High-Dynamic-Range Imaging & Tone Mapping
Today’s Agenda

- Spatial color vision
- JPEG
- The dynamic range challenge
- Multiple exposures
- Estimating the response curve
- HDR merging: linear case
- Tone mapping
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• **Spatial color vision**
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Contrast Sensitivity Function

Campbell-Robson Chart

decreasing contrast

increasing spatial frequency
Contrast Sensitivity Function (CSF)

• The sensitivity of the luminance channel is much higher than the sensitivities of Blue-Yellow and Red-Green opponent channels.

• The shape of Luminance CSF is different than those of the color channels.

• Chromatic channels have maximal sensitivity for uniform fields.

Figure 1-18. Spatial contrast sensitivity functions for luminance and chromatic contrast.
Photoshop demo

• Image > Mode > Lab color
• Go to channel panel, select Lightness
• Filter > Blur > Gaussian Blur, e.g. 4 pixel radius
  – very noticeable
• Undo, then select a & b channels
• Filter > Blur > Gaussian Blur, same radius
  – hardly visible effect
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Opponents and image compression

- JPG, MPG, television
- Color opponents instead of RGB
  - YCrCB, similar to YUV
- Compress color more than luminance
  - downsample by factor of two for jpeg
  - less bandwidth for TV
- Exploit contrast sensitivity function
  - Compress high frequencies more
JPEG Compression

• Convert to YCbCr
  – half the resolution for Cr &Cb

• Perform Discrete Cosine Transform
to work in frequency space
  – Local DCT, 8x8 pixel blocks

• Use CSF for quantization
  – more bits for frequencies
    with more sensitivity (medium)

• Other usual coding tricks
  – entropy coding, smart order of blocks
Example

- 800 x 533 image

RGB | Lightness | a
---|---|---
Low quality JPEG (0 in Photoshop, 172 KB)
High quality JPEG (12 in Photoshop, 460 KB)
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Light, exposure and dynamic range

- Inside is too dark
- Outside is too bright
- Sun overexposed
- Foreground too dark
Dynamic Range

• The "dynamic range" of a scene is the contrast ratio between its brightest and darkest parts.

• Typical images displayed on screen are 24-bits:
  - 8-bits per color component (RGB)
  - 256 different intensity levels

• Real-world dynamic range is far greater than 256 intensity levels!
Real world dynamic range

- Eye can adapt from \( \sim 10^{-6} \) to \( 10^6 \) cd/m\(^2\)
- Often 1:100,000 in a scene
The world is high dynamic range

- Relative brightness of different scenes, ranging from 1 inside a dark room lit by a monitor to 2,000,000 looking at the sun. (Photos courtesy of Paul Debevec)
Picture dynamic range: Guess!

Real world

pure black

pure white

$10^{-6}$

$10^6$

Picture

$10^{-6}$

$10^6$
Picture dynamic range

- Typically 1:20 or 1:50
  - Black is ~ 50x darker than white

- Max 1:500

Real world:

\[10^{-6} \quad 10^{6}\]

Picture:

\[10^{-6} \quad 10^{6}\]

Low contrast
The dynamic range problem

- media (approximate and debatable)
  - 10:1 photographic print (higher for glossy paper)
  - 20:1 artist’s paints
  - 200:1 slide film
  - 500:1 negative film
  - 1000:1 LCD display
  - 2000:1 digital SLR (~11 bits)

- challenges
  - choosing which 6-12 bits of the world to include in your photograph (cell phone to professional SLR, respectively)
  - metering the world to help you make this decision, since the world has more dynamic range than any light meter
  - compressing 12 bits into 4 bits for print, or 10 for LCD
    - this is the tone mapping problem
Picture dynamic range

- Typically 1: 20 or 1:50
  - Black is ~ 50x darker than white
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.

![Graph showing range of illumination levels and negative/sensor recording capacity.](image-url)
Problem 2: Display the information

- Match limited contrast of the medium
- Preserve details
Without HDR & tone mapping
With HDR & tone mapping
http://fstoppers.com/best-technique-for-shooting-interiors-hdr-or-flash
Can be extreme

Not always cheesy

Not always cheesy

Today’s Agenda

• Multiple-exposure High-Dynamic-Range imaging

• Tone mapping using the bilateral filter
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Multiple exposure photography

- Sequentially measure all segments of the range

Real world vs. Picture contrast:
- **High dynamic range** from $10^{-6}$ to $10^6$
- **Low contrast** at $10^{-6}$
Multiple exposure photography

- Sequentially measure all segments of the range

Real world: $10^{-6}$ to $10^{6}$

High dynamic range

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

Low contrast

slide by Fredo Durand
Multiple exposure photography

- Sequentially measure all segments of the range

Real world

High dynamic range

10^{-6}  \quad 10^6

Low contrast

Picture

10^{-6}  \quad 10^6

slide by Fredo Durand
Multiple exposure photography

- Sequentially measure all segments of the range

Real world: $10^{-6}$ to $10^{6}$

High dynamic range

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

Low contrast
Multiple exposure photography

- Sequentially measure all segments of the range

Real world

10^-6 \hspace{2cm} \text{High dynamic range} \hspace{2cm} 10^6

Picture

10^-6 \hspace{2cm} \text{Low contrast} \hspace{2cm} 10^6
Multiple exposure photography

- Sequentially measure all segments of the range

Real world

$10^{-6}$ \hspace{2cm} High dynamic range \hspace{2cm} $10^{6}$

Low contrast

$10^{-6}$

Picture

$10^{-6}$

10^6

Real world

Low contrast

Picture

10^6

Real world

Low contrast

Picture

10^6

Real world

Low contrast

Picture

10^6

Real world

Low contrast

Picture

10^6

Real world

Low contrast

Picture

10^6
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

Slide after Siggraph 2005 course on HDR
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• Multiple exposures
• **Estimating the response curve**
• HDR merging: linear case
• Tone mapping
HDR Imaging

• estimate camera response curve
• capture multiple low dynamic range (LDR) exposures
• fuse LDR images into 32 bit HDR image
• possibly convert to absolute radiance
• application specific use:
  – image-based rendering lighting
  – tonemapping
  – …
Estimating the Response Curve

- not required when working with linear RAW images
- easiest option: use calibration chart
Estimating the Response Curve

- not required when working with linear RAW images
- easiest option: use calibration chart

linear RAW

known reflectance

pixel value

0 64 128 196 255
Estimating the Response Curve

- not required when working with linear RAW images
- easiest option: use calibration chart

![Colorchecker chart with pixel value and known reflectance graph]

E.g. JPEG
Linearizing LDR Exposures

- capture exposure, apply lookup table

\[ I_{\text{lin}} = f^{-1}(I) \]

- e.g. JPEG
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HDR merging: linear case

Problem statements:
• We have N images
  – Images are encoded linearly
  – Only the exposure changes: no motion
Getting linear images

- [http://www.mit.edu/~kimo/blog/linear.html](http://www.mit.edu/~kimo/blog/linear.html)
- ./dcrawx86 -v -H 0 -g 2.2 0 -o 1 DSC_\*nef

In a linear image, the value at every pixel is directly related to the number of photons received at that location on the sensor.
Image formation

- Scene radiance $L(x,y)$ reaches the sensor at a pixel $x, y$
- For each image $i$, radiance gets multiplied by exposure factor $k_i$
  - depends on shutter speed, ISO, etc
- Noise $n$ gets added
- values above 1 get clipped
  - depends on photosite well capacity

$$I_i(x, y) = \text{clip}(k_i L(x,y) + n)$$
Dynamic range

- In the highlights, we are limited by clipping
- In the shadows, we are limited by noise
Merging HDR

\[ I_i(x, y) = \text{clip}(k_i L(x, y) + n) \]

- For each pixel
  - figure out which images are useful
  - scale values appropriately according, ideally, to \( k_i \)
  - Voila!
Which images are useful

- Eliminate clipped pixels
  - e.g. $>0.99$

- Eliminate pixels that are too dark / too noisy
  - e.g. $<0.002$
Assembling HDR

• Figure out scale factor between images
  - From exposure data
  - Or by looking at ratios $I_i(x, y)/I_j(x, y)$
    - but only when both are good

• Compute weight map $w_i$ for each image

• Reconstruct full image using weighted combination

\[
\text{out}(x, y) = \frac{1}{\sum w_i(x, y)} \sum w_i(x, y) \frac{1}{k_i} I_i(x, y)
\]
Computing $k_i$

\[ I_i(x, y) = \text{clip}(k_i L(x,y) + n) \]

- Only up to global scale factor
- Actually compute $k_i/k_j$ for pairs of images
- Focus on pixels where
  - no clipping occurs & noise is negligible
- \[ I_i(x, y) = k_i L(x,y) \]
- get $k_i/k_j$ by considering $I_i/I_j$
- If linearity holds, should be the same for all pixels
- Use median for extra robustness
Computing $k_i$

$$I_i(x, y) = \text{clip}(k_i L(x, y) + n)$$

- Only up to global scale factor, e.g. $k_i/k_0$
- Actually compute $k_i/k_j$ for pairs of images
  - $k_i/k_j = \text{median}(I_i(x, y)/I_j(x, y))$
    - for pixels st. $w_i(x, y) > 0$ AND $w_j(x, y) > 0$
- Then compute $k_i/k_0$ by chaining these ratios
Special cases

- Some pixels might be underexposed or overexposed in all images
- Simple solution: don’t eliminate dark pixels in the brightest image or bright pixels in the darkest one.
HDR combination papers

- Steve Mann
  [http://genesis.eecg.toronto.edu/wyckoff/index.html](http://genesis.eecg.toronto.edu/wyckoff/index.html)
- Paul Debevec
- Mitsunaga, Nayar, Grossberg
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Problem 2: Display the information

- Match limited contrast of the medium
- Preserve details
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?

Applied independently on R, G & B

Input  Gamma
Gamma compression on intensity

- Colors are OK, but details (intensity high-frequency) are muddy
Contrast Sensitivity Function (CSF)

Figure 1-18. Spatial contrast sensitivity functions for luminance and chromatic contrast.
Gamma compression on intensity

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

- Reduce contrast of low-frequencies
- Keep mid and high frequencies
Homomorphic filtering

- Oppenheim, in the sixties
- Images are the product of illumination and albedo
  - Similarly, many sounds are the product of an envelope and a modulation
- Illumination is usually slow-varying
- Perform albedo-illumination using low-pass filtering of the \( \log \) image

- See also Koenderink "Image processing done right"
  [http://www.springerlink.com/(l1bpumaapconcjngteojwqv)/app/home/contribution.asp?referrer=parent&backto=issue,11,53;journal,1538,3333;linkingpublicationresults,1:105633,1](http://www.springerlink.com/(l1bpumaapconcjngteojwqv)/app/home/contribution.asp?referrer=parent&backto=issue,11,53;journal,1538,3333;linkingpublicationresults,1:105633,1)
The halo nightmare

- For strong edges
- Because they contain high frequency

Low-freq.

High-freq.

Color

Reduce low frequency
Instead use bilateral filter

- Do not blur across edges
- Non-linear filtering

Large-scale

Detail

Color

Output

slide by Fredo Durand
Bilateral filter

- Tomasi and Manduci 1998
  - http://www.cse.ucsc.edu/~manduchi/Papers/ICCV98.pdf
- Developed for denoising
- 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
  - sigma filter
- Full survey:
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 $x$

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

slide by Fredo Durand
The problem of edges

Here, \( I(\xi) \) “pollutes” our estimate \( J(x) \)

It is too different

\[
J(x) = \sum_{\xi} f(x, \xi) \quad I(\xi)
\]
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]

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

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

[Tomasi and Manduchi 1998]

- The weights are different for each output pixel

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

Bilateral filter

Median 3x3
Basic denoising

Bilateral filter  Medial 5x5
Basic denoising

Bilateral filter

Bilateral filter – lower sigma
Basic denoising

Bilateral filter

Bilateral filter – higher sigma
Contrast reduction

Input HDR image

Contrast too high!
Contrast reduction

Input HDR image

Intensity

intensity
= 0.4R + 0.7G + 0.01B

Color

R' = R/intensity
G' = G/intensity
B' = B/intensity

important to use ratios (makes it luminance invariant)
Contrast reduction

Input HDR image

Intensity

Large scale

Bilateral
Filter in log

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

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

Input HDR image

Intensity

Bilateral Filter in log

Color

Large scale

Reduce contrast

Large scale
Contrast reduction

Input HDR image

Intensity

Fast Bilateral Filter

Large scale

Detail

Reduce contrast

Preserve!

Large scale

Detail

Color

slide by Fredo Durand
Contrast reduction

Input HDR image

Intensity

Fast Bilateral Filter

Large scale

Detail

Reduce contrast

Preserve!

Large scale

Detail

Color

Output

Color

slide by Fredo Durand
Log domain

• Very important to work in the log domain
• Recall: humans are sensitive to multiplicative contrast
• With log domain, our notion of “strong edge” always corresponds to the same contrast
Contrast reduction in log domain

- Set target large-scale contrast (e.g. $\log_{10} 100$)
  - i.e. in linear output, we want 1:100 contrast for large scale
- Compute range of input large scale layer:
  - $\text{largeRange} = \max (\text{inLogLarge}) - \min (\text{inLogLarge})$
- Scale factor $k = \log_{10} (100) / \text{largeRange}$
- Normalize so that the biggest value is 0 in log
- Optional: amplify detail by $\text{detailAmp}$

\[
\text{outLog} = \text{detailAmp} \times \text{inLogDetail} + k(\text{inLogLarge} - \max (\text{inLogLarge}))
\]
Final output

- From last slide:
  \[ \text{outLog} = \text{detailAmp} \times \text{inLogDetail} + k(\text{inLogLarge} - \max(\text{inLogLarge})) \]
- \[ \text{outIntensity} = 10^{\text{outLog}} \]
- Recall that \( R', G', B' \) is the intensity-normalized RGB color
- \[ \text{outR} = \text{outIntensity} \times R' \]
- \[ \text{outG} = \text{outIntensity} \times G' \]
- \[ \text{outB} = \text{outIntensity} \times B' \]
Input Images
Tone-mapped Result
Recap

Input HDR image

Intensity

Fast Bilateral Filter IN LOG

Color

Detail

Large scale

Reduce contrast

Preserve!

detail = input log - large scale

Output

Large scale

Detail

Color

slide by Fredo Durand
Bells and whistles: increase detail

Input HDR image

Intensity

Fast Bilateral Filter IN LOG

Color

Large scale

Detail

detail = input log - large scale

Reduce contrast

Amplify

Large scale

Detail

Color

Output

slide by Fredo Durand
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 Flash/no-flash paper [Eisemann 2004] for smarter function
Speed

- Direct bilateral filtering is slow (minutes)

- Fast algorithm: bilateral grid
  - http://groups.csail.mit.edu/graphics/bilagrid/
  - http://graphics.stanford.edu/papers/gkdtrees/
What have we learnt?

• Log is good
• Luminance is different from chrominance
• Separate components:
  – Low and high frequencies
• Strong edges are important
Alternative: exposure fusion

• One single step for both multiple-exposure merging & tone mapping
  – http://research.edm.uhasselt.be/~tmertens/exposure_fusion/

Figure 2. Exposure fusion is guided by weight maps for each input image. A high weight means that a pixel should appear in the final image. These weights reflect desired image qualities, such as high contrast and saturation. Image courtesy of Jacques Joffre.