Advanced Graphics and Image Processing

High dynamic range and tone mapping
Part 1/2 – context, the need for tone-mapping

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Cornell Box: need for tone-mapping in graphics

Rendering

Photograph
Real-world scenes are more challenging

- The match could not be achieved if the light source in the top of the box was visible
- The display could not reproduce the right level of brightness
Dynamic range

\[
\frac{\text{max } L}{\text{min } L} \quad \text{(for SNR>3)}
\]

Luminance
Dynamic range (contrast)

- As ratio:
  \[ C = \frac{L_{\text{max}}}{L_{\text{min}}} \]
  Usually written as C:1, for example 1000:1.

- As “orders of magnitude” or log10 units:
  \[ C_{10} = \log_{10} \frac{L_{\text{max}}}{L_{\text{min}}} \]

- As stops:
  \[ C_2 = \log_2 \frac{L_{\text{max}}}{L_{\text{min}}} \]
  One stop is doubling of halving the amount of light
High dynamic range (HDR)

Luminance [cd/m²]

Dynamic Range

1000:1

1500:1

30:1
Tone-mapping problem

- Moonless Sky: $3 \times 10^{-5}$ cd/m²
- Full Moon: $6 \times 10^3$ cd/m²
- Sun: $2 \times 10^9$ cd/m²

- Luminance range [cd/m²]
- Human vision
- Simultaneously adapted
- Tone mapping
- Conventional display
Why do we need tone mapping?

- To reduce dynamic range
- To customize the look
  - colour grading
- To simulate human vision
  - for example night vision
- To adapt displayed images to a display and viewing conditions
- To make rendered images look more realistic
- To map from scene- to display-referred colours

Different tone mapping operators achieve different goals
From scene- to display-referred colours

- The primary purpose of tone mapping is to transform an image from scene-referred to display-referred colours.
Tone-mapping in rendering

- Any physically-based rendering requires tone-mapping
- “HDR rendering” in games is pseudo-physically-based rendering
- Goal: to simulate a camera or the eye
- Greatly enhances realism

![Diagram showing the process of rendering with and without tone-mapping](image)
The simplest form of tone-mapping is the exposure/brightness adjustment:

\[ \text{Display-referred red value} = \frac{R_s}{L_{\text{white}}} \]

- R for red, the same for green and blue
- No contrast compression, only for a moderate dynamic range

The simplest form of display coding is the “gamma”

\[ R' = (R_d)^{\frac{1}{\gamma}} \]

- Prime (’) denotes a gamma-corrected value
- Typically \( \gamma = 2.2 \)
- For SDR displays only
High dynamic range and tone mapping
Part 2/2 – tone mapping techniques

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Techniques

- Arithmetic of HDR images
- Display model
- Tone-curve
- Color transfer
- Base-detail separation
- Glare
Arithmetic of HDR images

- How do the basic arithmetic operations
  - Addition
  - Multiplication
  - Power function

affect the appearance of an HDR image?

- We work in the luminance space (NOT luma)
- The same operations can be applied to linear RGB
  - Or only to luminance and the colour can be transferred
Multiplication – brightness change

- Multiplication makes the image brighter or darker
- It does not change the dynamic range!

\[ T(L_p) = B \cdot L_p \]
Power function – contrast change

\[ T(L_p) = \left( \frac{L_p}{L_{\text{white}}} \right)^c \]

- Contrast change (gamma)
- Luminance of white
- Power function stretches or shrinks image dynamic range
- It is usually performed relative to a reference white colour/luminance
- Apparent brightness changes is the side effect of pushing tones towards or away from the white point
- Slope on a log-log plot explains contrast change
Addition – black level

- Addition elevates black level, adds "fog" to an image
- It affects mostly darker tones
- It reduces image dynamic range

\[ T(L_p) = L_p + F \]

Black level (flare, fog)
Techniques

- Arithmetic of HDR images
- **Display model**
- Tone-curve
- Color transfer
- Base-detail separation
- Glare
Display-adaptive tone mapping

- Tone-mapping can account for the physical model of a display
  - How a display transforms pixel values into emitted light
  - Useful for ambient light compensation

Has a similar role as display encoding, but can account for viewing conditions
(Forward) Display model

- **GOG: Gain-Gamma-Offset**
  - Luminance
  - Peak luminance
  - Gamma
  - Gain
  - Pixel value 0-1
  - Offset
  - Display black level
  - Screen reflections
  - Reflectance factor (0.01)

\[
L = (L_{\text{peak}} - L_{\text{black}}) V^\gamma + L_{\text{black}} + L_{\text{refl}}
\]

\[
L_{\text{refl}} = \frac{k}{\pi} E_{\text{amb}}
\]

Ambient illumination (in lux)
Inverse display model

Symbols are the same as for the forward display model

\[ V = \left( \frac{L - L_{\text{black}} - L_{\text{refl}}}{L_{\text{peak}} - L_{\text{black}}} \right)^{(1/\gamma)} \]

Note: This display model does not address any colour issues. The same equation is applied to red, green and blue color channels. The assumption is that the display primaries are the same as for the sRGB color space.
Ambient illumination compensation

Non-adaptive TMO

Display adaptive TMO
Ambient illumination compensation

Non-adaptive TMO

Display adaptive TMO

Lux scale: $10^{-23}$ to $10^4$ and 300 to 10,000
Example: Ambient light compensation

- We are looking at the screen in bright light

\[ L_{\text{peak}} = 100 \text{ [cd} \cdot \text{m}^{-2}] \quad k = 0.005 \]

\[ L_{\text{black}} = 0.1 \text{ [cd} \cdot \text{m}^{-2}] \]

\[ E_{\text{amb}} = 2000 \text{ [lux]} \quad L_{\text{refl}} = \frac{0.005}{\pi} 2000 = 3.183 \text{ [cd} \cdot \text{m}^{-2}] \]

- We assume that the dynamic of the input is 2.6 (≈400:1)

\[ r_{in} = 2.6 \quad r_{out} = \log_{10} \left( \frac{L_{\text{peak}}}{L_{\text{black}} + L_{\text{refl}}} \right) = 1.77 \]

- First, we need to compress contrast to fit the available dynamic range, then compensate for ambient light

\[ L_{out} = \left( \frac{L_{\text{in}}}{L_{\text{wp}}} \right)^{\frac{r_{out}}{r_{in}}} - L_{\text{refl}} \]

The resulting value is in luminance, must be mapped to display luma / gamma corrected values (display encoded)

Simplest, but not the best tone mapping
Techniques

- Arithmetic of HDR images
- Display model
- **Tone-curve**
- Color transfer
- Base-detail separation
- Glare
Tone-curve

Best tone-mapping is the one which does not do anything, i.e. slope of the tone-mapping curves is equal to 1.
Tone-curve

But in practice contrast (slope) must be limited due to display limitations.
Global tone-mapping is a compromise between clipping and contrast compression.
Sigmoidal tone-curves

- Very common in digital cameras
  - Mimic the response of analog film
  - Analog film has been engineered over many years to produce good tone-reproduction
- Fast to compute
Sigmoidal tone mapping

- Simple formula for a sigmoidal tone-curve:

\[
R'(x, y) = \frac{R(x, y)^b}{\left(\frac{L_m}{a}\right)^b + R(x, y)^b}
\]

where \( L_m \) is the geometric mean (or mean of logarithms):

\[
L_m = \exp\left(\frac{1}{N} \sum_{(x,y)} \ln(L(x, y))\right)
\]

and \( L(x, y) \) is the luminance of the pixel \((x, y)\).
Sigmoidal tone mapping example

\[ a = 0.25 \]

\[ a = 1 \]

\[ a = 4 \]

\[ b = 0.5 \]

\[ b = 1 \]

\[ b = 2 \]
Histogram equalization

1. Compute normalized cumulative image histogram

\[ c(I) = \frac{1}{N} \sum_{i=0}^{I} h(i) = c(I - 1) + \frac{1}{N} h(I) \]

- For HDR, operate in the log domain

2. Use the cumulative histogram as a tone-mapping function

\[ Y_{out} = c(Y_{in}) \]

- For HDR, map the log-10 values to the \([-dr_{out}; 0]\) range
  - where \(dr_{out}\) is the target dynamic range (of a display)
Histogram equalization

- Steepest slope for strongly represented bins
- If many pixels have the same value - enhance contrast
- Reduce contrast, if few pixels
- Histogram Equalization distributes contrast distortions relative to the “importance” of a brightness level
Histogram adjustment with a linear ceiling

- [Larson et al. 1997, IEEE TVCG]

Linear mapping

Histogram equalization

Histogram equalization with a ceiling
Histogram adjustment with a linear ceiling

- Truncate the bins that exceed the ceiling;
- Distribute the removed counts to all bins;
- Repeat until converges

Ceiling, based on the maximum permissiblle contrast
Histogram adjustment with a linear ceiling

- Truncate the bins that exceed the ceiling;
- Distribute the removed counts to all bins;
- Repeat until converges

Ceiling, based on the maximum permissible contrast
Histogram adjustment with a linear ceiling

- Truncate the bins that exceed the ceiling;
- Distribute the removed counts to all bins;
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Ceiling, based on the maximum permissible contrast
Techniques

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Colour transfer in tone-mapping

- Many tone-mapping operators work on luminance, mean or maximum colour channel value
  - For speed
  - To avoid colour artefacts
- Colours must be transferred later from the original image
- Colour transfer in the linear RGB colour space:
  \[ R_{out} = \left( \frac{R_{in}}{L_{in}} \right)^s \cdot L_{out} \]
  - Output color channel (red)
  - Saturation parameter
  - Resulting luminance
- The same formula applies to green (G) and blue (B) linear colour values
Colour transfer: out-of-gamut problem

- Colours often fall outside the colour gamut when contrast is compressed.

Original image

- Reduction in saturation is needed to bring the colors into gamut.

Contrast reduced (s=1)

Sample of pixels

Gamut boundary

Saturation reduced (s=0.6)
Colour transfer: alternative method

- Colour transfer in linear RGB will alter resulting luminance.
- Colours can be also transferred and saturation adjusted using CIE u’v’ chromatic coordinates.

To correct saturation:

\[
\begin{align*}
u'_{out} &= (u'_\text{in} - u'_w) \cdot s + u'_w, \\
v'_{out} &= (v'_\text{in} - v'_w) \cdot s + v'_w
\end{align*}
\]

Chroma of the white:

- \( u'_w = 0.1978 \)
- \( v'_w = 0.4683 \)
Techniques

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Illumination & reflectance separation

\[ Y = I \cdot R \]
Illumination and reflectance

Reflectance
- White ≈ 90%
- Black ≈ 3%
- Dynamic range < 100:1
- Reflectance critical for object & shape detection

Illumination
- Sun ≈ $10^9$ cd/m$^2$
- Lowest perceivable luminance ≈ $10^{-6}$ cd/m$^2$
- Dynamic range 10,000:1 or more
- Visual system partially discounts illumination
Hypothesis: Distortions in reflectance are more apparent than the distortions in illumination.

Tone mapping could preserve reflectance but compress illumination.

For example:

\[ L_d = R \cdot T(I) \]

\[ L_d = R \cdot \left( \frac{I}{L_{\text{white}}} \right)^c \cdot L_{\text{white}} \]
How to separate the two?

- (Incoming) illumination – slowly changing
  - except very abrupt transitions on shadow boundaries
- Reflectance – low contrast and high frequency variations
Gaussian filter

- First order approximation
- Blurs sharp boundaries
- Causes halos

\[ f(x) = \frac{1}{2\pi\sigma_s} e^{\frac{-x^2}{2\sigma_s^2}} \]
Bilateral filter

- Better preserves sharp edges
- Still some blurring on the edges
- Reflectance is not perfectly separated from illumination near edges

\[ I_p \approx \frac{1}{k_s} \sum_{t \in \Omega} f(p-t) g(L_p - L_t) L_p. \]

[Tone mapping result

[Durand & Dorsey, SIGGRAPH 2002]
Weighted-least-squares (WLS) filter

- Stronger smoothing and still distinct edges

- Can produce stronger effects with fewer artifacts

- See „Advanced image processing” lecture

[Farbman et al., SIGGRAPH 2008]
Retinex

- Retinex algorithm was initially intended to separate reflectance from illumination [Land 1964]
- There are many variations of Retinex, but the general principle is to eliminate from an image small gradients, which are attributed to the illumination

1 step: compute gradients in log domain

2\textsuperscript{nd} step: set to 0 gradients less than the threshold

3\textsuperscript{rd} step: reconstruct an image from the vector field

For example by solving the Poisson equation

\[ \nabla^2 I = \text{div} G \]
Retinex examples

From: http://dragon.larc.nasa.gov/retinex/757/

From: http://www.ipol.im/pub/algo/lmps_retinex_poisson_equation/#ref_1
Gradient domain HDR compression

- Similarly to Retinex, it operates on log-gradients
- But the function amplifies small contrast instead of removing it

Contrast compression achieved by global contrast reduction
- Enhance reflectance, then compress everything
Techniques

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Glare

“Alan Wake” © Remedy Entertainment
Glare Illusion

Photography

Painting

Computer Graphics
HDR rendering in games
Scattering of the light in the eye

Ciliary corona and lenticular halo

Examples of simulated glare

[From Ritschel et al, Eurographics 2009]
Temporal glare

[From Ritschel et al, Eurographics 2009]
Point Spread Function of the eye

- What portion of the light is scattered towards a certain visual angle
- To simulate:
  - construct a digital filter
  - convolve the image with that filter

Green – daytime (photopic)
Red – night time (scotopic)

Selective application of glare

- **A)** Glare applied to the entire image
  \[ I_g = I \times G \]
  - Reduces image contrast and sharpness

- **B)** Glare applied only to the clipped pixels
  \[ I_g = I + I_{\text{clipped}} \times G - I_{\text{clipped}} \]
  - Better image quality

where \( I_{\text{clipped}} = \begin{cases} I & \text{for } I > 1 \\ 0 & \text{otherwise} \end{cases} \)
Selective application of glare

A) Glare applied to the entire image

Original image

B) Glare applied to clipped pixels only
Glare (or bloom) in games

- Convolution with large, non-separable filters is too slow
- The effect is approximated by a combination of Gaussian filters
  - Each filter with different “sigma”
- The effect is meant to look good, not be be accurate model of light scattering
- Some games simulate camera rather than the eye
Does the exact shape of the PSF matter?

- The illusion of increased brightness works even if the PSF is very different from the PSF of the eye.

[Yoshida et al., APGV 2008]
HDR rendering – motion blur

From LDR pixels  From HDR pixels
References

- Comprehensive book on HDR Imaging

- Overview of HDR imaging & tone-mapping

- Review of recent video tone-mapping
  - A comparative review of tone-mapping algorithms for high dynamic range video

- Selected papers on tone-mapping:
  - ...