Realistic Image Synthesis

- HDR Capture & Tone Mapping -

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# LDR vs HDR – Comparison

<table>
<thead>
<tr>
<th></th>
<th>Standard Dynamic Range</th>
<th>High Dynamic Range</th>
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</thead>
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<tr>
<td><strong>Quality of Contrast &amp; Color</strong></td>
<td><img src="image1.png" alt="Images" /></td>
<td><img src="image2.png" alt="Images" /></td>
</tr>
<tr>
<td>50 dB Camera Dynamic Range</td>
<td>50 dB</td>
<td>120 dB</td>
</tr>
<tr>
<td>1:200 Display Contrast</td>
<td>limited</td>
<td>1:15,000</td>
</tr>
<tr>
<td>limited Color Gamut</td>
<td>display-referred</td>
<td>vivid and saturated colors</td>
</tr>
<tr>
<td>display-referred Image Representation</td>
<td>scene-referred</td>
<td></td>
</tr>
<tr>
<td>display limited Fidelity</td>
<td></td>
<td>as good as the eye can see</td>
</tr>
</tbody>
</table>
Various Dynamic Ranges (1)

Luminance [cd/m²]

10^{-6} 10^{-4} 10^{-2} 10^0 10^2 10^4 10^6 10^8
Various Dynamic Ranges (2)

Luminance [$\text{cd/m}^2$]

Contrast
1:1000
1:1500
1:30

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High Dynamic Range

HDR Image

Usual (LDR) Image
# Measures of Dynamic Range

<table>
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<tr>
<th>Measures</th>
<th>Formula</th>
<th>Applications</th>
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<tbody>
<tr>
<td>Contrast ratio</td>
<td>( CR = 1 : \left( \frac{Y_{\text{peak}}}{Y_{\text{noise}}} \right) )</td>
<td>displays (1:500)</td>
</tr>
<tr>
<td>Orders of magnitude</td>
<td>( M = \log_{10}(Y_{\text{peak}}) - \log_{10}(Y_{\text{noise}}) )</td>
<td>HDR imaging (2.7 orders)</td>
</tr>
<tr>
<td>Exposure latitude (f-stops)</td>
<td>( L = \log_{2}(Y_{\text{peak}}) - \log_{2}(Y_{\text{noise}}) )</td>
<td>photography (9 f-stops)</td>
</tr>
<tr>
<td>Signal to noise ratio (SNR)</td>
<td>( \text{SNR} = 20 \times \log_{10}(A_{\text{peak}}/A_{\text{noise}}) )</td>
<td>digital cameras (53 [dB])</td>
</tr>
</tbody>
</table>
HDR Pipeline

Realistic Image Synthesis SS18 – HDR Image Capture & Tone Mapping
Lecture Overview

- Capture of HDR images and video
  - HDR sensors
  - Multi-exposure techniques
  - Photometric calibration

- Tone Mapping of HDR images and video
  - Early ideas for reducing contrast range
  - Image processing – fixing problems
  - Alternative approaches
  - Perceptual effects in tone mapping

- Summary
HDR: a normal camera can’t…

- linearity of the CCD sensor
- bound to 8-14bit processors
- saved in an 8bit gamma corrected image
**HDR Sensors**

- logarithmic response
- locally auto-adaptive
- hybrid sensors (linear-logarithmic)
Logarithmic HDR Sensor

- CMOS sensor (10bit)
- Transforms collected charge to logarithmic voltage (analog circuit)
- Dynamic range at the cost of quantization
- Very high saturation level
- High noise floor
- Non-linear noise
- Slow response at low luminance levels
- **Lin-log variants of sensor**
  - better quantization
  - lower noise floor
Locally Auto-adaptive Sensor

- Individual integration time for each pixel
- 16bit sensor
  - collected charge (8bit)
  - integration time (8bit)
- Irradiance from time and charge
- Complicated noise model
- Fine quantization over a wide range
- Non-continuous output!
HDR with a normal camera

Dynamic range of a typical CCD 1:1000

Exposure variation (1/60 : 1/6000) 1:100

Aperture variation (f/2.0 : f/22.0) ~1:100

Sensitivity variation (ISO 50 : 800) ~1:10

Total operational range 1:100,000,000 High Dynamic Range!

Dynamic range of a single capture only 1:1000.
Multi-exposure Technique (1)

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Multi-exposure Technique (2)

- **Input**
  - images captured with varying exposure
    - change exposure time, sensitivity (ISO), ND filters
    - same aperture!
    - exactly the same scene!

- **Unknowns**
  - camera response curve (can be given as input)
  - HDR image

- **Process**
  - recovery of camera response curve (if not given as input)
  - linearization of input images (to account for camera response)
  - normalization by exposure level
  - suppression of noise
  - estimation of HDR image (linear combination of input images)
Algorithm (1/3)

Camera Response

\[ y_{ij} = I(x_{ij} \cdot t_i) \]

Merge to HDR

- Linearize input images and normalize by exposure time
  \[ x_{ij} = \frac{I^{-1}(y_{ij})}{t_i} \]
  assume \( I \) is correct (initial guess)
- Weighted average of images (weights from certainty model)
  \[ x_j = \frac{\sum_i w_{ij} x_{ij}}{\sum_i w_{ij}} \]

Optimize Camera Response

Camera response

\[ I^{-1}(y_{ij}) = t_i x_j \]
assume \( x_j \) is correct

- Refine initial guess on response
  - linear eq. (Gauss-Seidel method)
  \[ E_m = \{(i, j) : y_{ij} = m\} \]
  \[ I^{-1}(m) = \frac{1}{\text{Card}(E_m)} \sum_{i, j \in E_m} t_i x_j \]
Algorithm (2/3)

- Certainty model (for 8bit image)
  - High confidence in middle output range
  - Dequantization uncertainty term
  - Noise level

\[ w(y_{ij}) = \exp\left(-4 \frac{(y_{ij} - 127.5)^2}{127.5^2}\right) \]

- Longer exposures are favored \( t_i^2 \)
  - Less random noise

- Weights

\[ w_{ij} = w(y_{ij}) t_i^2 \]
Algorithm (3/3)

1. Assume initial camera response $I$ (linear)
2. Merge input images to HDR
   \[
   x_j = \frac{\sum_i w(y_{ij}) t_i^2 \frac{I^{-1}(y_{ij})}{t_i}}{\sum_i w(y_{ij}) t_i^2}
   \]
3. Refine camera response
   \[
   E_m = \{(i, j) : y_{ij} = m\}
   \]
   \[
   I^{-1}(m) = \frac{1}{\text{Card}(E_m)} \sum_{i, j \in E_m} t_i x_j
   \]
4. Normalize camera response by middle value: $I^{-1}(m)/I^{-1}(m_{med})$
5. Repeat 2,3,4 until objective function is acceptable
   \[
   O = \sum_{i, j} w(y_{ij}) (I^{-1}(y_{ij}) - t_i x_j)^2
   \]
Other Algorithms

- [Debevec & Malik 1997]
  - in log space
  - assumptions on the camera response
    - monotonic
    - continuous
  - a lot to compute for >8bit

- [Mitsunaga & Nayar 1999]
  - camera response approximated with a polynomial
  - very fast

- Both are more robust but less general
  - not possible to calibrate non-standard sensors
Calibration (Response Recovery)

- Camera response can be reused
  - for the same camera
  - for the same picture style settings (e.g. contrast)

- Good calibration target
  - Neutral target (e.g. Gray Card)
    - Minimize impact of color processing in camera
  - Smooth illumination
    - Uniform histogram of input values
  - Out-of-focus
    - No interference with edge aliasing and sharpening
Recovered Camera Response

multiple exposures of out-of-focus color chart

recovered camera response (for each RGB channel separately)
Issues with Multi-exposures

- How many source images?
  - First expose for shadows: all output values above 128 (for 8bit imager)
  - 2 f-stops spacing (factor of 4) between images
  - one or two images with 1/3 f-stop increase will improve quantization in HDR image
  - Last exposure: no pixel in image with maximum value

- Alignment
  - Shoot from tripod
  - Otherwise use panorama stitching techniques to align images

- Ghosting
  - Moving objects between exposures leave “ghosts”
  - Statistical method to prevent such artifacts

- Practical only for images!
  - Multi-exposure video projects exist, but require care with subsequent frame registration by means of optical flow
Photometric Calibration

- Converts camera output to luminance
  - requires camera response,
  - and a reference measurement for known exposure settings

- Applications
  - predictive rendering
  - simulation of human vision response to light
  - common output in systems combining different cameras
Photometric Calibration (cntd.)

1. Acquire target
2. Measure luminance
3. Camera output values
4. Luminance values

Photometric Calibration (cntd.)

Realistic Image Synthesis SS18 – HDR Image Capture & Tone Mapping
HDR Sensor vs. Multi-exposure

- **HDR camera**
  - Fast acquisition of dynamic scenes at 25fps without motion artifacts
  - Currently lower resolution

- **LDR camera + multi-exposure technique**
  - Slow acquisition (impossible in some conditions)
  - Higher quality and resolution
  - High accuracy of measurements
Lecture Overview

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- Summary
HDR Tone Mapping

Objectives of tone mapping
- nice looking images
- perceptual brightness match
- good detail visibility
- equivalent object detection performance
- really application dependent…
Previous lectures…

**General Principle**

- **Approach**
  - Create model of the observer
  - Requirement:
    - Observer should perceive the same image from real and virtual display
  - Compute Tone-Mapping using concatenation and inversion of operators
  - Model usually operates only on luminance (no color)

![Diagram of tone reproduction operator](Computer Graphics WS05/06-Tone Mapping)
General Idea

- Luminance as an input
  - absolute luminance
  - relative luminance (luminance factor)

- Transfer function
  - maps luminance to a certain pixel intensity
  - may be the same for all pixels (global operators)
  - may depend on spatially local neighbors (local operators)
  - dynamic range is reduced to a specified range

- Pixel intensity as output
  - often requires gamma correction

- Colors
  - most algorithms work on luminance
    - use RGB to Yxy color space transform
    - inverse transform using tone mapped luminance
  - otherwise each RGB channel processed independently
General Problems

- Constraints in observation conditions
  - limited contrast
  - quantization
  - different ambient illumination
  - different luminance levels
  - adaptation level often incorrect for the scene
  - narrow field of view

- Appearance may not always be matched
Transfer Functions

- Linear mapping (naïve approach)
  - like taking a usual photo
- Brightness function
- Sigmoid responses
  - simulate our photoreceptors
  - simulate response of photographic film
- Histogram equalization
  - standard image processing
  - requires detection threshold limit to prevent contouring
Adapting Luminance

- Maps luminance on a scale of gray shades
- Task is to match gray levels
  - average luminance in the scene is perceived as a gray shade of medium brightness
  - such luminance is mapped on medium brightness of a display
  - the rest is mapped proportionally
- Practically adjusts brightness
  - sort of like using gray card or auto-exposure in photography
  - goal of adaptation processes in human vision
- Adapting luminance exists in many TM algorithms

\[
Y_A = \exp\left(\frac{\sum \log(Y + \varepsilon)}{N} - \varepsilon\right)
\]
Logarithmic Tone Mapping

- Logarithm is a crude approximation of brightness
- Change of base for varied contrast mapping in bright and dark areas
  - $\log_{10}$ maps better for bright areas
  - $\log_{2}$ maps better for dark areas
- Mapping parameter $bias$ in range 0.1:1

\[
Y' = \frac{Y}{Y_A}
\]

\[
L = L_{\text{max}} \cdot \frac{\log_{\text{base}(Y)}(Y' + 1)}{\log_{10}(\max(Y') + 1)}
\]

\[
\text{base}(Y') = 2 + 8 \cdot \left( \frac{Y'}{\max(Y')} \right)^{\log_{0.5} bias}
\]
Logarithmic Tone Mapping

These images illustrate how high luminance values are clamped to the maximum displayable values using different bias parameter values.

The scene dynamic range is 1:11,751,307.
### Sigmoid Response

- **Model of photoreceptor**
  
  \[ L = \frac{Y}{Y + (f \cdot Y_A)^m} L_{\text{max}} \]

- **Brightness parameter** \( f \)
- **Contrast parameter** \( m \)
- **Adapting luminance** \( Y_A \)
  - average in an image
  - measured pixel (equal to \( Y \))

---

**logarithmic mapping**

**sigmoid mapping**
Histogram Equalization (1)

- Adapts transfer function to distribution of luminance in the image

**Algorithm:**
- compute histogram
- compute transfer function (cumulative distribution)
- limit slope of transfer function to prevent contouring
  - contouring – visible difference between 1 quantization step
  - use threshold versus intensity function (TVI)
    - TVI gives visible luminance difference for adapting luminance

- Most optimal transfer function
- Not efficient when large uniform areas are present in the image
Histogram Equalization (2)

A linear mapping of the luminances that overexposes the view through the window. Greg Ward

A linear mapping of the luminances that underexposes the view of the interior. Greg Ward

The luminances mapped to preserve the visibility of both indoor and outdoor features.
Transfer Functions Compared

- **Interpretation**
  - steepness of slope is contrast
  - luminance for which output is ~0 and ~1 is not transferred
- **Usually low contrast for dark and bright areas!**
Problem with Details

- Strong compression of contrast puts micro-contrasts (details) below quantization level
Introducing Local Adaptation

- Eye adapts locally to observed area

\[ L = \frac{Y'}{Y' + 1} \quad Y' = \frac{Y}{Y_A} \quad L = \frac{Y'}{Y_L' + 1} \]

Gaussian blur of HDR image, \( \sigma \sim 1 \text{deg of visual angle.} \)
The Halo Artifact

- Scan line example:
  - Gaussian blur under- (over-) estimates **local adaptation** near a **high contrast edge**
  - **tone mapped image** gets too bright (too dark) closer to such an edge
- Smaller blur kernel reduces the artifact (but then no details)
- Larger blur kernel spreads the artifact on larger area
Adjusting Gaussian Blur

- So called: Automatic Dodging and Burning
  - for each pixel, test increasing blur size $\sigma_i$
  - choose the largest blur which does not show halo artifact

$$|Y_L(x, y, \sigma_i) - Y_L(x, y, \sigma_{i+1})| < \varepsilon$$
Photographic Tone Reproduction

- Map luminance using Zone System

\[
2^x L \quad 2^{x+1} L \quad 2^{x+2} L \quad 2^{x+3} L \quad 2^{x+4} L \quad \ldots \quad 2^{x+15} L \quad 2^{x+16} L
\]

Middle grey maps to Zone V

Print zones: Zone V 18% reflectance

- Find local adaptation for each pixel
  - appropriate size of Gaussian (automatic dodging & burning)

\[
\left| Y_L'(x, y, \sigma_i) - Y_L'(x, y, \sigma_{i+1}) \right| < \varepsilon
\]

- Tone map using sigmoid function
  - different blur levels from Gaussian pyramid

\[
L(x, y) = \frac{Y'(x, y)}{Y_L'(x, y, \sigma_{x,y}) + 1}
\]

\[
Y' = \frac{Y}{Y_A}, \quad Y_A = \exp\left(\frac{\sum \log(Y)}{N}\right)
\]
Photographic Tone Reproduction

**dodge**  luminance of pixels in bright regions is significantly decreased

**burn**  pixels in dark regions are compressed less, so their relative intensity increases

Automatic dodging-and-burning technique is more effective in preserving local details (notice the print in the book).
Bilateral Filtering

- Edge preserving Gaussian filter to prevent halo
- Conceptually based on intrinsic image models:
  - decoupling of illumination and reflectance layers
    - very simple task in CG
    - complicated for real-world scenes
  - compress range of illumination layer
  - preserve reflectance layer (details)
- Bilateral filter separates:
  - texture details (high frequencies, low amplitudes)
  - illumination (low frequencies, high contrast edges)
Illumination Layer (1)

- Identify low frequencies in the scene
  - Gaussian filtering leads to halo artifacts

\[
J_p = \frac{1}{W_p} \sum_{q \in N(p)} f_{\sigma_s}(\|p - q\|) \cdot I_q
\]

- Spatial kernel with large \(\sigma_s\)
  - Lost sharp edge
Illumination Layer (2)

- Edge preserving filter – no halo artifacts

\[
J_p = \frac{1}{W_p} \sum_{q \in N(p)} f_{\sigma_s}(\|p - q\|) \cdot g_{\sigma_r}(\|I_p - I_q\|) \cdot I_q
\]

- \(f\) spatial kernel with large \(\sigma_s\)
- \(g\) range kernel with very small \(\sigma_r\)
Tone Mapping Algorithm

Luminance in logarithmic domain.
Illumination & Reflectance
Gradient Compression Algorithm

1. Calculate gradients map of image
2. Calculate attenuation map
3. Attenuate gradients
4. Solve Poisson equation to recover image
Attenuation Map

1. Create Gaussian pyramid
2. Calculate gradients on levels
3. Calculate attenuation on levels - $\varphi_k$
4. Propagate levels to full resolution

$\varphi_k(x, y) = \frac{\alpha}{\|\nabla H_k(x, y)\|} \left( \frac{\|\nabla H_k(x, y)\|}{\alpha} \right)^{\beta}$
Transfer Function for Contrasts

\[ \varphi_k(x, y) = \frac{\alpha}{\|\nabla H_k(x, y)\|} \times \left( \frac{\|\nabla H_k(x, y)\|}{\alpha} \right)^\beta \]

- Attenuate large gradients
  - presumably illumination
- Amplify small gradients
  - hopefully texture details
  - but also noise
- Equation has a division by zero!

\[ \beta = 0.9 \]
\[ \alpha = 0.1 \]
Global vs. Local Compression

- Loss of overall contrast
- Loss of texture details
- Real-time even on CPU
- Simple GPU implementation

- Impression of high contrast
- Good preservation of fine details
- Solving Poisson equation takes time
- On GPU ~10fps still possible
Perceptual Effects in TM

- Simulate effects that do not appear on a screen but are typically observed in real-world scenes
  - veiling glare
  - night vision
  - temporal adaptation to light

- Increase believability of results, because we associate such effects with luminance conditions
Temporal Luminance Adaptation

- Compensates changes in illumination

- Simulated by smoothing adapting luminance in tone mapping equation

- Different speed of adaptation to light and to darkness
Night Vision

- Human Vision operates in three distinct adaptation conditions:

  - **Scotopic (Night Vision):**
    - Monochromatic vision
    - Limited visual acuity
  - **Mesopic:**
    - Good color perception
    - Good visual acuity
  - **Photopic (Daylight Vision):**

  ![Graph showing luminance levels and corresponding vision conditions](image)

- Low luminance conditions: Starlight and moonlight
- Medium luminance conditions: Office illumination
- High luminance conditions: Sunlight
Visual Acuity

- Perception of spatial details is limited with decreasing illumination level
- Details can be removed using convolution with a Gaussian kernel
- Highest resolvable spatial frequency:

\[
RF(Y) = 17.25 \cdot \arctan(1.4 \log_{10} Y + 0.35) + 25.72
\]
Veiling Luminance (Glare)

- Decrease of contrast and visibility due to light scattering in the optical system of the eye
- Described by the optical transfer function:

\[ OTF(\rho, d(\bar{Y})) = \exp\left(\frac{\rho}{20.9 - 2.1 \cdot d}^{1.3 - 0.07 \cdot d}\right) \]

$\rho$ spatial frequency, $d$ pupil aperture
Fast TM on GPU

- Simple transfer function is very fast
- What about those advanced algorithms
  - bilateral: fast approximate algorithms available
  - gradient domain: GPU needs ~1s per 1MPx
- Real-time?
  - automatic dodging & burning
  - Gaussian pyramid can be built fast on GPU
  - the pyramid can be used to add perceptual effects at no additional cost!
HDR Video Player with Perceptual Effects

- HDR Image Capture & Tone Mapping

- HDR Video Player with Perceptual Effects

- Realistic Image Synthesis SS18 – HDR Image Capture & Tone Mapping
Papers about Calibration

- Estimation-Theoretic Approach to Dynamic Range Improvement Using Multiple Exposures
  - M. Robertson, S. Borman, and R. Stevenson

- Recovering High Dynamic Range Radiance Maps from Photographs
  - Paul E. Debevec and Jitendra Malik
  - In: SIGGRAPH 97

- Radiometric Self Calibration
  - T. Mitsunaga and S.K. Nayar

- High Dynamic Range from Multiple Images: Which Exposures to Combine?
  - M.D. Grossberg and S.K. Nayar
Papers about Tone Mapping

- Adaptive Logarithmic Mapping for Displaying High Contrast Scenes
  - F. Drago, K. Myszkowski, T. Annen, and N. Chiba
  - In: Eurographics 2003

- Photographic Tone Reproduction for Digital Images
  - E. Reinhard, M. Stark, P. Shirley, and J. Ferwerda
  - In: SIGGRAPH 2002 (ACM Transactions on Graphics)

- Fast Bilateral Filtering for the Display of High-Dynamic-Range Images
  - F. Durand and J. Dorsey
  - In: SIGGRAPH 2002 (ACM Transactions on Graphics)

- Gradient Domain High Dynamic Range Compression
  - R. Fattal, D. Lischinski, and M. Werman
  - In: SIGGRAPH 2002 (ACM Transactions on Graphics)

- Dynamic Range Reduction Inspired by Photoreceptor Physiology
  - E. Reinhard and K. Devlin
  - In: IEEE Transactions on Visualization and Computer Graphics, 2005

- Time-Dependent Visual Adaptation for Realistic Image Display
  - S.N. Pattanaik, J. Tumblin, H. Yee, and D.P. Greenberg
  - In: Proceedings of ACM SIGGRAPH 2000

- Lightness Perception in Tone Reproduction for High Dynamic Range Images
  - G. Krawczyk, K. Myszkowski, H.-P. Seidel
  - In: Eurographics 2005

- Perceptual Effects in Real-time Tone Mapping
  - G. Krawczyk, K. Myszkowski, H.-P. Seidel
  - In: Spring Conference on Computer Graphics, 2005
Acknowledgements

- I would like to thank Grzesiek Krawczyk for making his slides available.