High Dynamic Range Images

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CS194: Image Manipulation & Computational Photography
Alexei Efros, UC Berkeley, Fall 2017

...with a lot of slides stolen from Paul Debevec
Why HDR?
Problem: Dynamic Range

The real world is high dynamic range.
Image

pixel (312, 284) = 42

42 photos?
Long Exposure

Real world

10^{-6}  
High dynamic range  
10^{06}

Picture

10^{-6}  
0 to 255  
10^{06}
Short Exposure

Real world

Picture

High dynamic range

10^{-6} to 10^{6}

0 to 255
Camera Calibration

• **Geometric**
  – How pixel coordinates relate to directions in the world

• **Photometric**
  – How pixel values relate to radiance amounts in the world
The Image Acquisition Pipeline

- Scene radiance (W/sr/m²)
- Sensor irradiance
- Sensor exposure
- Latent image
- Electronic Camera

Mathematical expression:

\[ \int \text{sensor irradiance} \, \Delta t = \text{sensor exposure} \]

\[ \text{latent image} = \text{sensor exposure} \]
\[
\log \text{Exposure} = \log (\text{Radiance} \times \Delta t)
\]

(images show a graph of pixel value against log exposure, with a curve that transitions from 0 to 255)
Varying Exposure
Camera is not a photometer!

- **Limited dynamic range**
  ⇒ Perhaps use multiple exposures?

- **Unknown, nonlinear response**
  ⇒ Not possible to convert pixel values to radiance

- **Solution:**
  - Recover response curve from multiple exposures, then reconstruct the *radiance map*
Recovering High Dynamic Range Radiance Maps from Photographs

Paul Debevec
Jitendra Malik

Computer Science Division
University of California at Berkeley

August 1997
Ways to vary exposure
Ways to vary exposure

- Shutter Speed (*)
- F/stop (aperture, iris)
- Neutral Density (ND) Filters
Shutter Speed

• Ranges: Canon D30: 30 to 1/4,000 sec.
• Sony VX2000: ¼ to 1/10,000 sec.

• Pros:
  • Directly varies the exposure
  • Usually accurate and repeatable

• Issues:
  • Noise in long exposures
Shutter Speed

• Note: shutter times usually obey a power series – each “stop” is a factor of 2

• \( \frac{1}{4}, 1/8, 1/15, 1/30, 1/60, 1/125, 1/250, 1/500, 1/1000 \) sec

• Usually really is:

• \( \frac{1}{4}, 1/8, 1/16, 1/32, 1/64, 1/128, 1/256, 1/512, 1/1024 \) sec
The Algorithm

Image series

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

$\text{Exposure} = \text{Radiance} \cdot \Delta t$

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

Assuming unit radiance for each pixel

After adjusting radiances to obtain a smooth response curve

Pixel value

ln Exposure

Pixel value

ln Exposure
The Math

- Let $g(z)$ be the discrete inverse response function.
- For each pixel site $i$ in each image $j$, want:

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

- Solve the overdetermined linear system:

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

fitting term

smoothness term
function [g,lE]=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 1)
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)

g = x(1:n);
lE = x(n+1:size(x,1));
Results: Digital Camera

Kodak DCS460
1/30 to 30 sec
Results: Color Film

- Kodak Gold ASA 100, PhotoCD
Recovered Response Curves

Red

Green

Blue

RGB
The Radiance Map
The Radiance Map

Linearly scaled to display device
Now

What?
Tone Mapping

• How can we do this?
  Linear scaling?, thresholding? Suggestions?
Simple Global Operator

• Compression curve needs to
  – Bring everything within range
  – Leave dark areas alone

• In other words
  – Asymptote at 255
  – Derivative of 1 at 0
Global Operator (Reinhart et al)

\[ L_{\text{display}} = \frac{L_{\text{world}}}{1 + L_{\text{world}}} \]
Global Operator Results
Reinhart Operator

Darkest 0.1% scaled to display device
What do we see?

 Vs.
What does the eye sees?

![Graph showing luminance range and visual function]

Figure 1: The range of luminances in the natural environment and associated visual parameters. After Hood (1986).

The eye has a huge dynamic range
Do we see a true radiance map?
Can we use this for range compression?
Compressing Dynamic Range