High Dynamic Range Images

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CS194: Image Manipulation & Computational Photography
Alexei Efros, UC Berkeley, Fall 2014

…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

High dynamic range

Picture

0 to 255
Short Exposure

Real world

10^{-6}

High dynamic range

0 to 255

Picture

10^{-6}

10^6

10^6
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

Lens

Shutter

Film
Development

CCD

ADC

Remapping

- film density
- analog voltages
- digital values
- pixel values
log Exposure = log (Radiance * \Delta t)

(CCD photon count)
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

- 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

- $\frac{1}{4}, \frac{1}{8}, \frac{1}{15}, \frac{1}{30}, \frac{1}{60}, \frac{1}{125}, \frac{1}{250}, \frac{1}{500}, \frac{1}{1000}$ sec

- Usually really is:

- $\frac{1}{4}, \frac{1}{8}, \frac{1}{16}, \frac{1}{32}, \frac{1}{64}, \frac{1}{128}, \frac{1}{256}, \frac{1}{512}, \frac{1}{1024}$ sec
The Algorithm

Image series

\[ \Delta t = 1 \text{ sec} \]
\[ \Delta t = \frac{1}{16} \text{ sec} \]
\[ \Delta t = \frac{1}{4} \text{ sec} \]
\[ \Delta t = 1 \text{ sec} \]
\[ \Delta t = 4 \text{ sec} \]

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

Exposure = Radiance \( \times \) \( \Delta t \)

\[ \log \text{Exposure} = \log \text{Radiance} + \log \Delta t \]
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:

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

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

Recovered response curve

Pixel value
log Exposure
Reconstructed radiance map
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?

Real World
Ray Traced World (Radiance)

Display/Printer

High dynamic range

0 to 255
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
What do we see?

Vs.
What does the eye sees?

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