HDR and Image-Based Lighting

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

The real world is high dynamic range.
Image

\text{pixel (312, 284) = 42}

42 photos?
Long Exposure

Real world

High dynamic range

Picture

0 to 255

0 to 255

10^{-6} to 10^6
Short Exposure

Real world

High dynamic range

Picture

0 to 255
Camera Calibration

- **Geometric**
  - How pixel \textit{coordinates} relate to \textit{directions} in the world

- **Photometric**
  - How pixel \textit{values} relate to \textit{radiance} amounts in the world
The Image Acquisition Pipeline

- **Scene Radiance** (W/sr/m²)
- **Sensor Irradiance**
- **Sensor Exposure** (Δt)
- **Latent Image**

**Electronic Camera**
Development → CCD → ADC → Remapping

- Development: film density
- CCD: analog voltages
- ADC: digital values
- Remapping: pixel values
Imaging system response function

\[ \log \text{Exposure} = \log (\text{Radiance} \times \Delta t) \]

(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*
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 $Z = f(\text{Exposure})$

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
The Math

- Let \( g(z) \) be the \textit{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:

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

- Log Exposure
- Pixel value
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?
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.
The eye has a huge dynamic range
Do we see a true radiance map?

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

Can we use this for range compression?
Compressing Dynamic Range

This reminds you of anything?
Inserting Synthetic Objects

Why does this look so bad?

- Wrong camera orientation
- Wrong lighting
- No shadows
Solutions

Wrong Camera Orientation

• Estimate correct camera orientation and render object
  – Requires camera calibration to do it right

Lighting & Shadows

• Estimate (eyeball) all the light sources in the scene and simulate it in your virtual rendering

But what happens if lighting is complex?

• Extended light sources, mutual illumination, etc.
Environment Maps

Simple solution for shiny objects

- Models complex lighting as a panoramic image
- i.e. amount of radiance coming in from each direction
- A plenoptic function!!!
Environment Mapping

Reflected ray: \( r = 2(n \cdot v)n - v \)

The projector function converts the reflection vector \((x, y, z)\) to the texture image \((u, v)\).

Texture is transferred in the direction of the reflected ray from the environment map onto the object.

What is in the map?
Environment Maps

The environment map may take various forms:

• Cubic mapping
• Spherical mapping
• other

Describes the shape of the surface on which the map “resides”

Determines how the map is generated and how it is indexed
Cubic Map Example
Cubic Mapping

The map resides on the surfaces of a cube around the object
  • Typically, align the faces of the cube with the coordinate axes

To generate the map:
  • For each face of the cube, render the world from the center of the object with the cube face as the image plane
    – Rendering can be arbitrarily complex (it’s off-line)

To use the map:
  • Index the R ray into the correct cube face
  • Compute texture coordinates
Spherical Map Example
Sphere Mapping

Map lives on a sphere

To generate the map:
  • Render a spherical panorama from the designed center point

To use the map:
  • Use the orientation of the R ray to index directly into the sphere
What approximations are made?

The map should contain a view of the world with the point of interest on the object as the Center of Projection

- We can’t store a separate map for each point, so one map is used with the COP at the center of the object
- Introduces distortions in the reflection, but we usually don’t notice
- Distortions are minimized for a small object in a large room

The object will not reflect itself!
What about real scenes?

From *Flight of the Navigator*
What about real scenes?

from Terminator 2
Real environment maps

We can use photographs to capture environment maps
  • The first use of panoramic mosaics

How do we deal with light sources? Sun, lights, etc?
  • They are much much brighter than the rest of the enviornment

User High Dynamic Range photography, of course!

Several ways to acquire environment maps:
  • Stitching HDR mosaics
  • Fisheye lens
  • Mirrored Balls
Scanning Panoramic Cameras

Pros:

- very high res (10K x 7K+)
- Full sphere in one scan – no stitching
- Good dynamic range, some are HDR

Issues:

- More expensive
- Scans take a while

Companies: Panoscan, Sphereon
Mirrored Sphere
Sources of Mirrored Balls

- 2-inch chrome balls ~ $20 ea.
  - McMaster-Carr Supply Company
    www.mcmaster.com
- 6-12 inch large gazing balls
  - Baker’s Lawn Ornaments
    www.bakerslawnorn.com
- Hollow Spheres, 2in – 4in
  - Dube Juggling Equipment
    www.dube.com

FAQ on www.debevec.org/HDRShop/
Reflective Calibrating Mirrored Sphere Reflectivity

Calibrating Mirrored Sphere Reflectivity

=> 59% Reflective
Real-World HDR Lighting Environments

Lighting Environments from the Light Probe Image Gallery:
http://www.debevec.org/Probes/
Acquiring the Light Probe
Assembling the Light Probe
Not just shiny...

We have captured a true radiance map

We can treat it as an extended (e.g. spherical) light source

Can use Global Illumination to simulate light transport in the scene

• So, all objects (not just shiny) can be lighted
• What’s the limitation?
Illumination Results

Rendered with Greg Larson's
Comparison: Radiance map versus single image
Putting it all together

Synthetic Objects
+
Real light!
CG Objects Illuminated by a Traditional CG Light Source
Illuminating Objects using Measurements of Real Light

http://radsite.lbl.gov/radiance/

Environment assigned “glow” material property in Greg Ward’s RADIANCE system.
Rendering with Natural Light

SIGGRAPH 98 Electronic Theater
RNL Environment mapped onto interior of large cube
MOVIE!

https://www.youtube.com/watch?v=F8Z3ubriTiY&ab_channel=PaulDebevec
We can now illuminate *synthetic objects* with *real light*.

*How do we add synthetic objects to a real scene?*
It’s not that hard!

http://www.nickbertke.com/
Real Scene Example

Goal: place synthetic objects on table
Light Probe / Calibration Grid
Modeling the Scene

light-based model

real scene
The \textit{Light-Based} Room Model
Modeling the Scene

light-based model

synthetic objects

local scene

real scene
The Lighting Computation

distant scene (light-based, unknown BRDF)

synthetic objects (known BRDF)

local scene (estimated BRDF)
Rendering into the Scene

Background Plate
Rendering into the Scene

Objects and Local Scene matched to Scene
Differential Rendering

Local scene w/o objects, illuminated by model
Differential Rendering (2)
Difference in local scene