Computer Graphics

HDR Imaging

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Overview

- HDR Acquisition
- Tone-Mapping
High Dynamic Range Imaging

- **Contrast Handling**
  - Input: HDR intensities in real-world scenes (e.g., from rendering)
  - Output: Typically, LDR devices

- **Acquisition of HDR input**
  - HDR cameras
    - Still rather exotic
  - LDR cameras
    - Requires multiple exposures to fully cover the high dynamic range
    - Now often integrated (e.g., into smartphones)

- **Display**
  - HDR displays
    - Modern displays are now getting more and more HDR capable
    - Sometime >1000 individual LED in backlight or micro-LED display
  - Display on LDR monitors
    - *Tone mapping* to perceptively compress HDR to LDR
Part I

HDR Acquisition
Acquisition of HDR from LDR

• **Limited dynamic range of cameras is a problem**
  – Shadows are underexposed
  – Bright areas are overexposed
  – Sensor’s temporal sampling density is not sufficient → saturation

• **Good sign**
  – Some modern CMOS imagers have a higher (and often sufficient) dynamic range than most traditional CCD sensors

• **Basic idea of multi-exposure techniques**
  – Combine multiple images with different exposure settings
  – Makes use of available sequential dynamic range

• **Other techniques available**
  – E.g., HDR video
Exposure Bracketing

- Acquiring HDR from LDR input devices
  - Take multiple photographs with different times of exposure

- Issues
  - How many exposure levels?
  - How much difference between exposures?
  - How to combine them?
Application

- Capture HDR env. maps from series of input images

- Used to illuminate virtual scenes with real-world environment
HDR in Real World Images

• **In photography**
  – $F$-number = focal length / aperture diameter
  – 1 f-stop incr.: $f$-# * $\sqrt{2} \rightarrow$ aperture area / 2

• **Natural scenes**
  – 37 stops (~10 orders of magnitude)
  – 18 stops ($2^{18} \approx 262,000$) at given time of day

• **Humans**
  – After adaptation: 30 stops (~9 orders of magnitude)
  – Simultaneously: 17 stops (~4 orders of magnitude)

• **Analog cameras**
  – 10-16 stops (~3 orders of magnitude)
  – Fish-eye pix of sky with diff. exposures show saturation (e.g., sun)
Dynamic Range of Cameras

- **E.g. photographic camera with standard CCD sensor**
  - Dynamic range of sensor: \(1:1,000\)
  - Exposure time (handheld cam.): \(1/60s \text{ – } 1/6,000s \approx 1:100\)
  - Varying aperture: \(f/2.0 \text{ – } f/22.0\) \(1:100\) (approx.)
  - Electronic: exposure bias / varying “sensitivity”: \(1:10\)
  - Total (sequential) dynamic range: \(1:100,000,000\)

- **But simultaneous dynamic range still only** \(1:1,000\)
  - Aperture: varying depth of field
  - Exposure time: only works for static scenes

- **Similar situation for analog cameras**
  - Chemical development of film instead of electronic processing
  - Allows for varying sensitivity
Multi-Exposure Techniques

- **Analog film**
  - Several emulsions of different sensitivity levels [Wyckoff 1960s]
    - Dynamic range of about $10^8$

- **Digital domain**
  - Similar approaches for digital photography
  - Commonly used method [Debevec et al. 97]
    - Select a small number of pixels from all images
    - Perform optimization of response curve with smoothness constraint
  - Newer method by [Robertson et al. 99]
    - Optimization over all pixels in all images

- **General idea of HDR imaging**
  - Combine multiple images with different exposure times
    - Pick for each pixel a well-exposed image
    - Response curve needs to be known to calibrate values between images
    - Change only exposure time, not aperture due to different depth-of-field!!
Multi-Exposure Techniques

- response curve
- linearized images
- scaling
- weighting function

floating point HDR image
HDR Imaging [Robertson et al. 99]

- **Principle of the approach**
  - Calculate an HDR image using the given response curve
  - Optimize response curve to better match resulting HDR image
  - Iterate till convergence: approx non-linear process w/ linear steps

- **Input**
  - Series of images $i$ with exposure times $t_i$ and pixels $j$
  - Response curve $f$ applied to incident energy yields pixel values $y_{ij}$

\[
y_{ij} = f(I_{y_{ij}}) = f(t_i x_j)
\]

- **Task**
  - Recover response curve: $f^{-1}(y_{ij}) = I_{y_{ij}}$
  - Determine irradiance $x_j$ at pixel $j$ from energies $I_{y_{ij}}$:

\[
x_j = I_{y_{ij}} / t_i
\]
Calculate estimates of HDR input values $x_j$ from images via maximum-likelihood approach

$$x_j = \frac{\sum_i w_{ij} t_i^2 x_{ij}}{\sum_i w_{ij} t_i^2} = \frac{\sum_i w_{ij} t_i I_{y_{ij}}}{\sum_i w_{ij} t_i^2}$$

Use a bell-shaped weighting function $w_{ij} = w(y_{ij})$
- Do not trust as much pixel values at extremes
  - Under-exposed: high relative error prone to noise
  - Over-exposed: saturated value

Use an initial camera response curve
- Simple assumption: linear response
Optimizing the response curve $l(y_{ij})$

- Minimization of objective function $O$ (sum of weighted errors)

$$O = \sum_{i,j} w_{ij} \left( l_{y_{ij}} - t_i x_j \right)^2$$

- Using standard Gauss-Seidel relaxation yields

$$I_{m} = \frac{1}{\text{Card}(E_m)} \sum_{i,j \in E_m} t_i x_j$$

$$E_m = \{(i,j): y_{ij} = m\}$$

- Normalization of $l$ so that $l_{128} = 1$
Both steps ... 
  - Calculation of an HDR image using $I$
  - Optimization of $I$ using the HDR image

... are now iterated until convergence
  - Criterion: decrease of $O$ below some threshold
    - Usually about 5 iterations are enough

Logarithmic plot of the response curve

$$v_{ij} = \log(f^{-1}(y_{ij}))$$

$$I_{ij} = \exp(v_{ij})$$

$$v_{ij} = \log(I_{ij})$$
Choice of Weighting Function

- \( w(y_{ij}) \) for response [Robertson et al. 99]

\[
w_{ij} = \exp\left(-4 \frac{(y_{ij} - 127.5)^2}{127.5^2}\right)
\]
- Gaussian-like bell-shaped function
- For 8-bit images, centered around \((2^8 - 1) / 2 = 127.5\)
- Possible width correction at both ends: over/under-exposure
- Motivated by general noise model: downweight high relative error

- \( w(y_{ij}) \) for HDR reconstruction [Robertson et al. 03]
  - Introduce certainty function \( c \) as derivative of response curve with logarithmic exposure axis: S-shape response \( \rightarrow \) bell-shaped curve
  - Approxim. response curve with cubic spline to compute derivative

\[
w_{ij} = w(y_{ij}) = c(I_{y_{ij}})
\]
Weighting Function

- **Consider response curve gradient**
  - Higher weight where response curve maps to large extent

- **Difference between exposures levels**
  - Ideally such that respective trusted regions (central part of weighting function) are roughly adjacent
HDR Generation

• **What difference to pick between exposures levels?**
  – Most often a difference of 2 stops (factor of 4) between exposures is sufficient
  – See [Grossberg & Nayar 2003] for more details

• **How many input images are necessary to get good results?**
  – Depends on dynamic range of scene illumination and on quality requirements
  – Often 3 images are fine (normal + lower & higher exposure)
Algorithm of Robertson et al.

• **Discussion**
  – Method is very easy
  – Doesn’t make assumptions about response curve shape
  – Converges quickly
  – Takes all available input data into account
    • As opposed to [Debevec et al. 97]
  – Can be extended to > 8-bit color depth
    • 16 bits should be followed by smoothing
    • Quantization to 8 bits eliminates large amount of noise
    • Higher precision with 16 bits more likely to still contain notable noise
Part II

Tone Mapping
Terms and Definitions

• **Dynamic range**
  - Factor between the highest and the smallest representable value
  - 2 strategies to increase dynamic range:
    • Make white brighter, or make black darker (more practical)
    • Reason for trend towards reflective rather than diffuse displays

• **Contrast**
  - Simple contrast: \[ C_S = \frac{L_{\text{max}}}{L_{\text{min}}} \]
  - Weber fraction: \[ C_W = \frac{\Delta L}{L_{\text{min}}} \text{ with } \Delta L = L_{\text{max}} - L_{\text{min}} \]
  - Michelson contrast: \[ C_M = \left| \frac{L_{\text{max}} - L_{\text{min}}}{L_{\text{max}} + L_{\text{min}}} \right| \]
  - Logarithmic ratio: \[ C_L = \log_{10} \left( \frac{L_{\text{max}}}{L_{\text{min}}} \right) \]
  - Signal to noise ratio (SNR): \[ C_{\text{SNR}} = 20 \cdot \log_{10} \left( \frac{L_{\text{max}}}{L_{\text{min}}} \right) \]
Contrast Measurement

• **Contrast detection threshold**
  – Smallest detectable intensity difference in a uniform field of view
  – E.g., Weber-Fechner perceptual experiments

• **Contrast discrimination threshold**
  – Smallest visible difference between two similar signals
  – Works in supra-detection-threshold domain (i.e., signals above it)
  – Often sinusoidal or square-wave pattern

![Contrast Detection](image1)

![Contrast Discrimination](image2)
Why Tone Mapping?

• **Mapping HDR radiance values to LDR pixel values?**
  – Luminance range for human visual perception
    • Min $10^{-5}$ cd/m$^2$: shadows under starlight
    • Max $10^5$ cd/m$^2$: snow in direct sunlight
  – Luminance of typical desktop displays
    • Typically, up to $\sim 500$ cd/m$^2$: about 2-3 orders of magnitude

• **Goal**
  – Compress the dynamic range of an input image to fit output range
  – Reproduce HVS to closely match perception of the real scene
    • Brightness and contrast
    • Adaptation of the eye to environment
    • Bright/dark input: glare, color perception, loss of visual acuity, …
General Principle

- **Original approach [Tumblin/Rushmeier]**
  - Create model of the observer
  - Requirement: observer looking at displayed virtual image should perceive the same brightness as when staring at the real scene
  - Compute tone-mapping as concatenation/inversion of operators
  - Model usually operates only on luminance (not on color)

- **Other models aim for visually pleasing images**
Heuristic Approaches

- **Linearly scale brightest value to 1 (in gray value)**
  - Problem: light sources are often several orders of magnitude brighter than the rest → the rest will be black

- **Linearly scale brightest non-light-source value**
  - Capping light source values to 1
  - Scale the rest to a value slightly below 1
  - Problem: bright reflections of light sources

- **General problem of simple linear scaling**
  - Absolute brightness gets lost
  - Scaling of light source intensity gets factored out → has no effect

- **Much better: linear scaling in the logarithmic domain**
  - Linear scaling of perceived brightness instead of input luminance
  - Much closer to human perception
  - Typically using $\log_{10}$
Maintaining Contrast

- **Contrast-based linear scaling factor [Ward 94]**
  - Make just visible differences in real world just visible on display
  - Preserve the visibility in the scene based on Weber’s contrast
  - Just noticeable contrast differences according to Blackwell [CIE 81] (subjective measurements)

\[
\Delta L(L_a) = 0.0594(1.219 + L_a^{0.4})^{2.5}
\]

- Minimum discernible difference in luminance for given visual adaptation level \(L_a\)

- **Goal:** proportionality constant \(m\)
  - Relates world luminance values \(L_w\) to display luminance values \(L_d\)
  - \(L_d = m L_w\)
Maintaining Contrast

- **Approach using “just noticeable difference” (JND)**
  - Find $m$ such that JND $\Delta L(L_{wa})$ at world adaptation luminance $L_{wa}$ and JND $\Delta L(L_{da})$ at display adaptation luminance $L_{da}$ verify
    \[
    \Delta L(L_{da}) = m(L_{wa}) \Delta L(L_{wa})
    \]
  - Substitution results in
    \[
    m(L_{wa}) = \left[ \frac{1.219 + L_{da}^{0.4}}{1.219 + L_{wa}^{0.4}} \right]^{2.5}
    \]
  - Compute $L_{da}$ from maximum display luminance: $L_{da} = L_{dmax} / 2$
  - Normalize scaling factor $sf$ in $[0, 1]$
    \[
    sf = \frac{1}{L_{dmax}} \left[ \frac{1.219 + (L_{dmax}/2)^{0.4}}{1.219 + L_{wa}^{0.4}} \right]^{2.5}
    \]
Maintaining Contrast

• Deriving the real-world adaptation $L_{wa}$
  – Depends on light distribution in field of view of observer
  – Simple approximation using a single value
    • Eyes try to adjust to average incoming brightness
    • Brightness $B$ based on input luminances:
      – $B = k L_{in}^a$ : Power-law [Stevens 61]
    • Comfortable brightness based on average of input luminances:
      – $\log_{10}(L_{wa}) = E\{\log_{10}(L_{in})\} + 0.84 \Rightarrow L_{wa} = 10^{\frac{\sum_n \log_{10}(L_{in})}{n}}$

• Problems of this approach
  – Single factor for entire image
    • Does not handle different adaptation for different locations in image
    • We do not perceive absolute differences in luminance: neighborhood
  – Brightness adaptation mainly acts on $1^\circ$ field of view of fovea rather than periphery $\rightarrow$ would require eye tracking
  – Adaptation to average results in clamping for too bright regions
Histogram Adjustment

- **Optimal mapping of the dynamic range [Ward 97]**
  - Compute an adjustment image
    - Assume known viewpoint with respect to the scene
    - Blur input image with distance-dependent kernel
      - Filter (average) non-overlapping regions covering 1° field of view, i.e., foveal solid angle of adaptation
      - Reference uses simple box filter
    - Reduce resolution
  - Compute the histogram of the image
    - Bin the luminance values
    - Adjust the histogram based on restrictions of HVS
      - Limit contrast enhancement

⇒ **Distributes contrast in the image in a visually meaningful way, but does not try to model human vision per se as outlined by [Tumblin/Rushmeier]**
Histogram Adjustment

• Definitions
  – $B_w = \log(L_w)$: compute world brightness from world luminance
  – $b_i$: create $N$ bins $i$ corresponding to ranges of $B_w$
  – $f(b_i)$: number of $B_w$ samples in bin $b_i$: $\propto$ PDF
  – $P(b) = \sum f(b_i)/T$: normalized sum of $f(b_i)$ for $b_i < b$: CDF ($\int$ of PDF)
  – $T$: sum over all $f(b_i)$, i.e., total number of samples

\[
T = \sum f(b_i)
\]

\[
\Delta b = \frac{\log(L_{w max}) - \log(L_{w min})}{N}
\]

– Bin step size $\Delta b$ (in $\log(\text{cd/m}^2)$) defined by min/max world luminance for the scene and number of histogram bins $N$

– Therefore, the PDF is

\[
dP(b) / db = f(b_i) / (T \Delta b)
\]
Naïve Histogram Equalization

• Compute display brightness $B_d = \log(L_d)$ using min and max display luminance $L_{dmin}$ and $L_{dmax}$

$$B_d = \log(L_{dmin}) + [\log(L_{dmax}) - \log(L_{dmin})]P(B_w)$$
Histogram Adjustment

Input luminances

Linear bright

Linear dark

[Ward 97]’s operator
Histogram Adjustment

- Linear mapping (scaling) vs. histogram adjustment
Histogram Adj. w/ Linear Ceiling

• **Problem**
  – Too exaggerated contrast in large highly-populated regions of the dynamic range: enhances features more than the HVS would

• **Idea**
  – Contrast-limited histogram equalization using a linear ceiling
    (linear scaling works well for low contrast images)
    \[
    \frac{dL_d}{L_d} \leq \frac{dL_w}{L_w} \Rightarrow \frac{dL_d}{dL_w} \leq \frac{L_d}{L_w}
    \]
  – Differentiate \( L_d = \exp(B_d) \) with respect to \( L_w \) using the chain rule
    \[
    \frac{dL_d}{dL_w} = \exp(B_d) \frac{f(B_w)}{T\Delta b} \frac{\log(L_d \text{max}) - \log(L_d \text{min})}{L_w} \leq \frac{L_d}{L_w}
    \]

• **Result**
  – Limiting the sample count per bin in the histogram
    \( \Leftrightarrow \) limit the magnitude of the PDF, i.e., the slope of the CDF
    \[
    f(B_w) \leq \frac{T\Delta b}{\log(L_d \text{max}) - \log(L_d \text{min})}
    \]
Histogram Adj. w/ Linear Ceiling

- **Implementing the contrast limitation**
  - Truncate too large bins w/ redistribution to neighbors (repeatedly)
  - Ditto without redistribution (gives better results)
  - Use modified $f(B_w)$ in histogram equalization vs. naïve approach
Histogram Adj. w/ Linear Ceiling

Linear mapping (simple scaling)  Naïve histogram equalization  Histogram adjustment with linear ceiling on contrast
• **Adjustment for JND**
  - Limiting the contrast to the ratio of JNDs (global scale factor)

\[
\frac{dL_d}{dL_w} \leq \frac{\Delta L_t(L_d)}{\Delta L_t(L_w)}
\]

  - That results in

\[
f(B_w) \leq \frac{\Delta L_t(L_d)}{\Delta L_t(L_w)} \frac{L_w}{L_d} \frac{T \Delta b}{[\log(L_{dmax}) - \log(L_{dmin})]}
\]

  - Implementation is similar as for previous histogram equalization
HA based on Hum. Contr. Sensi.

- Naïve histogram equalization
- HA with human sensitivity in bright bathroom
- HA with human sensitivity in dim bathroom
HA based on Hum. Contr. Sensi.

- Reduction of contrast sensitivity in dark scenes

Histogram adjustment with linear ceiling on contrast

Dim bathroom (1/100) with reduced contrast
Comparison

• [Tumblin/Rushmeier]
  – Sound methodology from a theoretical standpoint
  – Maybe not optimal models of HVS used in practical experiments
Comparison

[Tumblin/Rushmeier] tone mapping

Contrast-based linear scaling [Ward 94] tone mapping

Histogram adjustment [Ward 97] tone mapping
Local Tone Mapping

- **Usual contrast enhancement techniques**
  - Global tone-map. operator: apply same operation on entire image
  - Either enhance everything or require manual intervention
  - Change image appearance

- **Tone map. often gives numerically optimal solution**
  - No dynamic range left for enhancement

- **Local operators**
  - HVS adapts locally => apply ≠ tone-mapping operators in ≠ areas

![HDR image (reference) and Tone-mapping result](image.png)

[O'Connor 06]
Idea: Enhance Local Contrast

Measure lost contrast at several feature scales (preserve small-scale details but adjust overall large-scale contrast)

Enhance lost small-scale contrast in tone-mapped image (best allocation of LDR contrast rather than simulate HVS)

Communicate lost image contents

Maintain image appearance

Enhanced tone-mapped image
Adaptive Counter-Shading

- Create apparent contrast based on Cornsweet illusion
  - Introduce sharp visible edges between similar-brightness regions
- Countershading
  - Gradual darkening / brightening towards a contrasting edge
  - Restore contrast of small features with economic use of dyn. range
Construction of Simple Profile

• Profile from low-pass filtered reference
• Size and amplitude adjusted manually
• This is unsharp masking

Low-contrast signal (e.g. tone-mapped)

Counter-shading

High-contrast reference (e.g. HDR)
Where to Insert the Profiles?

- Measure lost contrast at several feature scales
Adaptive Counter-Shading

- Objectionable visibility of counter-shading profiles

Progress of restoration

Final contrast restoration
Subtle Correction of Details

Reference HDR image (clipped)  Tone mapping

Counter-shading of tone mapping  Counter-shading profiles
Improved Separation

Reference HDR image (clipped)

Tone mapping

Counter-shading of tone mapping

Counter-shading profiles