

Tone mapping

Digital Visual Effects, Spring 2009

Yung-Yu Chuang

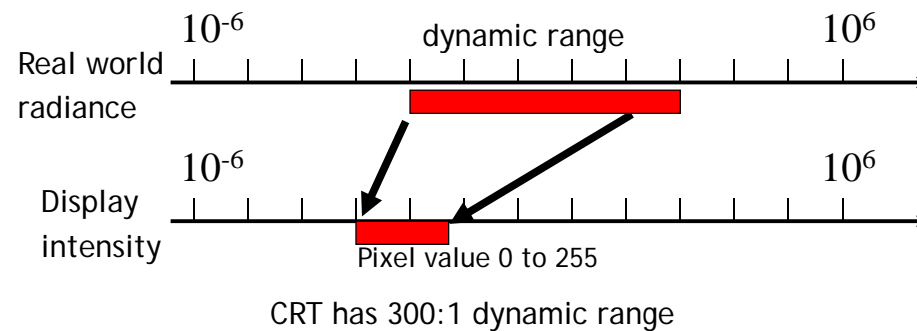
2009/3/5

with slides by Fredo Durand, and Alexei Efros

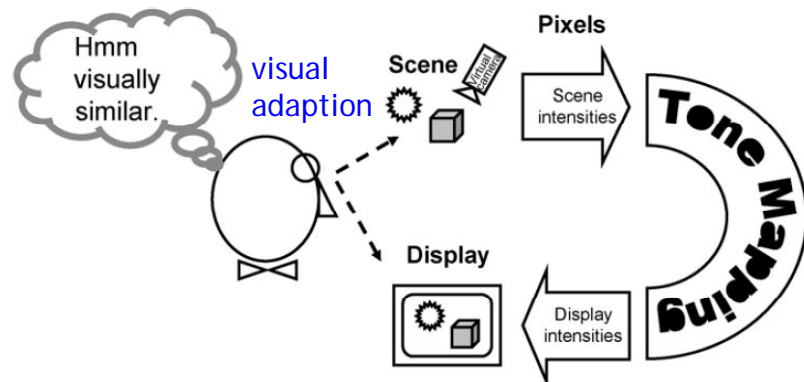
Tone mapping

- 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?



The ultimate goal is a visual match



We do not need to reproduce the true radiance as long as it gives us a visual match.

Eye is not a photometer!



- Dynamic range along the visual pathway is only around 32:1.
- The key is adaptation

Eye is not a photometer!



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

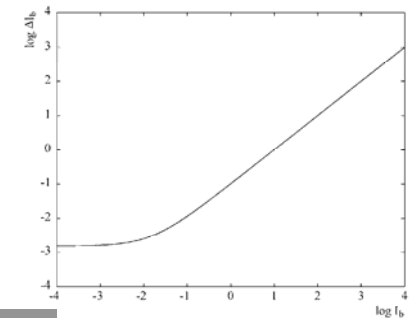
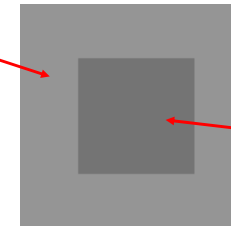
We are more sensitive to contrast

- Weber's law

Just-noticeable
Difference (JND)

$$\frac{\Delta I_b}{I_b} \sim 1\%$$

background
intensity



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

Preliminaries

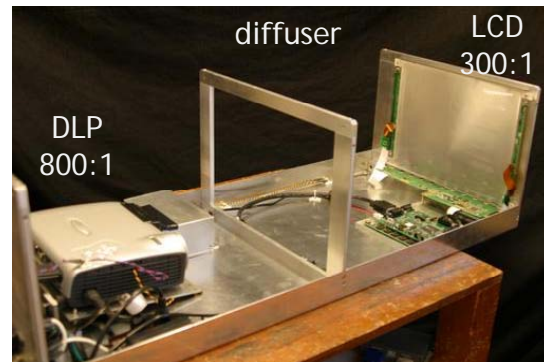
- For color images

$$\begin{bmatrix} R_d \\ G_d \\ B_d \end{bmatrix} = \begin{bmatrix} L_d \frac{R_w}{L_w} \\ L_d \frac{G_w}{L_w} \\ L_d \frac{B_w}{L_w} \end{bmatrix}$$

- Log domain is usually preferred.

HDR Display

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



Theoretically,
240,000:1.

Due to imperfect
optical depth,
54,000:1 measured

HDR display system, Sunnybrook Technology, SIGGRAPH2004

Sunnybrook HDR display

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

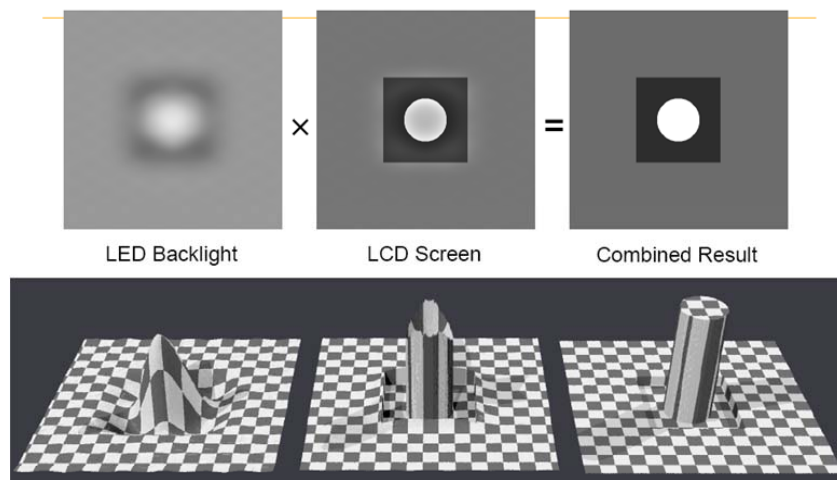


Low-res B&W backlight

High-res color foreground

Slide from the 2005 Siggraph course on HDR

How it works



Slide from the 2005 Siggraph course on HDR

Brightside HDR display



37"
200000:1

Acquired
by [Dolby](#)

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

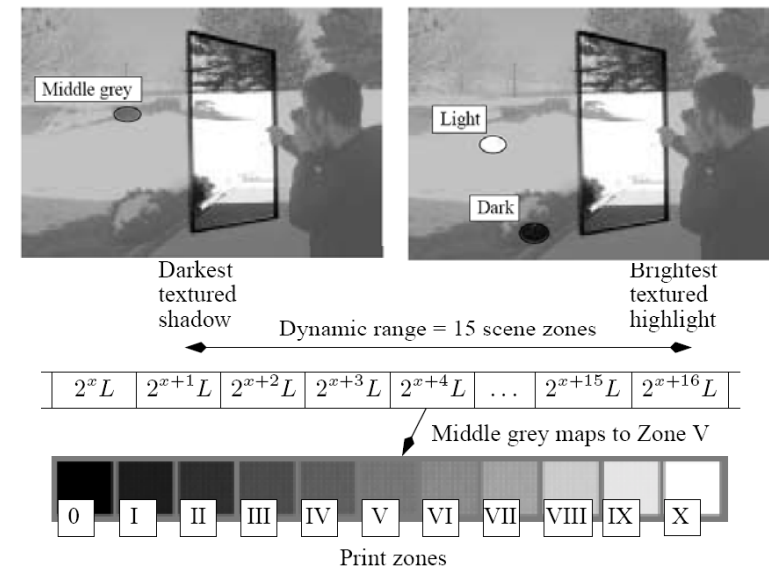
Photographic Tone Reproduction for Digital Images

Erik Reinhard Mike Stark
Peter Shirley Jim Ferwerda
SIGGRAPH 2002

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

Zone system



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

The Zones

The Zones

0 Solid black; the same as the film rebate

I Nearly black; just different from Zone 0

II The first hint of texture

III Textured shadow; the first recognizable shadow detail

IV Average shadow value on Caucasian skin, foliage and buildings

V Middle grey; the pivot value; light foliage, dark skin

VI Caucasian skin, textured light grey; shadow on snow

VII Light skin; bright areas with texture, such as snow in low sunlight

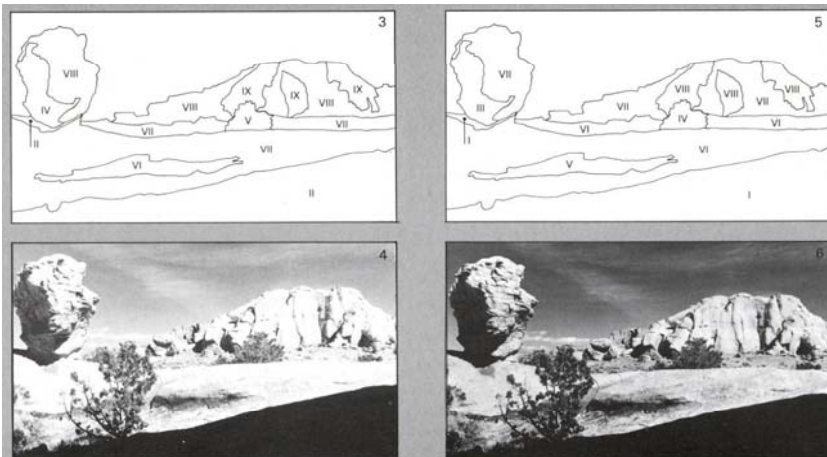
VIII Highest zone with any texture

IX Pure untextured white



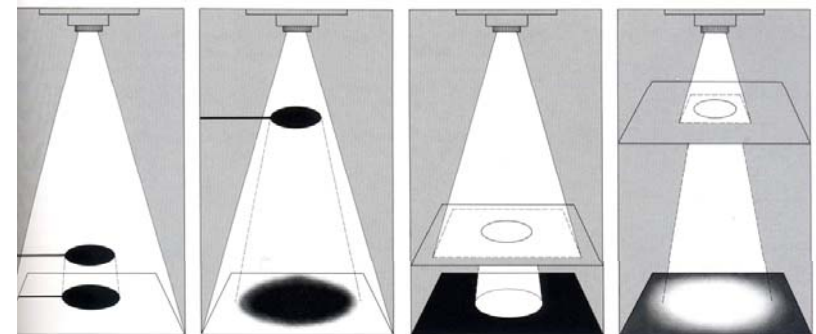
The Zone system

- You decide to put part of the system in a given zone

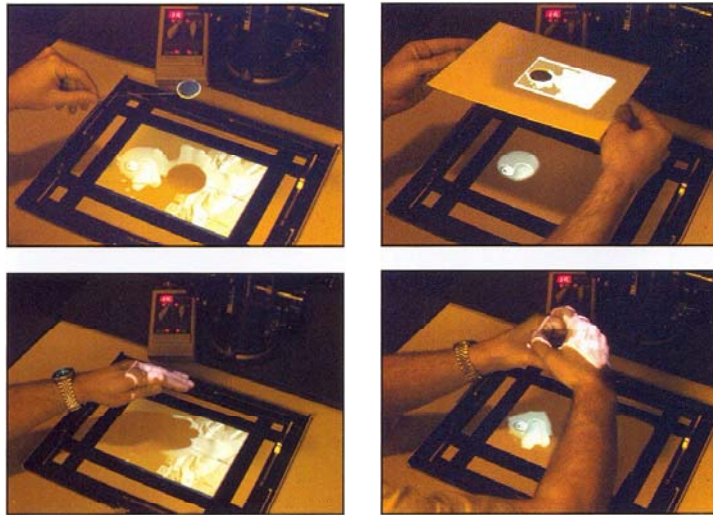


Dodging and burning

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



Dodging and burning

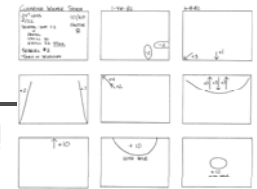


dodging

burning

From Photography by London et al.

Dodging and burning



- Must be done for every single print!



Straight print

After dodging and burning

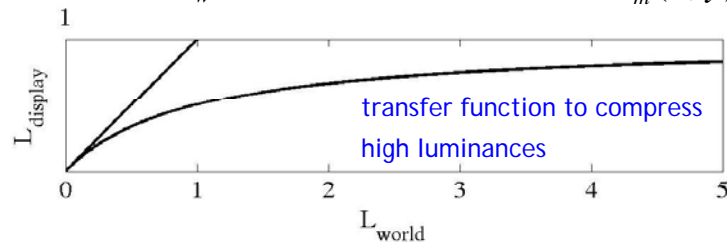
Global operator

$$\bar{L}_w = \exp\left(\frac{1}{N} \sum_{x,y} \log(\delta + L_w(x,y))\right)$$

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

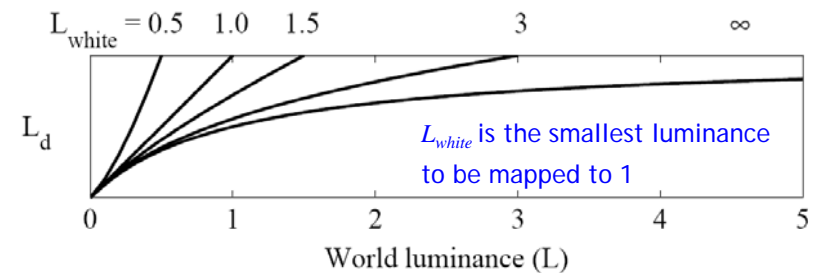
$$L_m(x,y) = \frac{a}{L_w} L_w(x,y) \quad L_d(x,y) = \frac{L_m(x,y)}{1 + L_m(x,y)}$$

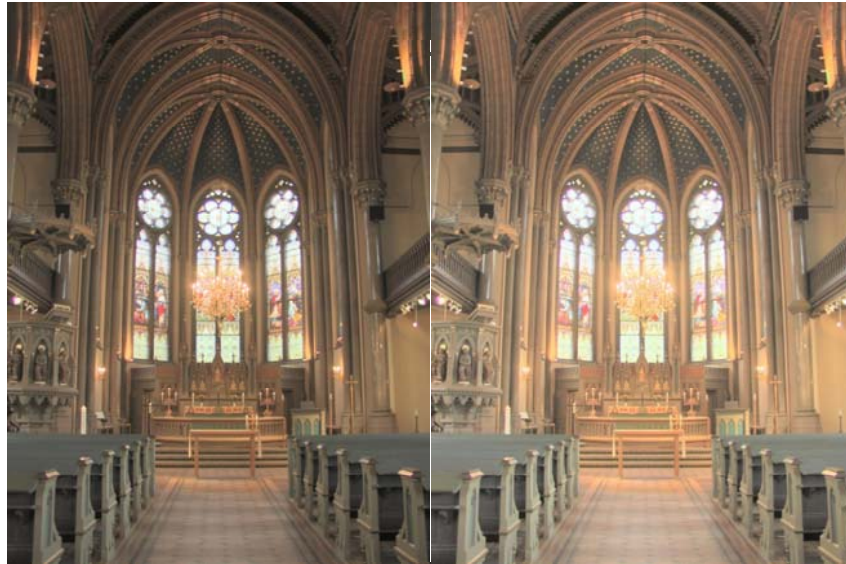


Global operator

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

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





low key (0.18)

high key (0.5)

Dodging and burning (local operators)

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

$$L_s^{blur}(x, y) = L_m(x, y) \otimes G_s(x, y)$$

$$V_s(x, y) = \frac{L_s^{blur}(x, y) - L_{s+1}^{blur}(x, y)}{2^\phi a/s^2 + L_s^{blur}}$$

$$s_{max} : |V_{s_{max}}(x, y)| < \epsilon$$

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



Simple operator

Dodging-and-burning

Fast Bilateral Filtering for the Display of High-Dynamic-Range Images

Frédo Durand & Julie Dorsey

SIGGRAPH 2002

Frequency domain

- First proposed by Oppenheim in 1968!
- Under simplified assumptions,

image = illuminance * 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

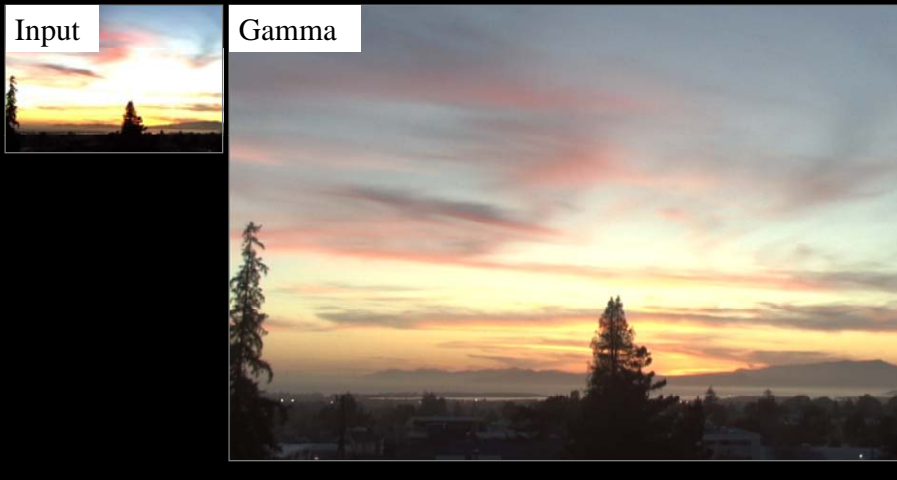
A typical photo

- Sun is overexposed
- Foreground is underexposed



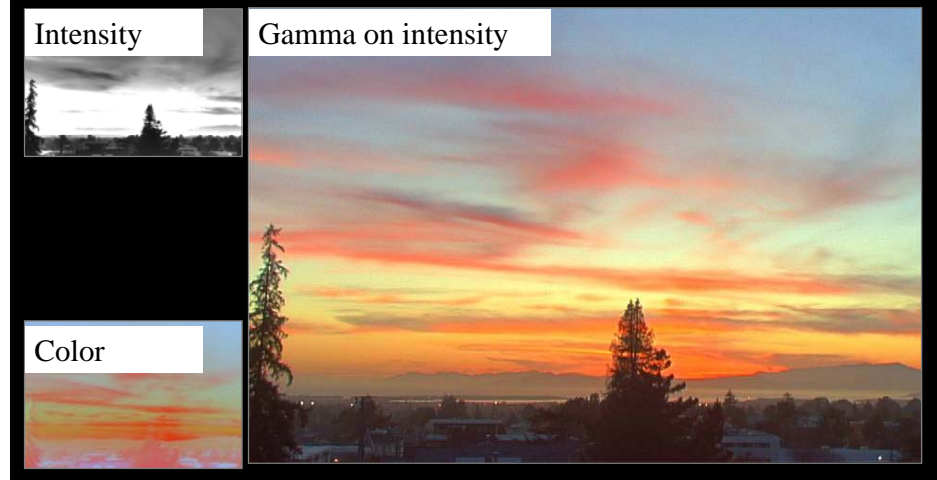
Gamma compression

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



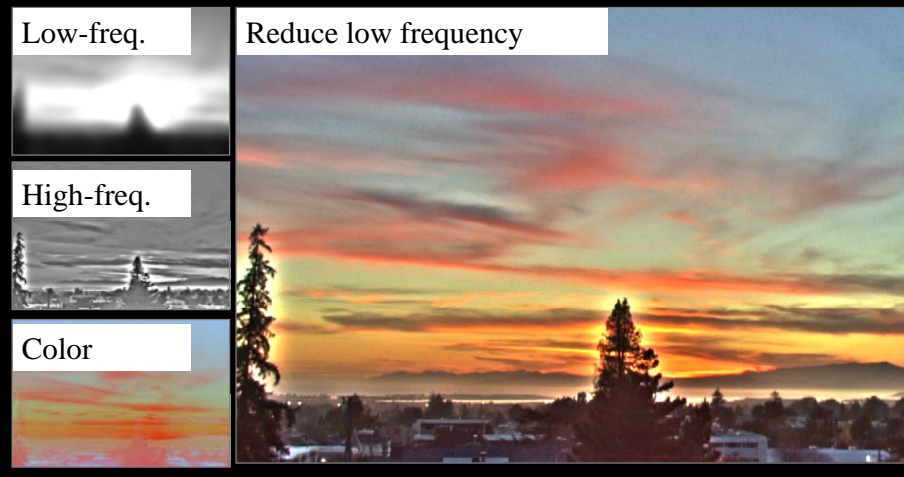
Gamma compression on intensity

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



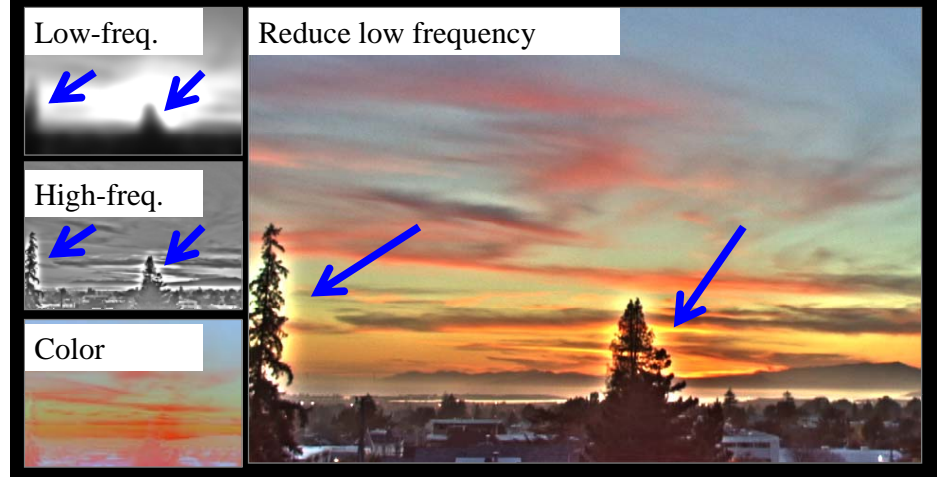
Chiu et al. 1993

- Reduce contrast of low-frequencies
- Keep high frequencies



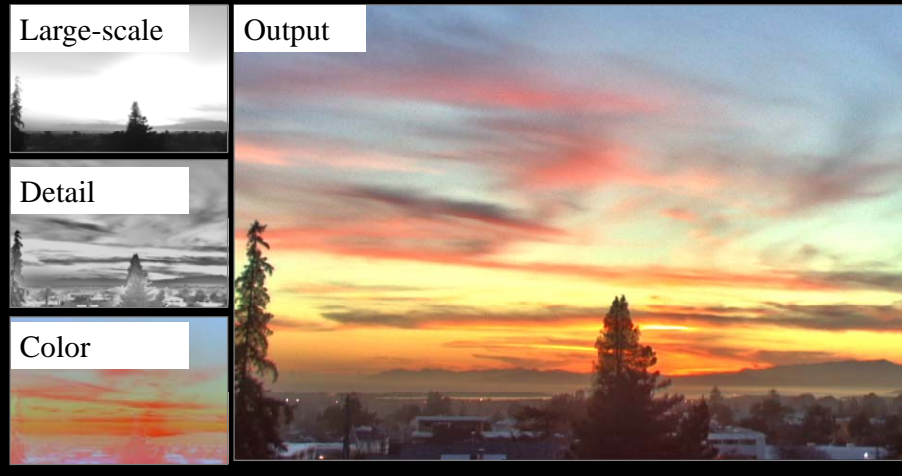
The halo nightmare

- For strong edges
- Because they contain high frequency



Durand and Dorsey

- Do not blur across edges
- Non-linear filtering



Edge-preserving filtering

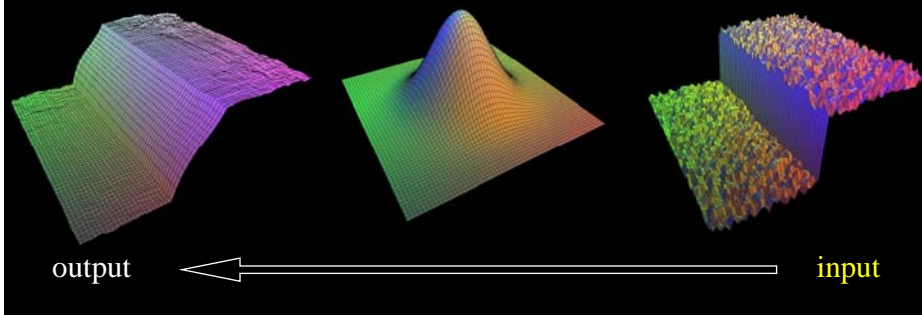
- Blur, but not across edges



- Anisotropic diffusion [Perona & Malik 90]
 - Blurring as heat flow
 - LCIS [Tumblin & Turk]
- Bilateral filtering [Tomasi & Manduci, 98]

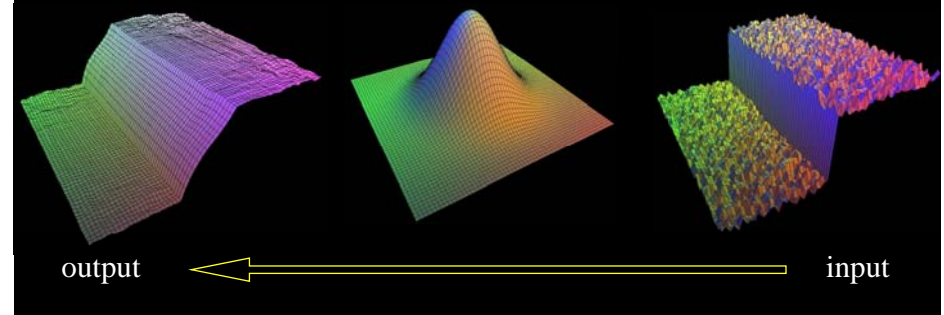
Start with Gaussian filtering

- Here, input is a step function + noise



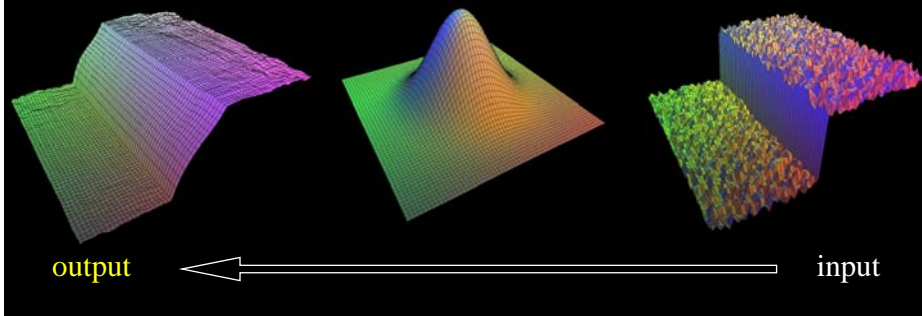
Start with Gaussian filtering

- Spatial Gaussian f

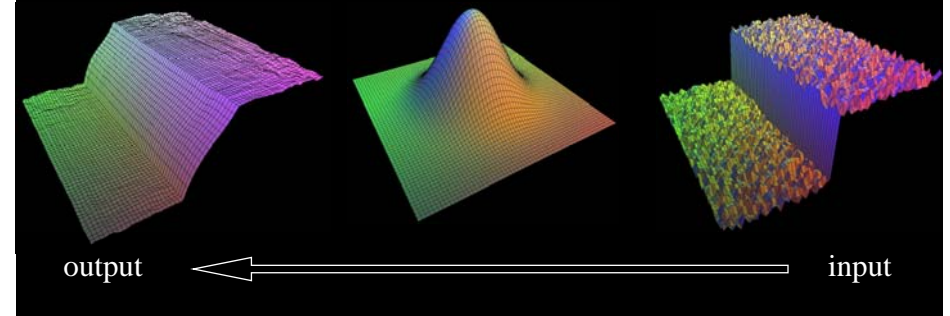


Start with Gaussian filtering

- Output is blurred

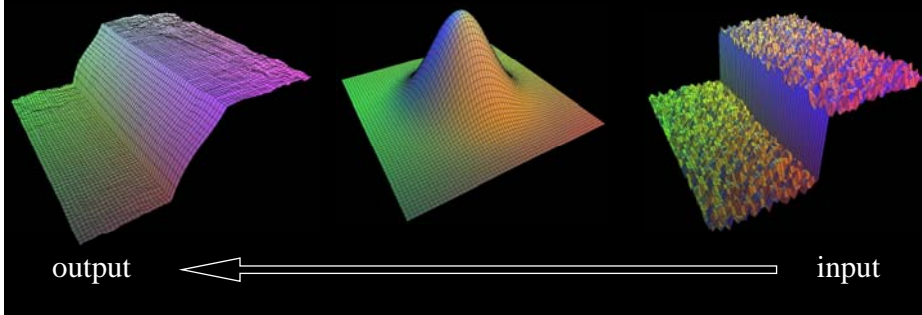


Gaussian filter as weighted average



The problem of edges

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



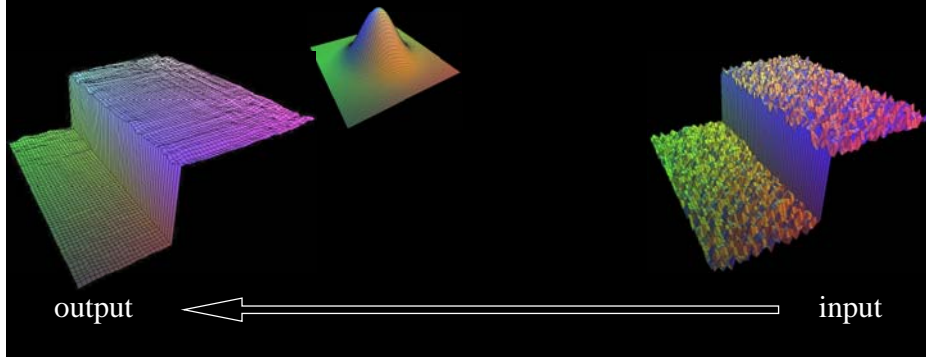
Principle of Bilateral filtering

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



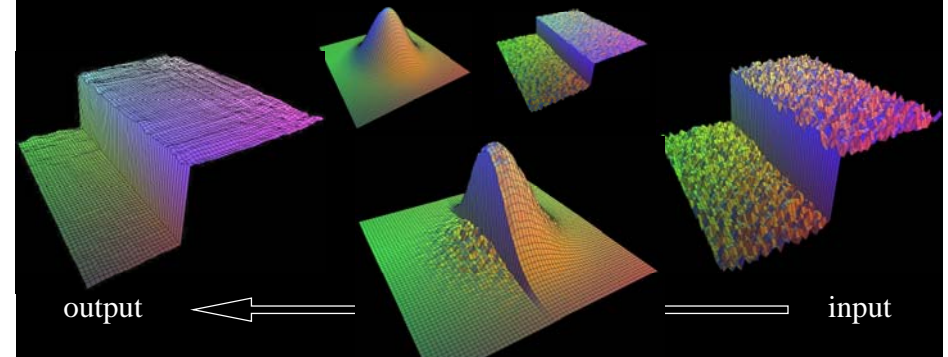
Bilateral filtering

- [Tomasi and Manduchi 1998]
- Spatial Gaussian f



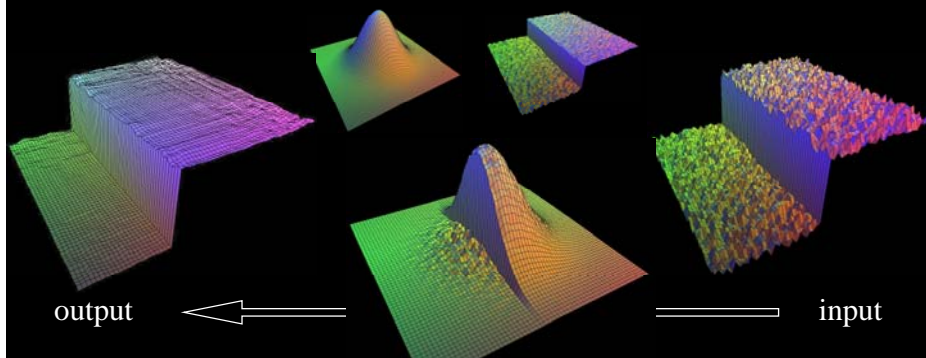
Bilateral filtering

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



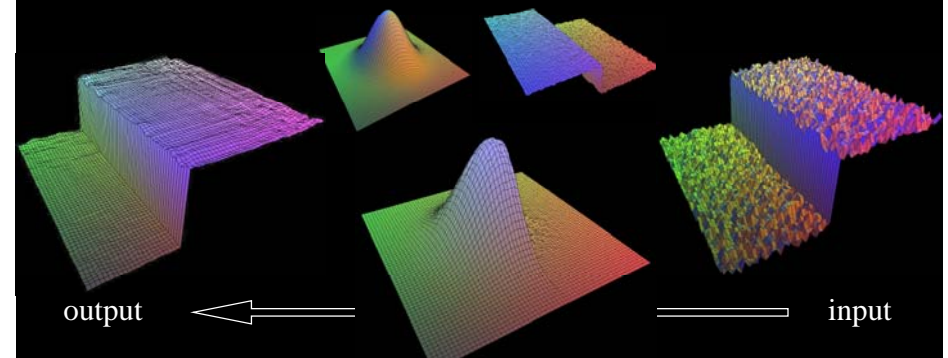
Normalization factor

- [Tomasi and Manduchi 1998]
- $k(x) =$



Bilateral filtering is non-linear

- [Tomasi and Manduchi 1998]
- The weights are different for each output pixel



Contrast reduction

Input HDR image



Contrast too high!

Contrast reduction

Input HDR image



Intensity



Color

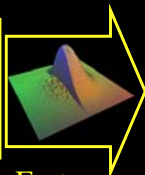


Contrast reduction

Input HDR image



Intensity

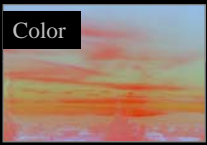


Large scale



Fast Bilateral Filter

Color

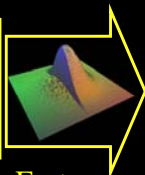


Contrast reduction

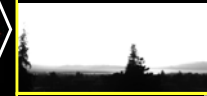
Input HDR image



Intensity



Large scale



Detail

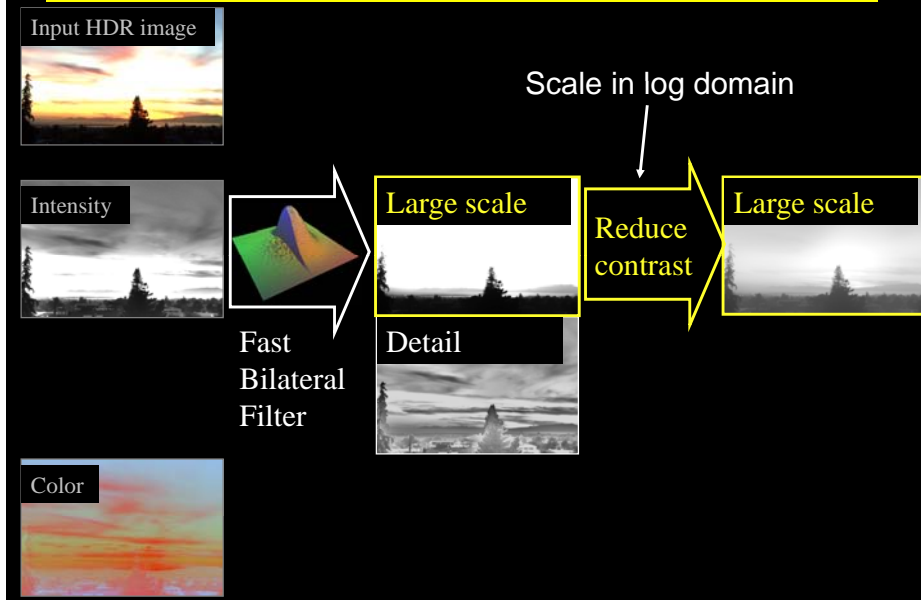


Fast Bilateral Filter

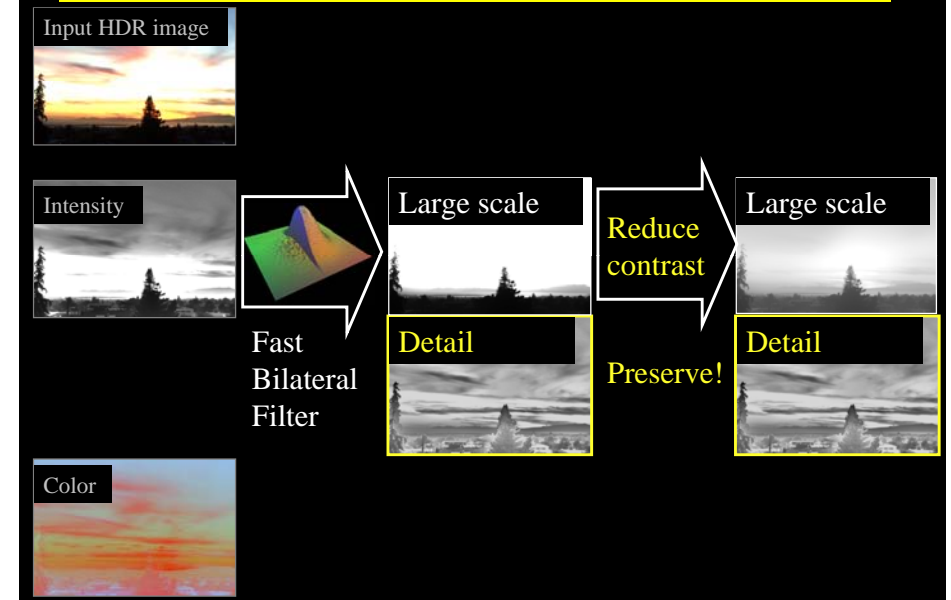
Color



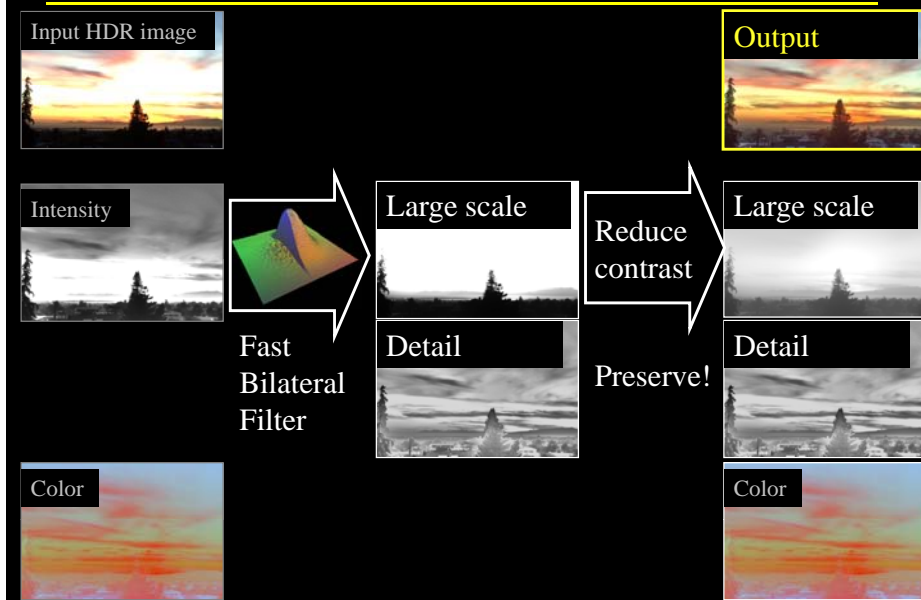
Contrast reduction



Contrast reduction



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.



Oppenheim

bilateral

Gradient Domain High Dynamic Range Compression

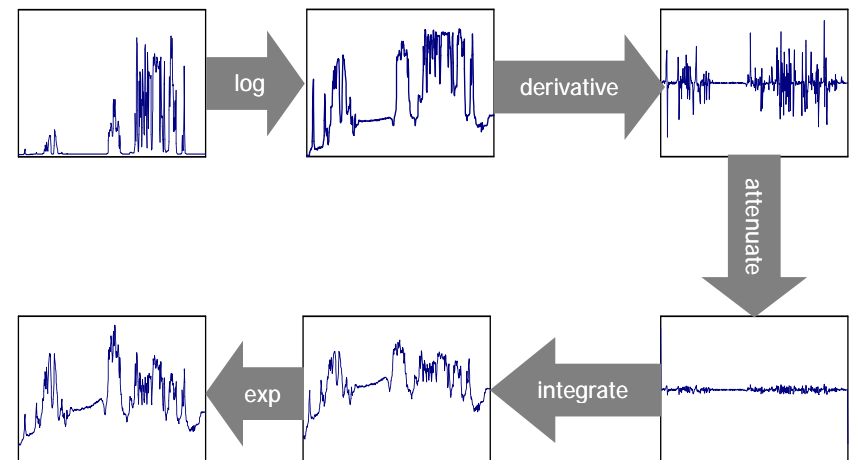
Raanan Fattal Dani Lischinski Michael Werman

SIGGRAPH 2002

Log domain

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

The method in 1D



The method in 2D

- Given: a log-luminance image $H(x,y)$
- Compute an *attenuation map* $\Phi(\|\nabla H\|)$
- Compute an attenuated gradient field \mathbf{G} :

$$G(x, y) = \nabla H(x, y) \cdot \Phi(\|\nabla H\|)$$

- Problem: \mathbf{G} is not integrable!

Solution

- Look for image \mathbf{I} with gradient closest to \mathbf{G} in the least squares sense.
- \mathbf{I} minimizes the integral: $\iint F(\nabla I, \mathbf{G}) dx dy$

$$F(\nabla I, \mathbf{G}) = \|\nabla I - \mathbf{G}\|^2 = \left(\frac{\partial I}{\partial x} - G_x\right)^2 + \left(\frac{\partial I}{\partial y} - G_y\right)^2$$

$$\longrightarrow \frac{\partial^2 I}{\partial x^2} + \frac{\partial^2 I}{\partial y^2} = \frac{\partial G_x}{\partial x} + \frac{\partial G_y}{\partial y} \quad \text{Poisson equation}$$

Solving Poisson equation

- No analytical solution
- Multigrid method
- Conjugate gradient method

Solve $\frac{\partial^2 I}{\partial x^2} + \frac{\partial^2 I}{\partial y^2} = \frac{\partial G_x}{\partial x} + \frac{\partial G_y}{\partial y}$

$G_x(x, y) - G_x(x-1, y) + G_y(x, y) - G_y(x, y-1)$

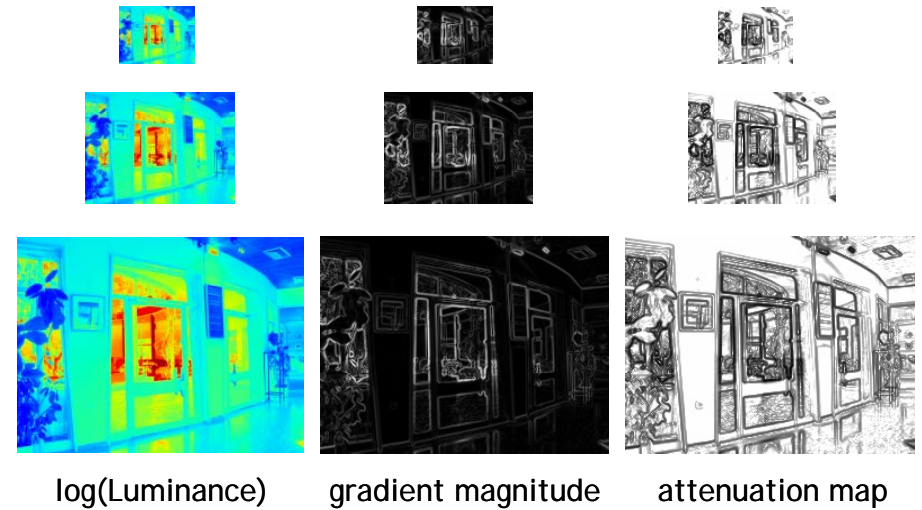
$I(x+1, y) + I(x-1, y) + I(x, y+1) + I(x, y-1) - 4I(x, y)$

$$\begin{bmatrix} \dots & 1 & \dots & 1 & -4 & 1 & \dots & 1 & \dots \end{bmatrix} \begin{bmatrix} \mathbf{I} \end{bmatrix} = \begin{bmatrix} \end{bmatrix}$$

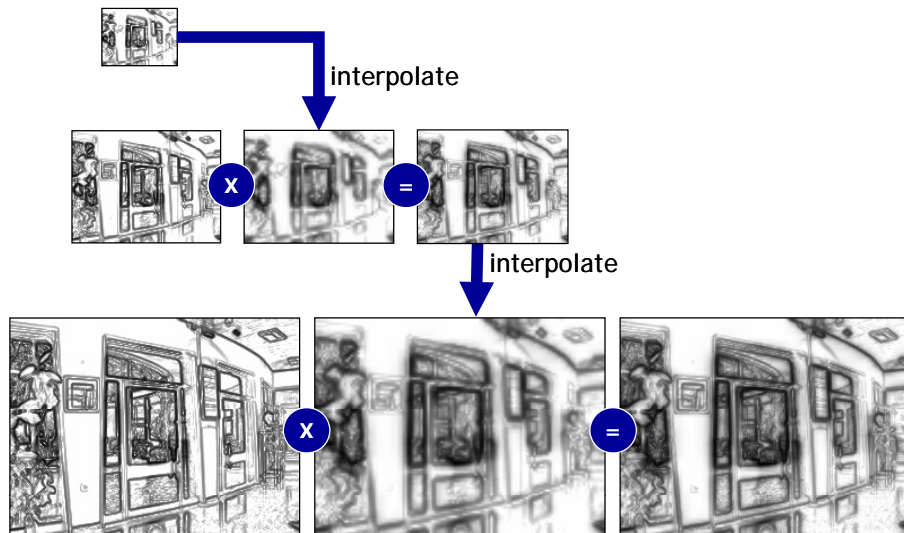
Attenuation

- 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

$$\text{Attenuation } \varphi_k(x, y) = \left(\frac{\|\nabla H_k(x, y)\|}{\alpha} \right)^{\beta-1} \quad \beta \sim 0.8$$
$$\alpha = 0.1\overline{\nabla H}$$



Multiscale gradient attenuation



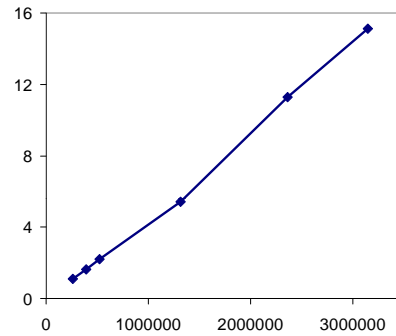
Final gradient attenuation map



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.]

Bilateral
[Durand et al.]

Photographic
[Reinhard et al.]

Informal comparison



Gradient domain
[Fattal et al.]

Bilateral
[Durand et al.]

Photographic
[Reinhard 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

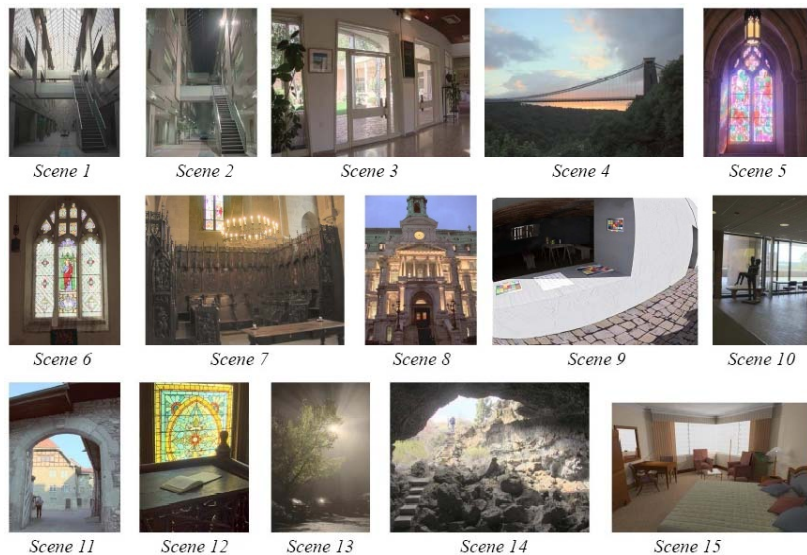
Patrick Ledda Alan Chalmers
Tom Troscinko Helge Seetzen

SIGGRAPH 2005

Six operators

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

23 scenes



Experiment setting



Preference matrix

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

	<i>tmo</i> ₁	<i>tmo</i> ₂	<i>tmo</i> ₃	<i>tmo</i> ₄	<i>tmo</i> ₅	<i>tmo</i> ₆	Score
<i>tmo</i> ₁	-	1	0	0	1	1	3
<i>tmo</i> ₂	0	-	0	1	1	0	2
<i>tmo</i> ₃	1	1	-	1	1	1	5
<i>tmo</i> ₄	1	0	0	-	0	0	1
<i>tmo</i> ₅	0	0	0	1	-	1	2
<i>tmo</i> ₆	0	1	0	1	0	-	2

preference matrix (*tmo*₂->*tmo*₄, *tom*₂ is better than *tmo*₄)

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



	<i>P</i>	<i>H</i>	<i>B</i>	<i>L</i>	<i>I</i>	<i>A</i>	Total
<i>P</i>	-	24	46	42	10	32	154
<i>H</i>	24	-	44	32	8	12	120
<i>B</i>	2	4	-	8	2	4	20
<i>L</i>	6	16	40	-	4	12	78
<i>I</i>	38	40	46	44	-	38	206
<i>A</i>	16	36	44	36	10	-	142

Summary

Overall Similarity: Color

<i>I</i>	<i>P</i>	<i>H</i>	<i>A</i>	<i>L</i>	<i>B</i>
<u>3712</u>	<u>3402</u>	<u>2994</u>	<u>2852</u>	<u>1902</u>	<u>1696</u>

Bright Detail

<i>I</i>	<i>A</i>	<i>P</i>	<i>H</i>	<i>B</i>	<i>L</i>
<u>823</u>	<u>688</u>	<u>569</u>	<u>549</u>	<u>474</u>	<u>347</u>

Dark Detail

<i>P</i>	<i>A</i>	<i>I</i>	<i>L</i>	<i>H</i>	<i>B</i>
<u>815</u>	<u>793</u>	<u>583</u>	<u>491</u>	<u>485</u>	<u>283</u>

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.
- Fredo Durand, Julie Dorsey, [Fast Bilateral Filtering for the Display of High Dynamic Range Images](#), SIGGRAPH 2002.
- Erik Reinhard, Michael Stark, Peter Shirley, Jim Ferwerda, [Photographics Tone Reproduction for Digital Images](#), SIGGRAPH 2002.
- Patrick Ledda, Alan Chalmers, Tom Troscianko, Helge Seetzen, [Evaluation of Tone Mapping Operators using a High Dynamic Range Display](#), SIGGRAPH 2005.
- Jiangtao Kuang, Hiroshi Yamaguchi, Changmeng Liu, Garrett Johnson, Mark Fairchild, [Evaluating HDR Rendering Algorithms](#), ACM Transactions on Applied Perception, 2007.