Scenes lit with point light sources lack realism...

Real-World HDR Lighting Environments

Lighting Environments from the Light Probe Image Gallery: http://www.debevec.org/Probes/

Illuminating Objects using Measurements of Real Light

Environment assigned “glow” material property in Greg Ward’s RADIANCE system.
http://radsite.lbl.gov/radiance/
http://www.debevec.org/CGAIBL/

Elements of HDRI and IBL

High Dynamic Range (HDR) Images
Pixels beyond 0-255
Pixel proportional to light levels

Light Probe Images
Omnidirectional HDR images, or HDR environment maps

Global Illumination
Illuminating CG objects with images of incident illumination
IBL Tutorial

In Jan/Feb
Computer Graphics
and Applications
and the SIGGRAPH
2002 IBL Course
Notes
www.debevec.org

Dynamic Range in the Real World

Office interior
Indirect light from
window
1/60th sec shutter
f/5.6 aperture
0 ND filters
0dB gain

Sony VX2000 video camera

Dynamic Range in the Real World

Outside in the shade
1/1000th sec shutter
f/5.6 aperture
0 ND filters
0dB gain

16 times the light as inside

Dynamic Range in the Real World

Outside in the sun
1/1000th sec shutter
f/11 aperture
0 ND filters
0dB gain

64 times the light as inside

Dynamic Range in the Real World

Straight at the sun
1/10,000th sec shutter
f/11 aperture
13 stops ND filters
0dB gain

5,000,000 times the light as inside

Dynamic Range in the Real World

Very dim room
1/4th sec shutter
f/1.6 aperture
0 stops ND filters
18dB gain

1/1500th the light than inside
“High Dynamic Range Lighting”  
Paul Debevec, USC Institute for Creative Technologies  

Dynamic Range in the Real World

High-Dynamic Range Photography

Gamma 2.2 graph

Implications:
- 128 is less than ¼ as bright as 255
- 128 is more than 4 times as bright as 64
- 175 is twice as bright as 128
- 93 is half as bright as 128

“128 + 128 = 175”
“128 / 2 = 93”

See also Charles Poynton’s Gamma FAQ:  
http://www.inforamp.net/~poynton/GammaFAQ.html

HDR Image File Formats

DirectX 9 HDR Data Formats

32-bit floating point textures
- D3DFMT_A32B32G32R32F / D3DFMT_R32F
- IEEE compatible

16-bit floating point textures
- D3DFMT_A16B16G16R16F
- saves memory bandwidth
- often sufficient dynamic range and precision

www.debevec.org/HDRShop

Chris Tchou and Paul Debevec. HDR Shop. SIGGRAPH 2001 Technical Sketch

March 24, 2004
**HDR Formats: RADIANCE Format (.pic, .hdr)**

Greg Ward’s “Real Pixels” format

<table>
<thead>
<tr>
<th>Red</th>
<th>Green</th>
<th>Blue</th>
<th>Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

32 bits / pixel

(145, 215, 87, 149) = (145, 215, 87) * 2^(149-128) = (1190000, 1760000, 713000)


**HDR Formats: Portable FloatMap (.pfm)**

12 bytes per pixel, 4 for each channel

<table>
<thead>
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</tr>
</tbody>
</table>

sign exponent mantissa

Text header similar to Jeff Poskanzer’s .ppm image format:

Floating Point TIFF similar

**HDR Formats: ILM’s OpenEXR (.exr)**

6 bytes per pixel, 2 for each channel, compressed

<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

sign exponent mantissa

- Several lossless compression options, 2:1 typical
- Compatible with the “half” datatype in NVidia’s Cg
- Supported natively on GeForce FX and Quadro FX
- Available at: [http://www.openexr.net/](http://www.openexr.net/)

**HDR Formats: Ward’s LogLuv TIFF**

based on human color perception

24 bits: 10 for log luminance
14 for chromaticity index
32 bits: 15 log luminance
8 u chrominance
8 v chrominance
1 sign


[http://positron.cs.berkeley.edu/~gwlarson/pixformat/tiffluv.html](http://positron.cs.berkeley.edu/~gwlarson/pixformat/tiffluv.html)

**Light Probe Images:**

*Capturing Real-World Illumination*

**Panoramic (Omnidirectional) Photography**

Other techniques:
- Panoramic Stitching (Realviz Stitcher)
- Fisheye Images
- Scanning Panoramic Cameras (Panoscan, Spheron)
Assembled from ten digital images, \( \Delta t = 1/4 \) to \( 1/10000 \) sec

Comparison: HDRI versus single image lighting

Image-Based Lighting: Illuminating Synthetic Objects with Real Light

Rendering with Natural Light, SIGGRAPH 98

Acquiring the Light Probe

Assembling the Light Probe

RNL Environment mapped onto interior of large cube
“High Dynamic Range Lighting”  
Paul Debevec, USC Institute for Creative Technologies

Renderer Output

Defocus & Glare Added

Soft Focus Added

Light Falloff (Vignetting) Added

Real-Time RNL  
Jason Mitchell, John Isidoro, Alex Vlachos

Rendered in Real Time on ATI RADEON™ 9700

RNL Example

www.debevec.org/RNL

RNL Example

2004 Game Developer’s Conference
**High Dynamic Range Lighting**
Paul Debevec, USC Institute for Creative Technologies

March 24, 2004

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**HDR Rendering Process**

- Scene Geometry
  - lit with HDR Light Probes

- Scene to HDR Scene
- Bloom Filter
- Tone Map
- Displayable Image

**Building the Scene**

- Render reflected scene into HDR planar reflection map for table top
- HDR light probe for distant environment
- HDR environment maps for local reflections from balls on pedestals
- Postprocess to get glows
- Tone map to displayable image

**Local Reflection**

- Distant HDR Light probe is always sampled with reflection vector in pixel shader
- Local environment map is sampled with a blend of the surface normal (N) and the reflection vector (R)

**Frame Postprocessing**

- Filter 50x50 pixel region with sum of three Gaussians
  - Gaussians are $\sigma=2$, $\sigma=6$ and $\sigma=14$

**Real Time Tone Mapping**

- Very Underexposed
- Underexposed
- Good exposure
- Overexposed

**Masaki Kawase DirectX 9 Demo**

http://www.daionet.gr.jp/~masa/
Capturing Light Probes in the Sun

How bright is the sun?

Radius = 695,000 km
Distance = 149,600,000 km

=> 0.5323 degrees in diameter seen from earth
= 0.00465 radians radius
1/0.00465² = 46,334 times brighter than "white"

Can we recover the sun?

α ≈ (1.166, 0.973, 0.701)

Shoot Diffuse Sphere

Solve for Sun Scaling Factor

α ≈ (1.166, 0.973, 0.701)
Verify composite probe matches diffuse ball

<table>
<thead>
<tr>
<th>Lit with Sun</th>
<th>Lit with Probe</th>
<th>Real Diffuse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real Diffuse</td>
<td>Rendered Diffuse</td>
<td>=</td>
</tr>
</tbody>
</table>

Avg. Error (0.5%, 0.3%, 0.2%) RMS Error = (2.2%, 1.8%, 1.3%)

Background plate

Synthetic objects added

Lighting Entire Environments with Outdoor Light Probes

Rendered in Arnold by Marcos Fajardo.
“High Dynamic Range Lighting”  
Paul Debevec, USC Institute for Creative Technologies  
March 24, 2004

**Making High Dynamic Range Lighting Efficient**

Rendering Light Probes as Light Sources

"LightGen" by Jon Cohen et al. at www.debevec.org/HDRShop  
Supports Maya, RADIANCE, Mental Ray, Lightwave
Structured Importance Sampling of Environment Maps

Sameer Agarwal
Henrik Wann Jensen
Serge Belongie
Ravi Ramamoorthi

Importance Sampling
3000 samples
Noisy and slow!

Structured Importance Sampling of Environment Maps

Sameer Agarwal
Henrik Wann Jensen
Serge Belongie
Ravi Ramamoorthi

Structured Importance Sampling
300 samples
Yay!

Step 1) Partition into regions of increasing brightness
Step 2) Use Hochbaum-Schmoys Algorithm to place samples in the brightest region(s)
Step 3) Repeat for the next brightest region, but make sure you consider the samples you added above first
Step 4) Repeat until you’ve covered the whole environment.

Approximating Environments

Light Stage 1.0

“High Dynamic Range Lighting”
Paul Debevec, USC Institute for Creative Technologies

March 24, 2004

Light Stage – 4D Reflectance Field

Modulated Images

Light Stage Results

Lighting Reflectance Functions

Environments from the Light Probe Image Gallery
wwwDebevec.org

Smith and Rowe. Compressed domain processing of JPEG-encoded images. 1996

Interactive Lighting Demo
Chris Tchou, Dan Maas
SIGGRAPH 2000 Creative Applications Laboratory
wwwDebevec.org/FaceDemo

Real-Time IBL with Spherical Harmonics

Frequency Space Environment Map Rendering
Ravi Ramamoorthi, Pat Hanrahan, SIGGRAPH2002

Precomputed Radiance Transfer for Real-Time Rendering in Dynamic, Low-Frequency Lighting Environments
Peter-Pike Sloan, Jan Kautz, John Snyder, SIGGRAPH2002

2004 Game Developer’s Conference
Real-time IBL Techniques for Complex BRDFs

- Ramamoorthi and Hanrahan, Frequency Space Environment Map Rendering, Siggraph 2002.

Real-time IBL Techniques


All-Frequency Shadows Using Non-linear Wavelet Lighting Approximation

- Approx. lighting L (EM) in (non-linear) wavelet basis
- Light transport T as sparse matrix
- B = TL (sparse matrix-vector mult.)
- Better than spherical harmonics!
  - blurred lighting
  - soft shadows

Non-linear Lighting Approximation

All frequencies!
- 2D Harr transform - orthonormal basis
- Weighting (error minimization)
  - Unweighted
  - Transport weighted
  - Area weighted
- High energy lights (> 10^4)
- Low energy lights (< 10^2)
- Further investigation required!
  - Weighting scheme
  - Spherical wavelets

Image-Relighting Comparison

Image-Based Lighting in FLAT LUX

Paul Debevec, Tim Hawkins, Wesley Swinuk, R. P. Duke, Christine Cheng, Tai Uartemark, Jenny Huang
SIGGRAPH ’99 Electronic Theater
Assembled Panorama

Light Probe Images

Interior of St. Peter’s reconstructed from one viewpoint
Debevec, Taylor, and Malik. Modeling and Rendering Architecture from Photographs. SIGGRAPH 96

Lighting Calculation
“Impostor” light sources
Renderings made with Radiance: http://radsite.lbl.gov/radiance/

HDR Lighting Real-World Reflectance Properties
Gardner, Tchou, Hawkins, and Debevec SIGGRAPH 2003

Recovered Ward Model Reflectance Parameters

ρ α
N D
The Ward Model with Translucency (Single Light Source)

\[
\frac{1}{\pi} \left( \rho_d \cos \theta + \rho_t \cos(\theta + \pi) + \rho_s \frac{\cos \theta}{\cos \theta} \right) \exp\left[ -\frac{\tan^2 \delta^2}{\alpha^2} \right]
\]

Note: all cosines are clamped to be non-negative

In terms of vectors

\[
\frac{1}{\pi} \left( \rho_d \langle \mathbf{L} \cdot \mathbf{R} \rangle + \rho_t \langle \mathbf{L} \cdot -\mathbf{R} \rangle + \rho_s \langle \mathbf{L} \cdot \mathbf{R} \rangle \right) \exp\left[ -\frac{\tan^2 \delta^2}{\alpha^2} \right]
\]

Where:
\[
\delta = \cos^{-1}(\mathbf{L} \cdot \mathbf{V}) = \cos^{-1}(\mathbf{H} \cdot \mathbf{N}) = \text{half angle}
\]

Interpolated / Constant Values

\[
\frac{1}{\pi} \left( \rho_d \langle \mathbf{L} \cdot \mathbf{R} \rangle + \rho_t \langle \mathbf{L} \cdot -\mathbf{R} \rangle + \rho_s \langle \mathbf{L} \cdot \mathbf{R} \rangle \right) \exp\left[ -\frac{\tan^2 \delta^2}{\alpha^2} \right]
\]

I = light intensity
L = light direction vector
V = view (camera) direction vector
H = half angle vector

HDR Texture Maps

\[
\frac{1}{\pi} \left( \rho_d \langle \mathbf{L} \cdot \mathbf{R} \rangle + \rho_t \langle \mathbf{L} \cdot -\mathbf{R} \rangle + \rho_s \langle \mathbf{L} \cdot \mathbf{R} \rangle \right) \exp\left[ -\frac{\tan^2 \delta^2}{\alpha^2} \right]
\]

\[
\rho_d = \text{Diffuse reflectance (RGB)}
\rho_t = \text{Translucent transmission (RGB)}
\rho_s = \text{Specular reflectance (RGB)}
\alpha = \text{Specular roughness (A)}
N = \text{Surface normal (XYZ)}
\]

Gaussian Specular Lobe Table

\[
\frac{1}{\pi} \left( \rho_d \langle \mathbf{L} \cdot \mathbf{R} \rangle + \rho_t \langle \mathbf{L} \cdot -\mathbf{R} \rangle + \rho_s \langle \mathbf{L} \cdot \mathbf{R} \rangle \right) \exp\left[ -\frac{\tan^2 \delta^2}{\alpha^2} \right]
\]

Stored in a texture map indexed by \((\alpha, \mathbf{H} \cdot \mathbf{N})\)

LLS Real-Time Demo...
“High Dynamic Range Lighting”  
Paul Debevec, USC Institute for Creative Technologies

High Dynamic Range Display System

Emerging Technologies

Helge Seetzen  
Lorne Whitehead  
Dept. of Physics of Astronomy  
University of British Columbia

Wolfgang Stuerzlinger  
Andrejs Vorozcovs  
Dept. of Computer Science  
York University

Greg Ward  
AnyHere Consulting

Projector  
Fresnel Lens and Diffuser  
LCD

Dual-VGA Graphic Card in PC  
LCD Controller

Thanks!

Jason Mitchell, Chris Brennan, Masaki Kawase  
Chris Tchou, Andrew Gardner, Tim Hawkins, H.P. Duiker,  
Westley Sarokin

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http://www.debevec.org/