) \]

- **Spatially-non-uniform tone reproduction operators**
  - Adaptation is localized. Thus, the mapping function might be different for various image regions.
  - Key issue: size of local neighborhood used for the adaptation computation
    \[ L_d(x, y) = m(x, y)L_u(x, y) \]

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
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## Comparison

|-----------------|----------------|-------------|---------|

- **Brightness Matching**
  - Brightness preservation based on a mathematical model of human vision
    - Stevens & Stevens function
    - Suprathreshold 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 (1)

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**Realistic Image Synthesis – Tone Mapping**

- **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

---

**Realistic Image Synthesis SS04 – Tone Mapping**

- **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

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

  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

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

  Then the recalculation of $L_d$ to the display units $n$ (0 < $n$ < 1), for the display with the gamma – correction $\gamma$ can be performed as

  \[
  n = \left(\frac{L_d}{L_{d,max}} - \frac{1}{C_{max}}\right)^{1/\gamma}
  \]

  $C_{max} \approx 35$ max contrast for CRTs

---

Realistic Image Synthesis SS04 – Tone Mapping
**Tumblin & Rushmeier (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.
    - \[ B = 10^\beta L^{\alpha} \]
    - \[ \alpha = 0.4 \log_{10}(L_a) + 2.92 \]
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  - $L_a$ the luminance of the adaptation level
  - $L$ luminance, $B$ brightness in brils

- 1 micro-lambert = \( \frac{1}{100 \pi} \text{cd/m}^2 \)

---

**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
    - \[ L_d = L_w^\alpha \left( \frac{\alpha_e}{\alpha_a} \right) 10^{\left( \frac{\beta_e - \beta_a}{\alpha_a} \right)} \]
    - it is assumed that the real world adaptation level $L_{a\text{(real)}}$ is
    - \[ \log_{10}(L_{a\text{(real)}}) = E \left[ \log_{10}(L_a) \right] + 0.84 \]
    - where $E$ is the statistical average over the image, and
    - \[ L_{a\text{(max)}} = 100 \text{cd/m}^2 \]
  - Then the recalculation of $L_d$ to the display units $n$ (0 < $n$ < 1),
    - for the display with the gamma – correction $\gamma$ can be performed as
    - \[ n = \left( \frac{L_{d\text{,max}}}{L_{d\text{,max}}} - (1/C_{\text{max}}) \right)^{1/\gamma} \quad C_{\text{max}} \approx 35 \text{ max contrast for CRTs} \]
Tumblin & Rushmeier (4)

- Bright scenes exaggerate contrast unrealistically

\[
L_w = L_{wa}
\]

Realistic Image Synthesis – Tone Mapping

Ward (1)

Threshold vision model:

Accordingly to Blackwell the luminance difference \( \Delta L \) that is just noticeable at an adaptation level \( L_a \) (measured in \( \text{cd/} m^2 \)) 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:

\[
L_d = mL_w, \quad \text{where} \ m \ \text{is given by}:
\]

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

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

Realistic Image Synthesis SS04 – Tone Mapping
**Tumblin & Rushmeier (4)**

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Ward (2)

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

Ferwerda et al. (1)

- Extended the dark response of Ward’s method down to $10^{-4} \text{ cd/m}^2$.
- Proper modeling luminance sensitivity, color sensitivity, and spatial acuity with decreasing light.
- Display luminance is not monotonically increasing function of $L_{wa}$ near 1 \text{ cd/m}^2. As for Ward’s method scenes with $L_{wa} > 100 \text{ cd/m}^2$ are strictly normalized, and image contrast is not modified.
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Visibility of a Snellen chart and a Macbeth Colorchecker for various levels of adaptation luminance.

Ferwerda et al. (2)

Threshold Model of Adaptation
Sensitivity as a gain control mechanism

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

Ferwerda et al. (3)
Ferwerda et al. (2)

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

Realistic Image Synthesis SS04 - Tone Mapping

Ferwerda et al. (3)

• Threshold Model of Adaptation
• Sensitivity as a gain control mechanism

\[
\begin{align*}
[X, Y, Z]_{\text{cone}} \times \text{Sensitivity}_{\text{cone}} \\
+ [X, Y, Z]_{\text{rod}} \times \text{Sensitivity}_{\text{rod}} \\
= [X, Y, Z]_{\text{total}}
\end{align*}
\]
Luminance, Chrominance Values

Spectral efficiency functions

\[ X = 683 \frac{\text{lm}}{\text{watt}\times 380\text{nm}} \int_{380\text{nm}}^{700\text{nm}} L(\lambda) \tilde{x}(\lambda) \, d\lambda \]

\[ Y = 683 \frac{\text{lm}}{\text{watt}\times 380\text{nm}} \int_{380\text{nm}}^{700\text{nm}} L(\lambda) \tilde{y}(\lambda) \, d\lambda \]

\[ Z = 683 \frac{\text{lm}}{\text{watt}\times 380\text{nm}} \int_{380\text{nm}}^{700\text{nm}} L(\lambda) \tilde{z}(\lambda) \, d\lambda \]

\[ X' = Y' = Z' = 1700 \frac{\text{lm}}{\text{watt}\times 380\text{nm}} \int_{380\text{nm}}^{700\text{nm}} L(\lambda) \tilde{Y}'(\lambda) \, d\lambda \]

Ferwerda et al. (5): Purkinje Shift
**Luminance, Chrominance Values**

Spectral efficiency functions

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X = 683 \frac{\text{lm}}{\text{watt}} \int_{380 \text{nm}}^{700 \text{nm}} L(\lambda) \tilde{x}(\lambda) \, d\lambda
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For rods

\[
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\]

**Ferwerda et al. (5): Purkinje Shift**

For rods and cones, the efficiency functions are shown with a graph indicating the change in sensitivity across different wavelengths.
Simulating daylight vision
(1000 cd/m²)

Simulating night vision
(0.04 cd/m²)
Simulating daylight vision
(1000 cd/m^2)

Simulating night vision
(0.04 cd/m^2)
Dark adaptation

t= 0 s  
lum= 1412 cd/m²

t= 25 s  
lum= 0.1 cd/m²

1 min. 40 s  
lum= 0.1 cd/m²

3 min. 20 s  
lum= 0.1 cd/m²

Light adaptation

t= 0 s  
lum= 0.1 cd/m²

t= 1 s  
lum= 5800 cd/m²

25 s
lum= 5800 cd/m²

1 min. 15 s
lum= 5800 cd/m²
Dark adaptation

t= 0 s  lum= 1412 cd/m²

t= 25 s  lum= 0.1 cd/m²

t= 50 s  lum= 0.1 cd/m²

t= 1 min. 40 s  lum= 0.1 cd/m²

t= 3 min. 20 s  lum= 0.1 cd/m²

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 et al. (6)

Global Methods: Comparison

- A: Original Tumblin-Rushmeier '93
- B: Ward '94
- C: Farwuda et al. '96
- D: Revised Tumblin-Rushmeier '98
Ferwerda et al. (6)

Global Methods: Comparison

![Comparison Diagram]
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.

Ward-Larson et al. (1)

Greg Ward, Holly Rushmeier, and Christine Piatko
A Visibility Matching Tone Reproduction Operator for High Dynamic Range Scenes.
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Ward-Larson et al. (2)

A false color image showing the world luminance values for a window office in candelas per meter squared (cd/m² or Nits).

Greg Ward
Ward-Larson et al. (3)

Realistic Image Synthesis – Tone Mapping

A linear mapping of the luminance that oversaturates the view through the window.

A linear mapping of the luminance that underrepresents the view of the interior.

The luminance mapped to preserve the visibility of both indoor and outdoor structures.

Ward-Larson et al. (4)

Realistic Image Synthesis SS04 – Tone Mapping

World to Display Luminance Mapping

Greg Ward
Ward-Larson et al. (3)

Realistic Image Synthesis SS04 – Tone Mapping

Ward-Larson et al. (4)

Realistic Image Synthesis - Tone Mapping
Ward-Larson et al. (5)

Histogram Adjustment Procedure

procedure match_visibility()
1. compute 1° foveal sample image
   compute veill image
   add veil to foveal adaptation image
   add veill 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
Realistic Image Synthesis SS04 – Tone Mapping

Ward-Larson et al. (5)

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```plaintext
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end
```

Ward-Larson et al. (6)

Realistic Image Synthesis SS04 – Tone Mapping
Ward-Larson et al. (7)

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.
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Ward-Larson et al. (8) - Problems

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*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.
Ward-Larson et al. (9) – Application Example

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Fixed Base Logarithm Mapping

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

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

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

\[
\begin{align*}
\text{sceneLum} &= \frac{L_x}{L_{\text{adapt}}} \\
\text{sceneMaxLum} &= \frac{L_{x_{\max}}}{L_{\text{adapt}}} \\
\text{imageLum} &= \frac{L_{\text{adapt}}}{\log_{\text{base}}(\text{sceneMaxLum} + 1)} \cdot \log(\text{sceneLum} + 1) \\
&= \frac{L_{\text{adapt}}}{\log_{10}(\text{sceneMaxLum} + 1)} \cdot \log(\text{sceneLum} + 1)
\end{align*}
\]

Realistic Image Synthesis – Tone Mapping
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\]

\[
\text{imageLum} = \frac{\log(\text{sceneLum} + 1)}{2 + 8 \cdot \frac{\text{sceneLum}}{\text{sceneMaxLum}}} \]

Realistic Image Synthesis SS04 - Tone Mapping
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
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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.

\[
L_{a}(i, j) = \frac{L_{w}(i, j)}{kL_{blur}(i, j)}
\]

$L_{blur}$ is obtained through low-pass filtration of the image. The wider filter support the lower spatial frequency of the scaling factor for $L_{a}$. 
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\(L_{blur}\) is obtained through low-pass filtration of the image. The wider filter support the lower spatial frequency of the scaling factor for \(L_u\).
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:
    \[ n = \frac{p \cdot L}{p \cdot L - L + L_{\text{max}}} \]
  - 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
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### Schlick

- 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

Jonathan Frankle, John McCann  
Method and Apparatus for Lightness Imaging. 1983

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### Retinex

- Black-white Mondrian under linearly changed illumination

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Realistic Image Synthesis – Tone Mapping

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Realistic Image Synthesis – Tone Mapping

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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
    \[
    \log L = \log OP(xs, ys) + \log R(x, y) - \log R(xs, ys)
    \]
    if \( \log L > \log L_{scene} \) then \( L = L_{scene} \)
  - In the first iteration \( OP(xs, ys) = L_{max} \)

- 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 variation of the Stanford Memorial church.

The three color channels were computed separately.
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Modern Local Methods

Spatially non-uniform tone reproduction operators:

- **Layering Method, Foveal Method, and LCIS**
  - Tumblin (1999)
- **Bilateral Filtering, Trilateral Filtering**
- **Gradient Domain HDR Compression**
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  - A spatially uniform variation: Photoreceptor Inspired Tone Mapping
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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.
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Tumblin – Layering Method (2)

- Example scene

Deep shadow: 0.4 cd/m² → (50, 30, 23)
Lightbulb: 175,000 cd/m² → (255, 255, 255)
Shroud reflection: 40,000 cd/m² → (240, 240, 240)
Bright wood: 1,600 cd/m² → (250, 199, 154)

Tumblin – Layering Method (3)

- Layer separations:

\[
\text{Scene}(x, y) = K_d(x, y)I_d(x, y) + K_s(x, y)I_s(x, y) + K_t(x, y)I_t(x, y)
\]
Realistic Image Synthesis SS04 – Tone Mapping

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### Tumblin – Layering Method (4)

<table>
<thead>
<tr>
<th>Truncation</th>
<th>Compression</th>
<th>&quot;Layering&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image_a.png" alt="Image A" /></td>
<td><img src="image_b.png" alt="Image B" /></td>
<td><img src="image_c.png" alt="Image C" /></td>
</tr>
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</table>

- **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

---

### Tumblin – Foveal Method (1)

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

  ![Image D](image_d.png)  ![Image E](image_e.png)
Tumblin – Layering Method (4)

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Realistic Image Synthesis – Tone Mapping

Tumblin – Foveal Method (2)

- Image pyramid is used for fast computation of $I_{w,a}$ as a weighted sum of neighborhood pixel values.

![Image pyramid diagram]

- 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 smooths 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 (1)

- Based on an anisotropic diffusion procedure
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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.

\[
I_i^{(n)} = I_i + \frac{\lambda}{4} \sum_{p \in \text{neighborhood}(i)} g(I_p - I_i)(I_p' - I_i')
\]

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}}
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Low Curvature Image Simplifier (3)

Jack Tumblin, Greg Turk

LCIS: A boundary hierarchy for detail-preserving contrast reduction. SIGGRAPH 99
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\[ l_{s+1} = l_s + \frac{\lambda}{4} \sum_{p \in \text{neighborhood}(x)} g(l_{s} - l_p) (l_{s} - l_p) \]

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Realistic Image Synthesis – Tone Mapping

Low Curvature Image Simplifier (5)

Realistic Image Synthesis SS04 – Tone Mapping
Low Curvature Image Simplifier (4)

Detail-preserving contrast reduction method using an LCS hierarchy.

Low Curvature Image Simplifier (5)
Low Curvature Image Simplifier (6)

Gamma Compression Results
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


Decomposition: Base & Detail Layers

Base

Detail
**Bilateral Filtering of HDR Images**

**Local operator (spatially variant)**

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**Decomposition: Base & Detail Layers**

![Base Image](image1.jpg)  ![Detail Image](image2.jpg)
**Gaussian Filtering**

Proposed by Chiu at al. 1993
Blurring across the edges results in halo artifacts.

\[ J = f \otimes l \]

- \( f \) spatial kernel with large \( \sigma_s \)

**Bilateral Filtering**

Edge preserving filter – no halo artifacts.

\[ J = (f \times g) \otimes l \]

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- \( g \) range kernel with very small \( \sigma_r \)
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Bilateral Filtering – Tone Mapping

Luminance calculations in log-space (brightness approximation)

Bilateral Filtering – Results

Good contrast compression with well preserved details
Bilateral Filtering – Tone Mapping

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Bilateral Filtering – Improvements

1. **Speed-up**
   Piecewise-linear bilateral filtering

2. **Uncertainty correction**
   Not enough similar pixels to decouple large-scale and small-scale features – halo artifacts at specular highlights.
   Solution: interpolation between HDR & LDR image.

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Bilateral Filtering – Weak Aspects

1. **Poor smoothing in high gradient regions**
2. **Blends together disjoint regions**
3. **Smoothes and blunts cliffs, valleys & ridges**
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1. **Tilt the filter window**
   according to bilaterally smoothed gradients

2. **Limit the filter window**
   to connected regions of similar smoothed gradients

3. **Adjust 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
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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 - \( \phi \)
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Realistic Image Synthesis SS04 – Tone Mapping

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Realistic Image Synthesis – Tone Mapping
Gradient Integration Problem

1. Boundary conditions
   **Neumann boundary condition** – the derivative in direction normal to the boundary is zero
   \[ \nabla I \cdot n = 0 \]
   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
  - Loss of overall contrast
  - Loss of texture details
  - Short execution time
  - Simple hardware implementation

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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)

   \[ L(x, y) = \frac{aL_{e}(x, y)}{L_{e}(x, y)} \quad L_{e}(x, y) = \frac{L(x, y)}{1 + L(x, y)} \]

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

   \[ L_{a}(x, y) = \frac{L(x, y)}{1 + V(x, y, \sigma_{m}(x, y))} \]
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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

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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
   \[ V = \frac{I}{I + \sigma(I_a) V_{\max}} \]
   \[ \sigma(I_a) = (f I_a)^m \]
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
**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**

   \[ V = \frac{l}{1 + \sigma(l_a)} V_{\text{max}} \]

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### Photoreceptor – Results

- 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 rods and cones response
2. Time-dependent terms to model visual adaptation

Physically based and accurate results.

**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 rods and cones response
2. Time-dependent terms to model visual adaptation

Physically based and accurate results.

---

Rods & Cones Responses

Sigmoid response: \[ R(L) = \frac{L^n}{L^n + \sigma_{L_a}^n} R_{\text{max}} \quad n \approx 0.74 \]

\[ \sigma_{L_a} \] half-saturation constant dependent on current luminance adaptation level

\[
\begin{align*}
R(L) & \quad \text{saturation level} \\
\frac{1}{2} R_{\text{max}} & \quad \text{adaptation level} \\
L_{a} & \quad \text{scene luminance intensity}
\end{align*}
\]

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
Rods & Cones Responses

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**Visual System Model**

**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 \( t_{\text{rod}}=150\,[\text{ms}] \), cones \( t_{\text{cone}}=80\,[\text{ms}] \).

   \[
   A_{\text{cone},t} = (A_{\text{cone},t-1} - G_{\text{cone}}) \cdot (1 - e^{-t/T_{\text{cone}}}) \quad t_{\text{cone}} = 80\,[\text{ms}]
   \]

2. **Pigment kinetics – long term**
   Time-dependent bleaching term \( B \) is affected by process of pigment depletion \( J \) and pigment regeneration \( K \): \( \Delta B = K - J \).
   Depletion depends on current goal adaptation \( G \) and bleaching term \( B \).
   Regeneration depends only on current bleaching term \( B \).
   Time constant for rods \( \tau_{\text{rod}}=400\,[\text{s}] \), cones \( \tau_{\text{cone}}=110\,[\text{s}] \).

   \[
   \tau_{\text{cone}} = \frac{T \cdot B_{\text{cone},t-1} - G_{\text{cone}}}{2.2 \times 10^6} \quad \tau_{\text{cone}} = 110\,[\text{s}]
   \]

   \[
   \tau_{\text{cone}} = \frac{1 - B_{\text{cone},t-1}}{G_{\text{cone}} \cdot K_{\text{cone},t}} \quad \tau_{\text{cone}} = 110\,[\text{s}]
   \]

   \[
   \sigma \quad \text{half-saturation constant (depends on } A)\]

Realistic Image Synthesis – Tone Mapping
1. Luminance adaptation - short term
changes in goal luminance adaptation $G$ are smoothed with exponential filters; adaptation time for rods $t_{rod}=150[ms]$, cones $t_{cone}=80[ms]$.

$$A_{cone,i} = (A_{cone,i-1} - G_{cone}) + (1 - e^{-t/t_{cone}}) \quad t_{cone} = 80[ms]$$

2. Pigment kinetics - long term
Time-dependent bleaching term $B$ is affected by process of pigment depletion $J$ and pigment regeneration $K$: $\Delta B = K - J$
depletion depends on current goal adaptation $G$ and bleaching term $B$,
regeneration depends only on current bleaching term $B$,
time constant for rods $\tau_{rod}=400[s]$, cones $\tau_{cone}=110[s]$.

$$I_{cone,i} = T \cdot \frac{B_{cone,i-1} - G_{cone}}{2.2 \times 10^9} \quad K_{cone,i} = T \cdot \frac{1 - B_{cone,i-1}}{\tau_{cone}} \quad \tau_{cone} = 110[s]$$
Inverse Appearance Model

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

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 linearly scaled so that the black/white values in the image correspond to black/white intensities 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] 2.5[s] – fully adapted

2. **Dark adaptation**
   
   steady state 0[s] – light off 2[s] 20[s] 300[s]
Inverse Appearance Model

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Time-Dependent Visual Adaptation

1. **Light adaptation**
   - Steady state
   - 0[s] – light on
   - 0.5[s]
   - 1[s]
   - 2.8[s] – fully adapted

2. **Dark adaptation**
   - Steady state
   - 0[s] – light off
   - 2[s]
   - 20[s]
   - 300[s]
Example Results #1

Bilateral Filtering

Photographic TR

Photoreceptor TM

Gradient Compression

Example Results #2

Bilateral Filtering

Photographic TR

Photoreceptor TM

Gradient Compression
Example Results #1

Realistic Image Synthesis SS04 – Tone Mapping

Example Results #2

Realistic Image Synthesis SS04 – Tone Mapping
Example Results #3

- Bilateral Filtering
- Photographic TR
- Photoreceptor TM
- Gradient Compression

Example Results #4a

- Tumblin and Turk
- Ashikhmin
- Retinex
Example Results #3

Bilateral Filtering
Photographic TR
Photoreceptor TM
Gradient Compression

Example Results #4a

Tumblin and Turk  Ashikhmin  Retinex
Example Results #4b

Realistic Image Synthesis – Tone Mapping

Durand and Dorsey  Fattal et al.  Reinhard et al.

Ashikhmin
Fattal et al.
Durand and Dorsey
Reinhard et al.
Example Results #4b

<table>
<thead>
<tr>
<th>Durand and Dorsey</th>
<th>Fattal et al.</th>
<th>Reinhard et al.</th>
</tr>
</thead>
</table>

Realistic Image Synthesis SS04 - Tone Mapping
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
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Multi-Dimensional Scaling

Proximity matrix of distances between U.S. cities

MDS reconstruction of the U.S. map

Realistic Image Synthesis SS04 - Tone Mapping
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
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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

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