Tone mapping

Digital Visual Effects
_Yung-Yu Chuang_

*Tone mapping*

- How should we map scene luminances (up to 1:100,000) to display luminances (only around 1:100) to produce a satisfactory image?
  - Linear scaling?, thresholding?

*Real world radiance vs. Display intensity*:
- Dynamic range along the visual pathway is only around 32:1.
- The key is adaptation.

*The ultimate goal is a visual match*

*Eye is not a photometer!*

- We do not need to reproduce the true radiance as long as it gives us a visual match.
Eye is not a photometer!

Are the headlights different in two images? Physically, they are the same, but perceptually different.

How humans deal with dynamic range

- We’re more sensitive to contrast (multiplicative)
  - A ratio of 1:2 is perceived as the same contrast as a ratio of 100 to 200
  - Makes sense because illumination has a multiplicative effect
  - Use the log domain as much as possible
- Dynamic adaptation (very local in retina)
  - Pupil (not so important)
  - Neural
  - Chemical
- Different sensitivity to spatial frequencies

We are more sensitive to contrast

- Weber’s law
  - Just-noticeable Difference (JND)
  - \[ \frac{\Delta I_b}{I_b} \approx 1\% \]
  - background intensity
  - flash

Preliminaries

- For color images
  \[
  \begin{bmatrix}
  R_d \\
  G_d \\
  B_d \\
  \end{bmatrix} =
  \begin{bmatrix}
  R_w \\
  G_w \\
  B_w \\
  \end{bmatrix}
  \]
  \[
  \begin{bmatrix}
  L_d \\
  L_d \\
  L_d \\
  \end{bmatrix}
  \]

- Log domain is usually preferred.
**HDR Display**

- Once we have HDR images (either captured or synthesized), how can we display them on normal displays?

<table>
<thead>
<tr>
<th>DLP</th>
<th>LCD</th>
<th>Diffuser</th>
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<tbody>
<tr>
<td>800:1</td>
<td>300:1</td>
<td>Theoretically, 240,000:1.</td>
</tr>
<tr>
<td>Due to imperfect optical depth, 54,000:1 measured</td>
<td></td>
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</tbody>
</table>

HDR display system, Sunnybrook Technology, SIGGRAPH 2004

**Sunnybrook HDR display**

- Use Bright Source + Two 8-bit Modulators
  - Transmission multiplies together
  - Over 10,000:1 dynamic range possible

![Low-res B&W backlight](image1.png) ![High-res color foreground](image2.png)

Slide from the 2005 Siggraph course on HDR

**How it works**

![LED Backlight x LCD Screen = Combined Result](image3.png)

Slide from the 2005 Siggraph course on HDR

**Brightside HDR display**

- 37"
- 200000:1
- Acquired by Dolby

![Brightside HDR Display](image4.png)

Slide from the 2005 Siggraph course on HDR
Tone mapping operators

- Spatial (global/local)
- Frequency domain
- Gradient domain

3 papers from SIGGRAPH 2002

- Photographic Tone Reproduction for Digital Images
- Fast Bilateral Filtering for the Display of High-Dynamic-Range Images
- Gradient Domain High Dynamic Range Compression

Photographic Tone Reproduction for Digital Images

Erik Reinhard    Mike Stark
Peter Shirley    Jim Ferwerda
SIGGRAPH 2002

Global v.s. local

Example: Gamma Compression

Example: Adaptive Histogram Equalization

Photographic tone reproduction

- Proposed by Reinhard et. al. in SIGGRAPH 2002
- Motivated by traditional practice, zone system by Ansel Adams and dodging and burning
- It contains both global and local operators
The Zone system

- Formalism to talk about exposure, density
- Zone = intensity range, in powers of two
- In the scene, on the negative, on the print

Source: Ansel Adams
**Dodging and burning**

- During the print
- Hide part of the print during exposure
  - Makes it brighter

From The Master Printing Course, Rudman

**Global operator**

\[
\tilde{L}_u = \exp\left(\frac{1}{N} \sum_{x,y} \log(\delta + L_m(x, y))\right)
\]

Approximation of scene’s key (how light or dark it is). Map to 18% of display range for average-key scene

User-specified; high key or low key

\[
L_m(x, y) = \frac{a}{L_w(x, y)}
\]

\[
L_d(x, y) = \frac{L_m(x, y)}{1 + L_m(x, y)}
\]
Global operator

It seldom reaches 1 since the input image does not have infinitely large luminance values.

\[ L_d(x, y) = \frac{L_m(x, y) \left( 1 + \frac{L_m(x, y)}{L_{white}^2(x, y)} \right)}{1 + L_m(x, y)} \]

\[ L_{white} = 0.5 \quad 1.0 \quad 1.5 \quad 3 \quad \infty \]

\[ L_d \]

World luminance (L)

L_{white} is the smallest luminance to be mapped to 1

Dodging and burning (local operators)

- Area receiving a different exposure is often bounded by sharp contrast
- Find largest surrounding area without any sharp contrast

\[ L_{s_{blur}}(x, y) = L_m(x, y) \otimes G_s(x, y) \]

\[ V_s(x, y) = \frac{L_{s_{blur}}(x, y) - L_{s_{blur}}(x, y)}{2^s a/s^2 + L_{s_{blur}}} \]

\[ s_{max} \cdot |V_{s_{max}}(x, y)| < \varepsilon \]

Dodging and burning (local operators)

\[ L_d(x, y) = \frac{L_m(x, y)}{1 + L_{s_{max}}^{blur}(x, y)} \]

- A darker pixel (smaller than the blurred average of its surrounding area) is divided by a larger number and become darker (dodging)
- A brighter pixel (larger than the blurred average of its surrounding area) is divided by a smaller number and become brighter (burning)
- Both increase the contrast
Dodging and burning

Frequency domain
- First proposed by Oppenheim in 1968!
- Under simplified assumptions,
  \[ \text{image} = \text{illuminance} \times \text{reflectance} \]
  
  low-frequency attenuate more
  high-frequency attenuate less

Oppenheim
- Taking the logarithm to form density image
- Perform FFT on the density image
- Apply frequency-dependent attenuation filter
  \[ s(f) = (1 - c) + c \frac{kf}{1 + kf} \]
- Perform inverse FFT
- Take exponential to form the final image

Fast Bilateral Filtering for the Display of High-Dynamic-Range Images
Fredo Durand & Julie Dorsey
SIGGRAPH 2002
A typical photo
- Sun is overexposed
- Foreground is underexposed

Gamma compression
- $X \rightarrow X^\gamma$
- Colors are washed-out

Gamma compression on intensity
- Colors are OK, but details (intensity high-frequency) are blurred

Chiu et al. 1993
- Reduce contrast of low-frequencies
- Keep high frequencies
The halo nightmare

- For strong edges
- Because they contain high frequency

Durand and Dorsey

- Do not blur across edges
- Non-linear filtering

Edge-preserving filtering

- Blur, but not across edges
- Anisotropic diffusion [Perona & Malik 90]
  - Blurring as heat flow
  - LCIS [Tumblin & Turk]
- Bilateral filtering [Tomasi & Manduci, 98]
Start with Gaussian filtering

- Spatial Gaussian $f$

$$J = f \otimes I$$

Gaussian filter as weighted average

$$J(x) = \sum_{\xi} f(x, \xi) I(\xi)$$

The problem of edges

- Here, $I(\xi)$ “pollutes” our estimate $J(x)$
- It is too different

$$J(x) = \sum_{\xi} f(x, \xi) I(\xi)$$
Principle of Bilateral filtering

- [Tomasi and Manduchi 1998]
- Penalty $g$ on the intensity difference

$$J(x) = \frac{1}{k(x)} \sum_{\xi} f(x, \xi) \ g(I(\xi) - I(x)) \ I(\xi)$$

Bilateral filtering

- [Tomasi and Manduchi 1998]
- Spatial Gaussian $f$

$$J(x) \ \frac{1}{k(x)} \ \ f(x, \xi) \ \ g(I(\xi) - I(x)) \ \ I(\xi)$$

Bilateral filtering

- [Tomasi and Manduchi 1998]
- Spatial Gaussian $f$
- Gaussian $g$ on the intensity difference

$$J(x) \ \frac{1}{k(x)} \ \ f(x, \xi) \ \ g(I(\xi) - I(x)) \ \ I(\xi)$$

Normalization factor

- [Tomasi and Manduchi 1998]
- $k(x) = \sum_{\xi} \left[ f(x, \xi) \ g(I(\xi) - I(x)) \right]$
Contrast reduction

\[ J(x) = \frac{1}{k(x)} \sum_{\xi} f(x, \xi) g(I(\xi) - I(x)) I(\xi) \]

Contrast reduction

Input HDR image

Contrast too high!

Contrast reduction

Input HDR image

Intensity

Color

Large scale

Fast Bilateral Filter

Contrast reduction
Bilateral filter is slow!

- Compared to Gaussian filtering, it is much slower because the kernel is not fixed.
- Durand and Dorsey proposed an approximate approach to speed up.
- Paris and Durand proposed an even-faster approach in ECCV 2006. We will cover this one when talking about computational photography.

Log domain

- Logarithm is a crude approximation to the perceived brightness.
- Gradients in log domain correspond to ratios (local contrast) in the luminance domain.

Gradient Domain High Dynamic Range Compression

Raanan Fattal    Dani Lischinski    Michael Werman

SIGGRAPH 2002
The method in 1D

- Given: a log-luminance image \( H(x,y) \)
- Compute an attenuation map \( \Phi(\|\nabla H\|) \)
- Compute an attenuated gradient field \( G \):
  \[
  G(x, y) = \nabla H(x, y) \cdot \Phi(\|\nabla H\|)
  \]
- Problem: \( G \) may not be integrable!

Solution

- Look for image \( I \) with gradient closest to \( G \) in the least squares sense.
- \( I \) minimizes the integral:
  \[
  \iint F(\nabla I, G) dx dy
  \]
  \[
  F(\nabla I, G) = \|\nabla I - G\|^2 = \left( \frac{\partial I}{\partial x} - G_x \right)^2 + \left( \frac{\partial I}{\partial y} - G_y \right)^2
  \]

- Poisson equation:
  \[
  \frac{\partial^2 I}{\partial x^2} + \frac{\partial^2 I}{\partial y^2} = \frac{\partial G_x}{\partial x} + \frac{\partial G_y}{\partial y}
  \]

The method in 2D

- Given: a log-luminance image \( H(x,y) \)
- Compute an attenuation map \( \Phi(\|\nabla H\|) \)
- Compute an attenuated gradient field \( G \):
  \[
  G(x, y) = \nabla H(x, y) \cdot \Phi(\|\nabla H\|)
  \]
- Problem: \( G \) may not be integrable!

Solve

- Poisson equation:
  \[
  \frac{\partial^2 I}{\partial x^2} + \frac{\partial^2 I}{\partial y^2} = \frac{\partial G_x}{\partial x} + \frac{\partial G_y}{\partial y}
  \]
  \[
  G_x(x, y) - G_x(x-1, y) + G_y(x, y) - G_y(x, y-1)
  \]
  \[
  I(x+1,y) + I(x-1,y) + I(x,y+1) + I(x,y-1) - 4I(x,y)
  \]

\[
\begin{bmatrix}
.. & 1 & ... & 1 & -4 & 1 & ... & 1 & ..
\end{bmatrix}
\begin{bmatrix}
I
\end{bmatrix}
= 
\begin{bmatrix}
\end{bmatrix}
\]
Solving Poisson equation

- No analytical solution
- Multigrid method
- Conjugate gradient method

Attenuation

- Any dramatic change in luminance results in large luminance gradient at some scale
- Edges exist in multiple scales. Thus, we have to detect and attenuate them at multiple scales
- Construct a Gaussian pyramid $H_i$

Attenuation

$$\varphi_k(x, y) = \left( \frac{\|\nabla H_k(x, y)\|}{\alpha} \right)^{\beta - 1}$$

$$\alpha = 0.1 \nabla H$$

Multiscale gradient attenuation
Final gradient attenuation map

Performance
- Measured on 1.8 GHz Pentium 4:
  - 512 x 384: 1.1 sec
  - 1024 x 768: 4.5 sec
- Can be accelerated using processor-optimized libraries.

Informal comparison

Gradient domain [Fattal et al.]
Photographic [Reinhard et al.]
Bilateral [Durand et al.]
Informal comparison

Gradient domain [Fattal et al.]
Bilateral [Durand et al.]
Photographic [Reinhard et al.]

Evaluation of Tone Mapping Operators using a High Dynamic Range Display

Patrick Ledda    Alan Chalmers
Tom Troscinko    Helge Seetzen

SIGGRAPH 2005

Six operators

- H: histogram adjustment
- B: bilateral filter
- P: photographic reproduction
- I: iCAM
- L: logarithm mapping
- A: local eye adaption

23 scenes

Scene 1  Scene 2  Scene 3  Scene 4  Scene 5
Scene 6  Scene 7  Scene 8  Scene 9  Scene 10
Scene 11 Scene 12 Scene 13 Scene 14 Scene 15
Experiment setting

- HDR display to temapping
- Result tonemapping result

Preference matrix

- Ranking is easier than rating.
- 15 pairs for each person to compare. A total of 345 pairs per subject.

<table>
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<tr>
<th></th>
<th>tmo1</th>
<th>tmo2</th>
<th>tmo3</th>
<th>tmo4</th>
<th>tmo5</th>
<th>tmo6</th>
<th>Score</th>
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</table>

preference matrix (tmo2->tmo4, tom2 is better than tmo4)

Statistical measurements

- Statistical measurements are used to evaluate:
  - Agreement: whether most agree on the ranking between two tone mapping operators.
  - Consistency: no cycle in ranking. If all are confused in ranking some pairs, it means they are hard to compare. If someone is inconsistent alone, his ranking could be dropped.

Overall similarity

- Scene 8

<table>
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<tr>
<th></th>
<th>P</th>
<th>H</th>
<th>B</th>
<th>L</th>
<th>I</th>
<th>A</th>
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<td>2</td>
<td>4</td>
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<tr>
<td>L</td>
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Summary

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<th>Overall Similarity: Color</th>
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<table>
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<table>
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</tbody>
</table>

Not settled yet!

- Some other experiment said bilateral are better than others.
- For your reference, photographic reproduction performs well in both reports.
- There are parameters to tune and the space could be huge.

References

- Raanan Fattal, Dani Lischinski, Michael Werman, Gradient Domain High Dynamic Range Compression, SIGGRAPH 2002.