HIGH-DYNAMIC-RANGE PHOTOGRAPHY + TONE MAPPING

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Light, exposure and dynamic range

Exposure: how bright is the scene overall?

Dynamic range: contrast in the scene
- ratio of brightest to darkest intensity
The dynamic range challenge
Examples

Inside is too dark
Outside is too bright

Sun overexposed
Foreground too dark

After a slide by Frédo Durand
Low Dynamic Range (LDR)

- ✓ detail in shadows
- ✗ clipped highlights
- ✓ detail in highlights
- ✗ noisy/clipped shadows

[Durand and Dorsey 02]
Real world dynamic range

Eye can adapt from $\sim 10^{-6}$ to $10^6 \text{ cd/m}^2$

Often 1 : 100,000 in a scene
The real world is high dynamic range.
# Dynamic Range Examples

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*approximate and debatable*
Problem 1: Record the information

The range of illumination levels that we encounter is $10^{-6}$ to $10^6$ orders of magnitude.

Film/sensors can record 2-3 orders of magnitude.
Problem 2: Display the information

Match limited contrast of the medium while preserving details

Real world: $10^{-6}$ to $10^6$ high dynamic range

Picture/display: $10^{-6}$ to $10^6$ low contrast

After a slide by Frédo Durand
Without HDR & tone mapping
With HDR & tone mapping

[Wojciech Jarosz]
HDR today

HDR Off

HDR On
Application: Motion blur

Simulated Motion  Simulated Motion Blur  Actual Motion blur

LDR  [Debevec et al. 97]  HDR  [Debevec et al. 97]  [Debevec et al. 97]
Application: Inserting Synthetic Objects

[Debevec 98]
Application: Inserting Synthetic Objects

[Debevec 98]
Image Based Environment Lighting

HDR

LDR

[Reynante M. Martinez]

[Reynante M. Martinez]
App: Measuring material properties

Marble Block

HDR Photograph (log scale)
Application: Photography

“Sunset from Rigi Kaltbad”

[Wojciech Jarosz 2014]
Can be extreme

By Anthony Wong
http://abduzeedo.com/20-beautiful-hdr-pictures-part-3
Not always cheesy

By Alexandre Buisse

After a slide by Frédo Durand
Today

Multiple-exposure High-Dynamic-Range imaging

Tone mapping the image for display/print
At the end

Some practical tips when taking the photo
Representing HDR images

In general, need to represent extremely small and extremely large values

Typically some form of floating-point representation

Our FloatImage class already does this!

We’ll talk about storing/encoding HDR images later
Capturing HDR images
Capturing HDR

If the scene doesn’t have extreme dynamic range
- might not need “HDR” at all
- could just take one RAW image (> 8 bits)
- already higher dynamic range than display/JPEG
- make sure to use low ISO (and tripod)
“Abandoned Ship at Point Reyes” [Wojciech Jarosz 2014]
Capturing HDR

If the scene doesn’t have extreme dynamic range
- might not need HDR at all
- could just take one RAW image (> 8 bits)

High dynamic range scene
- bracket exposures
Multiple exposure photography

Sequentially measure all segments of the range

Real world: $10^{-6}$ high dynamic range $10^6$

Picture: $10^{-6}$ low contrast

After a slide by Frédéric Durand
Multiple exposure photography

Sequentially measure all segments of the range

Real world: 10^{-6} \quad high \text{ dynamic range} \quad 10^{6}

Picture: 10^{-6} \quad low \text{ contrast} \quad 10^{6}

After a slide by Frédéric Durand
Multiple exposure photography

Sequentially measure all segments of the range

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

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

low contrast

After a slide by Frédéric Durand
Multiple exposure photography

Sequentially measure all segments of the range

Real world:

Picture:

low contrast

high dynamic range

After a slide by Frédo Durand
Sequentially measure all segments of the range

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

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

After a slide by Frédéric Durand
Multiple exposure photography

Sequentially measure all segments of the range

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

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

high dynamic range

low contrast
“Matterhorn and Riffelsee”

[Wojciech Jarosz 2010]
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

**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

**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
HDR merging: linear case
Problem statement

We have N images
- images are encoded linearly
- only exposure changes: no motion

We want 1 single HDR image
- encoded with FloatImage class
- one value per x, y, c
- values may be >1
Getting linear images

http://www.mit.edu/~kimo/blog/linear.html


http://www.guillermoluijk.com/tutorial/dcraw/index_en.htm

./dcrawx86 -v -H 0 -g 2.2 0 -o 1 DSC_*nef
Image formation: photons to floats

Scene radiance $L(x,y)$ reaches the sensor at a pixel $x, y$

Value of pixel?

- depends on shutter speed, aperture, ISO (multiplicative factor)
- clips if $>1$
- noise gets added
Image formation: photons to floats

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, aperture, ISO)
- noise $n$ gets added
- values above 1 get clipped (depends on photosite well capacity)

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

In the highlights, we are limited by clipping
In the shadows, we are limited by noise

\[ l_i(x, y) = \text{clip}(k_i \times L(x,y) + n) \]
Simple in principle:
- imageA = 1/30th second (“brighter” image)
- imageB = 1/120th second (“darker” image)
- imageHDR = average(4·imageB, remove-clipped(imageA))
- assumes images have been linearized
General HDR merging

For each pixel
- figure out which images are useful
- scale values appropriately (ideally according to $k_i$)
- average scaled values from useful images

$l_i(x, y) = \text{clip}(k_i \cdot L(x, y) + n)$
Which images are useful?

Eliminate clipped pixels
- e.g. >0.99

Eliminate pixels that are too dark / too noisy
- e.g. <0.002
Eliminate bad pixels

In Assignment 5
We compute a weight map for each image
We use binary weights (0 or 1)
- but can be extended to full scalar (to better handle noise)
Weights can be different for different channels
Assembling HDR

Figure out scale factor between images
- from exposure data, or
- by looking at ratios $I_i(x,y)/I_i(x,y)$ (only when both are good)

Compute weight map $w_i$ for each image

Reconstruct full image using weighted combination

$$out(x,y) = \frac{1}{\sum w_i(x,y)} \sum w_i(x,y) \frac{1}{k_i} I_i(x,y)$$
Computing $k_i$ in PA 5

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

$l_i(x, y) = k_i \cdot L(x,y)$
get $k_i/k_j$ by considering $l_i/l_j$
If linearity holds, should be the same for all pixels
Use median for extra robustness
Computing $k_i$ in PA 5

Only up to global scale factor, e.g. $k_i/k_0$

Actually compute $k_i/k_j$ for pairs of images

$k_i/k_j = \text{median}(l_i(x,y)/l_j(x,y))$

- for pixels st. $w_i(x,y)>0$ AND $w_j(x,y)>0$

Then compute $k_i/k_0$ by chaining these ratios

$l_i(x, y) = \text{clip}(k_i*L(x,y)+n)$
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.
In the end: HDR image

Encoded with same FloatImage class

One single float value per x, y, c

numbers may be >1
Questions?
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://people.csail.mit.edu/hasinoff/hdrnoise/
Tone mapping
Today

Multiple-exposure High-Dynamic-Range imaging

Tone mapping the image for display/print
Problem 2: Display the information

Match limited contrast of the medium while preserving details

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

Photo/display: 10^{-6} - 10^{6}

high dynamic range

low contrast
Tone mapping

Called tone mapping operators

Two general categories:
- Global (spatially invariant)
- Local (spatially varying)
Tone mapping for very HDR scenes

Scene has >100,000:1 dynamic range, JPEG has 255:1

How can we compress the scene’s dynamic range?
Naïve technique?

Scene has \( >100,000:1 \) dynamic range, JPEG has \( 255:1 \) dynamic range.

How can we compress the scene’s dynamic range?

Scale linearly?

- If we scaled linearly from \( 100,000:1 \) to \( 255:1 \), everything but the sun would be black!
Global tone mapping operators

Gamma compression, applied independently on R,G,B
- output = e · input^\gamma (\gamma = 0.5 here)

Colors become washed-out.
- Why?

In addition to the gamma transform during RAW-to-JPEG conversion
Global tone mapping operators

Gamma compression on intensity only
Colors are OK, but details (high-frequency intensity) not
The importance of local contrast
Purposes of tone mapping

Technical:
- fitting a wide range of values into a small space while preserving differences between values as much as possible

Artistic
- reproduce what the photographer/artist feels she saw
- stylize the look of a photo
Mach bands
La Grande Jatte, Georges Seurat, 1884
Dodging & Burning

Dodging (makes print lighter)

Burning (makes print darker)
Dodging & Burning
Oppenheim 1968, Chiu et al. 1993

Reduce contrast of low-frequencies, preserve high frequencies

Reduction methods:
- Reduce low frequency
- Low-freq.
- High-freq.
- Color
Homomorphic filtering

Oppenhein, in the sixties

Images are the product of illumination and albedo

Illumination is usually slow-varying

Perform albedo-illumination separation using low-pass filtering of the log image

The halo nightmare

For strong edges; because they contain high frequency

Low-freq.

High-freq.

Color

Reduce low frequency

After a slide by Frédo Durand
The halo nightmare

Similar to unsharp mask of luminance in log domain

Low-freq.

High-freq.

Color

Reduce low frequency
Don’t blur across edges, decompose using bilateral filter

Durand and Dorsey 2002
Contrast reduction

Input HDR image

Contrast too high!
Contrast reduction

Input HDR image

Intensity

\[ \text{intensity} = 0.4R + 0.7G + 0.01B \]

Color

\[ R' = \frac{R}{\text{intensity}} \]
\[ G' = \frac{G}{\text{intensity}} \]
\[ B' = \frac{B}{\text{intensity}} \]

Important to use ratios (makes it luminance invariant)
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)

After a slide by Frédou Durand
Contrast reduction

Input HDR image

Intensity

Bilateral Filter in log

Large scale

Detail

Detail = log intensity - large scale (residual)

After a slide by Frédo Durand
Contrast reduction

Input HDR image

Intensity

Bilateral Filter in log

Large scale

Detail

Color

Reduce contrast

Large scale

After a slide by Frédéric Durand
Contrast reduction

Input HDR image

Intensity

Bilateral Filter in log

Large scale

Reduce contrast

Preserve!

Detail

Large scale

Detail

Color
Contrast reduction

After a slide by Frédo 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. targetRange = $\log_{10}(100)$)
- i.e. in linear output, we want 1:100 contrast for large scale

Compute range of input’s large-scale layer:
- largeRange = max(inLogLarge) - min(inLogLarge)

Scale factor $k = \frac{\text{targetRange}}{\text{largeRange}}$

Normalize so that the biggest value is 0 in log

Optional: amplify detail by detailAmp

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

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

\[
\text{outIntensity} = 10^{\text{outLog}}
\]

Recall that \(R', G', B'\) is the intensity-normalized RGB color

- \(\text{outR} = \text{outIntensity} \times R'\)
- \(\text{outG} = \text{outIntensity} \times G'\)
- \(\text{outB} = \text{outIntensity} \times B'\)
Recap

Input HDR image

Intensity

Bilateral Filter in log

Large scale

Detail

Bilateral Filter in log

Large scale

Detail

Reduce contrast

Preserve!

detail = input log - large scale

Color

Output

Color

After a slide by Frédo Durand
Bells and whistles: increase detail

After a slide by Frédo Durand

Input HDR image

Intensity

Bilateral Filter in log

Large scale

Detail

detail = input log - large scale

Reduce contrast

Amplify

Output

Large scale

Detail

Color

Color
After a slide by Frédo 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
After a slide by Frédou Durand

## Speed

Direct bilateral filtering is slow (minutes)

### Fast algorithm: bilateral grid

- [http://groups.csail.mit.edu/graphics/bilagrid/](http://groups.csail.mit.edu/graphics/bilagrid/)
Questions?
Related tools

Photoshop “Local adaptation”

Lightroom “Fill Light”
  - or “Shadows”

Photomatix “Details Enhancer”
Slide credits

Frédo Durand
Marc Levoy