HDR imaging and the Bilateral Filter

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Picture dynamic range: Guess!

Real world: pure black $10^{-6}$ to pure white $10^6$

Picture: $10^{-6}$ to $10^6$
Picture dynamic range

- Typically 1:20 or 1:50
  - Black is \(~ 50\times\) darker than white

- Max 1:500

Real world

```
\begin{array}{c|c}
10^{-6} & 10^6 \\
\hline
\end{array}
```

Picture

```
\begin{array}{c|c}
10^{-6} & 10^6 \\
\hline
\end{array}
```

Low contrast
Problem 1: record the information

- The range of illumination levels that we encounter is 10 to 12 orders of magnitudes.
- Negatives/sensors can record 2 to 3 orders of magnitude.
Problem 2: Display the information

- Match limited contrast of the medium
- Preserve details

Real world

10^{-6} \quad \text{High dynamic range} \quad 10^6

Low contrast

Picture

10^{-6} \quad 10^6
Multiple exposure photography

- Sequentially measure all segments of the range

Real world

10^{-6} \quad \text{High dynamic range} \quad 10^6

Low contrast

Picture

10^{-6} \quad 10^6
Multiple exposure photography

- Sequentially measure all segments of the range

Real world: $10^{-6} \rightarrow$ High dynamic range: $10^{6}$

Picture: $10^{-6} \rightarrow$ Low contrast: $10^{6}$
Multiple exposure photography

- Sequentially measure all segments of the range

Real world

10^{-6} \quad \text{High dynamic range} \quad 10^{6}

Picture

10^{-6} \quad \text{Low contrast} \quad 10^{6}

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Multiple exposure photography

- Sequentially measure all segments of the range

Real world

\[10^{-6} \quad \text{High dynamic range} \quad 10^6\]

Picture

\[10^{-6} \quad \text{Low contrast} \quad 10^6\]
Multiple exposure photography

• Sequentially measure all segments of the range

Real world

10^{-6} \quad \text{High dynamic range} \quad 10^{6}

Picture

10^{-6} \quad \text{Low contrast} \quad 10^{6}

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Multiple exposure photography

- Sequentially measure all segments of the range

Real world

- $10^{-6}$
- High dynamic range
- $10^6$

Picture

- $10^{-6}$
- Low contrast
- $10^6$

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How do we vary exposure?

• Options:
  – Shutter speed
  – Aperture
  – ISO
  – Neutral density filter
Tradeoffs

- **Shutter speed**
  - Range: ~30 sec to 1/4000sec (6 orders of magnitude)
  - Pros: reliable, linear
  - Cons: sometimes noise for long exposure

- **Aperture**
  - Range: ~f/1.4 to f/22 (2.5 orders of magnitude)
  - Cons: changes depth of field
  - Useful when desperate

- **ISO**
  - Range: ~100 to 1600 (1.5 orders of magnitude)
  - Cons: noise
  - Useful when desperate

- **Neutral density filter**
  - Range: up to 4 densities (4 orders of magnitude) & can be stacked
  - Cons: not perfectly neutral (color shift), not very precise, need to touch camera (shake)
  - Pros: works with strobe/flash, good complement when desperate
Questions?
HDR image using multiple exposure

- Given N photos at different exposure
- Recover a HDR color for each pixel

- We’ll study Debevec and Malik’s 97 algorithm
If we know the response curve

- Just look up the inverse of the response curve
- But how do we get the curve?
Calibrating the response curve

• Two basic solutions
  – Vary scene luminance and see pixel values
    • Assumes we control and know scene luminance
  – Vary exposure and see pixel value for one scene luminance
    • But note that we can usually not vary exposure more finely than by 1/3 stop

• Best of both:
  – Vary exposure
  – Exploit the large number of pixels
The Algorithm

Image series

Δt = 10 sec
Δt = 1 sec
Δt = 1/10 sec
Δt = 1/100 sec
Δt = 1/1000 sec

Pixel Value $Z = f(\text{Exposure})$

exposure: essentially # photons

Exposure = Radiance $\times$ Δt

$\log \text{Exposure} = \log \text{Radiance} + \log \Delta t$

Slide adapted from Alyosha Efros who borrowed it from Paul Debevec
Δt don't really correspond to pictures. Oh well.
Response curve

- Exposure is unknown, fit to find a smooth curve

Assuming unit radiance for each pixel

After adjusting radiances to obtain a smooth response curve

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The math

- unknowns: response curve $f$ and radiance of pixels
- for each pixel $i$ and image $j$
  - Pixel Value $Z_{ij} = f(\text{Exposure}_{i,j})$
  - $\log \text{Exposure} = \log \text{Radiance}_i + \log \Delta t_j$
- Easier to deal with inverse function (in log) $g = \log (f^{-1})$

$$\log \text{Radiance}_i + \log \Delta t_j = g(Z_{ij})$$

- We have $\#\text{pixels} \times \#\text{images}$ equations
Inverse response curve \( g \)

- Discretize pixel values
  - but ignore saturated black and white pixels
- Enforce smoothness (improves results)
The Math

- For each pixel site $i$ in each image $j$, want:
  \[ \log \text{Radiance}_i + \log \Delta t_j = g(Z_{ij}) \]

- Solve the overdetermined linear system:

\[
\sum_{i=1}^{N} \sum_{j=1}^{P} \left[ \log \text{Radiance}_i + \log \Delta t_j - g(Z_{ij}) \right] + \lambda \sum_{z=Z_{\text{min}}}^{Z_{\text{max}}} g''(z)^2
\]

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function [g,1E]=gsolve(Z,B,l,w)

n = 256;
A = zeros(size(Z,1)*size(Z,2)+n+1,n+size(Z,1));
b = zeros(size(A,1),1);

k = 1;                   % Include the data-fitting equations
for i=1:size(Z,1)
    for j=1:size(Z,2)
        wij = w(Z(i,j)+1);
        A(k,Z(i,j)+1) = wij; A(k,n+i) = -wij; b(k,1) = wij * B(i,j);
        k=k+1;
    end
end
A(k,129) = 1;             % Fix the curve by setting its middle value to 0
k=k+1;

for i=1:n-2
    % Include the smoothness equations
    A(k,i)=l*w(i+1); A(k,i+1)=-2*l*w(i+1); A(k,i+2)=l*w(i+1);
    k=k+1;
end

x = A\b;                  % Solve the system using SVD
Result: digital camera

Kodak DCS460
1/30 to 30 sec

Recovered response curve

Pixel value

log Exposure

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Reconstructed radiance map
Result: color film

- Kodak Gold ASA 100, PhotoCD

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Recovered response curves

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Recap

- **Curve calibration**
  - Take many images of static scene (1/3 stop)
  - Solve optimization problem

- **HDR multiple-exposure merging**
  - Take multiple exposures (e.g. every 2 stops)
  - (optional) align images
  - for each pixel, use picture(s) where properly exposed
    - use inverse response curve and exposure time
  - Output: one image where each pixel has full dynamic range, stored e.g. in float aka radiance map
The Radiance map

Slide stolen from Alyosha Efros who stole it from Paul Debevec
The Radiance map

Linearly scaled to display device

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Questions?
Problem 2: Display the information

- Match limited contrast of the medium
- Preserve details

Real world

10^{-6} \rightarrow 10^6

Low contrast

High dynamic range

Picture

10^{-6} \rightarrow 10^6

Low contrast
The second half: contrast reduction

- Input: high-dynamic-range image
  - (floating point per pixel)
Naïve technique

• Scene has 1:10,000 contrast, display has 1:100
• Simplest contrast reduction?
Naïve: Gamma compression

- $X \rightarrow X^\gamma$ (where $\gamma=0.5$ in our case)
- But… colors are washed-out. Why?

Input

Gamma

applied independently on R, G & B

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Gamma compression on intensity

- Colors are OK, but details (intensity high-frequency) are blurred
Oppenheim 1968, Chiu et al. 1993

- Reduce contrast of low-frequencies
- Keep high frequencies

Low-freq. | Reduce low frequency
---|---

High-freq.

Color
The halo nightmare

• For strong edges
• Because they contain high frequency

Low-freq.  

High-freq.  

Color  

Reduce low frequency
Our approach

- Do not blur across edges
- Non-linear filtering
Bilateral filter

• Tomasi and Manduci 1998
  http://www.cse.ucsc.edu/~manduchi/Papers/ICCV98.pdf

• Related to
  – SUSAN filter
    [Smith and Brady 95] http://citeseer.ist.psu.edu/smith95susan.html
  – Digital-TV [Chan, Osher and Chen 2001]
    http://citeseer.ist.psu.edu/chan01digital.html
Start with Gaussian filtering

• Here, input is a step function + noise

\[ J = f \otimes I \]
Gaussian filter as weighted average

- Weight of $\xi$ depends on distance to $x$

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

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

[Tomasi and Manduchi 1998]

- Spatial Gaussian f
- Gaussian g on the intensity difference

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

[Tomasi and Manduchi 1998]

- \( k(x) = \sum_{\xi} f(x, \xi) \cdot g(I(\xi) - I(x)) \)

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

Noisy input

Bilateral filter 7x7 window
Basic denoising

Bilateral filter

Median 3x3
Basic denoising

Bilateral filter

Median 5x5
Basic denoising

Bilateral filter

Bilateral filter – lower
Questions?
Why do we say it is non-linear?

• It does not respect $\text{bila}(f+g)=\text{bila}(f)+\text{bila}(g)$
Bilateral filtering is non-linear

[Tomasi and Manduchi 1998]

- The weights are different for each output pixel

\[ J(x) = \frac{1}{k(x)} \sum_{\xi} f(x, \xi) g(I(\xi) - I(x)) I(\xi) \]
• The bilateral filter uses the 3D distance
Questions?
Handling uncertainty

- Sometimes, not enough “similar” pixels
- Happens for specular highlights
- Can be detected using normalization $k(x)$
- Simple fix (average with output of neighbors)
Contrast reduction

Input HDR image

Contrast too high!
Contrast reduction

Input HDR image

Intensity

Color
Contrast reduction

Input HDR image

Intensity

Bilateral Filter

in log

Large scale

Color

Spatial sigma: 2 to 5% image size
Range sigma: 0.4 (in log 10)
Contrast reduction

Input HDR image

Intensity

Color

Bilateral Filter in log

Large scale

Detail

Detail = log intensity - large scale (residual)
Contrast reduction

Input HDR image

Intensity

Bilateral Filter in log

Large scale

Detail

Color

Reduce contrast

Large scale
Contrast reduction

Input HDR image

Intensity

Fast Bilateral Filter

Large scale

Detail

Reduce contrast

Preserve!

Large scale

Detail

Color
Contrast reduction

Input HDR image

Fast Bilateral Filter

Intensity

Large scale

Detail

Color

Reduce contrast

Preserve!

Output

Large scale

Detail

Color
Reduction

• To reduce contrast of base layer
  – scale in the log domain
  $\Rightarrow \gamma$ exponent in linear space

• Set a target range: $\log_{10} (5)$

• Compute range in the base (log) layer: $(\text{max-min})$

• Deduce $\gamma$ using an elaborate operation known as division

• You finally need to normalize so that the biggest value in the (linear) base is 1 (0 in log):
  – Offset the compressed based by its max
Contrast reduction in log domain

- Set target large-scale contrast (e.g. $\log_{10} 10$)
  - In **linear** output, we want 1:10 contrast for large scale
- Compute range of input large scale layer:
  - largeRange = $\max(\text{inLogLarge}) - \min(\text{inLogLarge})$
- Scale factor $k = \log_{10} (10) / \text{largeRange}$
- Normalize so that the biggest value is 0 in log

\[
\text{outLog} = \text{inLogDetail} + \text{inLogLarge} \times k - \max(\text{inLogLarge})
\]
Alternative explanation

• Explanation 1 (previous slides):
  – \( \text{outLog} = k \text{inLogLarge} + \text{inLogDetail} \) (ignoring offset)

• Explanation 2
  – \( \text{outLog} = k \text{inLogIntensity} + (1-k) \text{detail} \)
  – Reduce contrast of full intensity layer
  – Add back some detail

• Same final effect since
  – \( \text{inLogDetail} + \text{inLogLarge scale} = \text{inLogIntensity} \)
  – But different philosophy: decomposition vs. add back detail
What matters

• Spatial sigma: not very important
• Range sigma: quite important
• Use of the log domain for range: critical
  – Because HDR and because perception sensitive to multiplicative contrast
  – CIELab might be better for other applications
• Luminance computation
  – Not critical, but has influence
  – see our Flash/no-flash paper [Eisemann 2004] for smarter function
Speed

• Direct bilateral filtering is slow (minutes)

• Next time: acceleration
Tone mapping evaluation

• Recent user experiments to evaluate competing tone mapping

• Interestingly, the former concludes bilateral is the worst, the latter that it is the best!
  – They choose to test a different criterion: fidelity vs. preference

• More importantly, they focus on algorithm and ignore parameters

From Kuang et al.

Adapted from Ledda et al.
Alternative explanation

• Contrast reduction w/ intrinsic layers
  [Tumblin et al. 1999]

• For 3D scenes: Reduce only illumination layer
Dirty vision for cool graphics

Three wrongs make one right

• Analyze image
  – Intrinsic image: albedo & illumination
  – Simple bilateral filter

• Modify
  – In our case, reduce contrast of large-scale (illumination)

• Recombine
  – Get final image
Related tools

• Photoshop “Local adaptation”

• Lightroom Fill Light

• Lightzone Relight
Questions?
References
Other tone mapping references

- Tumblin, J., "Three Methods For Detail-Preserving Contrast Reduction For Displayed Images" [http://www.cs.northwestern.edu/~jet/publications.html](http://www.cs.northwestern.edu/~jet/publications.html)
- Photographic Tone Reproduction for Digital Images
  Erik Reinhard, Mike Stark, Peter Shirley and Jim Ferwerda [http://www.cs.utah.edu/~reinhard/cdrom/](http://www.cs.utah.edu/~reinhard/cdrom/)
- Retinex at Nasa [http://dragon.larc.nasa.gov/retinex/background/retpubs.html](http://dragon.larc.nasa.gov/retinex/background/retpubs.html)
Tone mapping code

- http://www.mpi-sb.mpg.de/resources/pfstools/
- http://scanline.ca/exrtools/
- http://www.cis.rit.edu/mcsl/icam/hdr/
http://people.csail.mit.edu/sparis/bf_course/
http://www.hdrsoft.com/resources/dri.html
http://www.clarkvision.com/imagedetail/dynamicrange2/
http://www.debevec.org/HDRI2004/
http://www.luminous-landscape.com/tutorials/hdr.shtml
http://www.anyhere.com/gward/hdrenc/
http://www.openexr.com/
http://gl.ict.usc.edu/HDRShop/
http://www.anyhere.com/
http://www.cybergrain.com/tech/hdr/
HDR combination papers

• Steve Mann http://genesis.eecg.toronto.edu/wyckoff/index.html
• Paul Debevec http://www.debevec.org/Research/HDR/
• Mitsunaga, Nayar, Grossberg http://www1.cs.columbia.edu/CAVE/projects.rad_cal/rad_cal.php
Questions?
Smarter HDR capture


Implemented in Photosphere http://www.anyhere.com/

- Image registration (no need for tripod)
- Lens flare removal
- Ghost removal

Images Greg Ward
Image registration

- How to robustly compare images of different exposure?
- Use a black and white version of the image thresholded at the median
  - Median-Threshold Bitmap (MTB)
- Find the translation that minimizes difference
- Accelerate using pyramid
Alignment Results

5 unaligned exposures  Close-up detail  MTB alignment

Time: About .2 second/exposure for 3 MPixel image

Slide from Siggraph 2005 course on HDR
Automatic “Ghost” Removal

Before

After
Variance-based Detection
Region Masking

Slide from Siggraph 2005 course on HDR

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Best Exposure in Each Region
Lens Flare Removal
Extension: HDR video

- Kang et al. Siggraph 2003
  http://portal.acm.org/citation.cfm?id=882262.882270

Figure 1: High dynamic range video of a driving scene. Top row: Input video with alternating short and long exposures. Bottom row: High dynamic range video (tonemapped).
Figure 3: Two input exposures from the driving video. The radiance histogram is shown on top. The red graph goes with the long exposure frame (bottom left), while the green graph goes with the short exposure frame (bottom right). Notice that the combination of these graphs spans a radiance range greater than a single exposure can capture.
HDR encoding

- Most formats are lossless
- Adobe DNG (digital negative)
  - Specific for RAW files, avoid proprietary formats
- RGBE
  - 24 bits/pixels as usual, plus 8 bit of common exponent
  - Introduced by Greg Ward for Radiance (light simulation)
  - Enormous dynamic range
- OpenEXR
  - By Industrial Light + Magic, also standard in graphics hardware
  - 16bit per channel (48 bits per pixel) 10 mantissa, sign, 5 exponent
  - Fine quantization (because 10 bit mantissa), only 9.6 orders of magnitude
- JPEG 2000
  - Has a 16 bit mode, lossy
HDR formats

- Summary of all HDR encoding formats (Greg Ward): http://www.anyhere.com/gward/hdrenc/hdr_encodings.html
- http://www.openexr.com/
- High Dynamic Range Video Encoding (MPI) http://www.mpi-sb.mpg.de/resources/hdrvideo/
HDR code

- HDRShop [http://gl.ict.usc.edu/HDRShop/] (v1 is free)
- Greg Ward Phososphere HDR browser and image combination with registration (Macintosh, command-line version under Linux) with source code [http://www.anyhere.com/]
- Photoshop CS2
- Idruna [http://www.idruna.com/photogenicshdr.html]
- MPI PFScalibration (includes source code) [http://www.mpii.mpg.de/resources/hdr/calibration/pfs.html]
- EXR tools [http://scanline.ca/exrtools/]
- HDR Image Editor [http://www.acm.uiuc.edu/siggraph/HDRIE/]
- CinePaint [http://www.cinepaint.org/]
- Photomatix [http://www.hdrsoft.com/]
- EasyHDR [http://www.astro.leszno.net/easyHDR.php]
- Artizen HDR [http://www.supportingcomputers.net/Applications/Artizen/Artizen.htm]
- Automated High Dynamic Range Imaging Software & Images [http://www2.cs.uh.edu/~somalley/hdri_images.html]
- Optipix [http://www.imaging-resource.com/SOFT/OPT/OPT.HTM]
HDR images

- http://www.debevec.org/Research/HDR/
- http://www.flickr.com/groups/hdr/
- http://www2.cs.uh.edu/~somalley/hdri_images.html#hdr_others
- http://www.sachform.de/download_EN.html
- http://lcavwww.epfl.ch/~Elmeylan/HdrImages/February06/February06.html
- http://lcavwww.epfl.ch/~Elmeylan/HdrImages/April04/april04.html