High dynamic range and tone mapping

Advanced Graphics

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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

\[
\frac{\text{max } L}{\text{min } L}
\]

(for SNR > 3)
Dynamic range (contrast)

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

- As “orders of magnitude”
  or \( \log_{10} \) 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)

Dynamic Range

- 1000:1
- 1500:1
- 30:1

Luminance [cd/m²]
Visible colour gamut

- The eye can perceive more colours and brightness levels than
  - a display can produce
  - a JPEG file can store

- The premise of HDR:
  - Visual perception and not the technology should define accuracy and the range of colours
  - The current standards not fully follow to this principle
Tone-mapping problem

Tone mapping

conventional display

human vision

luminance range [cd/m²]

simultaneously adapted

Moonless Sky $3 \cdot 10^{-5} \text{ cd/m}^2$

Full Moon $6 \cdot 10^3 \text{ cd/m}^2$

Sun $2 \cdot 10^9 \text{ cd/m}^2$
Why do we need tone mapping?

- To reduce excessive 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

Different tone mapping operators achieve different goals
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

Half-Life 2: Lost coast
Techniques

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

- How does 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 to luminance-only and the colour can be transferred
Multiplication – brightness change

\[ T(L_p) = B \cdot L_p \]

- Multiplication makes the image brighter or darker
- It does not change the dynamic range!
Power function – contrast change

- Power function stretches or shrinks image dynamic range
- It is usually performed relative to reference white
- Apparent brightness changes is the side effect of pushing tones towards or away from the white point

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

Contrast change (gamma)

Luminance of white
Addition – black level

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

- Addition elevates black level, adds fog to an image
- It does NOT make the overall image brighter
- It reduces dynamic range

Black level (flare, fog)
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Two ways to do tone-mapping

Display model can account for:
- Display peak luminance
- Display dynamic range (contrast)
- Ambient light

 Liminance, linear RGB
 HDR image → Tone mapping A → LDR image

 Luma, „gamma corrected” RGB, sRGB
 HDR image → Tone mapping B → Inverse display model → LDR image

Sometimes known as “gamma”
Display model

- Tone-mapping needs to account for the physical model of a display
  - How a display transforms pixel values into emitted light
(Forward) Display model

- GOG: Gain-Gamma-Offset

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

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

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

- 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

10

Non

10^23
300

10,000 lux
Example: Ambient light compensation

- We are looking at the screen in bright light
  \[ L_{\text{peak}} = 100 \text{ [cd} \cdot \text{m}^{-2}] \quad k = 0.005 \]
  \[ L_{\text{black}} = 0.1 \text{ [cd} \cdot \text{m}^{-2}] \]
  \[ E_{\text{amb}} = 2000 \text{ [lux]} \]
  \[ L_{\text{refl}} = \frac{0.005}{\pi} 2000 = 3.183 \text{ [cd} \cdot \text{m}^{-2}] \]

- We assume that the dynamic of the input is 2.6 (≈400:1)
  \[ r_{\text{in}} = 2.6 \quad r_{\text{out}} = \log_{10} \frac{L_{\text{peak}}}{L_{\text{black}} + L_{\text{refl}}} = 1.77 \]

- First, we need to compress contrast to fit the available dynamic range, then compensate for ambient light
  \[ L_{\text{out}} = \left( \frac{L_{\text{in}}}{L_{\text{peak}}} \right)^{\frac{r_{\text{out}}}{r_{\text{in}}}} - L_{\text{refl}} \]

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

Simplest, but not the best tone mapping
Techniques

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

Image histogram

log displayed luminance

log input luminance factor (HDR image)
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 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 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 permissible 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;
- Repeat until converges

Ceiling, based on the maximum permissible contrast
Tone-curve as an optimization problem

Goal: Minimize the visual difference between the input and displayed images

input scene → tone-mapping → argmin E → Visual metric → Display model → display
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Colour transfer in tone-mapping

- Many tone-mapping operators work on luminance
  - For speed
  - To avoid colour artefacts
- Colours must be transferred later from the original image
- Colour transfer in the linear RGB colour space:

  \[
  R_{\text{out}} = \left( \frac{R_{\text{in}}}{L_{\text{in}}} \right)^s \cdot L_{\text{out}}
  \]

- 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

Contrast reduced (s=1)

Red channel

Luminance

Sample of pixels

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

Saturation reduced (s=0.6)

Gamut boundary
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:

\[
\begin{align*}
    u_{\text{out}}' &= (u_{\text{in}}' - u_w') \cdot s + u_w' \\
    v_{\text{out}}' &= (v_{\text{in}}' - v_w') \cdot s + v_w'
\end{align*}
\]

Chroma of the white:

\[
\begin{align*}
    u_w' &= 0.1978 \\
    v_w' &= 0.4683
\end{align*}
\]
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Illumination & reflectance separation

$Y = I \times R$
Illumination and reflectance

Reflectance

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

Illumination

- Sun ≈ $10^9\ \text{cd/m}^2$
- Lowest perceivable luminance ≈ $10^{-6}\ \text{cd/m}^2$
- Dynamic range 10,000:1 or more
- Visual system partially discounts illumination
Reflectance & Illumination TMO

- Hypothesis: Distortions in reflectance are more apparent than the distortions in illumination
- Tone mapping could preserve reflectance but compress illumination

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

- for example:

\[ L_d = R \cdot \left( \frac{I}{L_{\text{white}}} \right)^c \cdot L_{\text{white}} \]
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

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

- Blurs sharp boundaries
- Causes halos

Tone mapping result
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 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

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

For example by solving the Poisson equation
Retinex examples

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

From: http://www.ipol.im/pub/algo/lmps_retinex_poisson_equation/#ref_1
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.
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Glare
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]
The model assumes that glare is mostly caused by diffraction and scattering.

Can simulate temporal effects.

[From Ritschel et al, Eurographics 2009]
Temporal glare

Dynamic glare
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)

An OTF is the Fourier transform of a PSF
Convolution with larger kernels is faster in the Fourier domain
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

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

A) Glare applied to the entire image

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
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What changes at low illumination?

- Global contrast
  - Relative brightness

- Local contrast
  - Visibility of small details

- Color
  - Purkinje shift
  - Saturation
Brightness reduction – tone-curve

- Perceptually-based night-vision tone-curve
  - [Wanat et al. 2014]
  - Requires rather complex optimization

- Empirical approach (not perceptual)

\[ y_{out} = b \cdot y_{in}^{\gamma} + f \]

- Reduce brightness
- Reduce contrast
- Add „fog”

\[ \gamma = 0.9 \]
\[ b = 0.8 \]
\[ f = 0.01 \]
Local contrast

- **Gabor patch**
  - basic contrast stimulus
  - the shape matches the response pattern of the receptive fields on the retina

\[ G = l_{\text{max}} - l_{\text{mean}} \]

- **Contrast**
  - Max log luminance
  - Mean log luminance

\[ G = l_{\text{max}} - l_{\text{mean}} \]
Supra-threshold contrast matching

- Kulikowski’s model of matching contrast [Kulikowski 1976]
  - Contrast is perceived the same at different luminance levels when the physical contrast reduced by the corresponding detection threshold is equal at those luminance levels

\[ G(L_A) - G_T(L_A) = G(L_B) - G_T(L_B) \]
Supra-threshold contrast matching

- The lines connect contrast of the same perceived magnitude
Local contrast processing

\[ m = \frac{c - G_t + \tilde{G}_t}{c} \]

Kulikowski's model

Contrast boost

Local contrast

Frequency

Source image
Laplacian pyramid

Target image
Laplacian pyramid

Detection threshold source

Detection threshold target

Background luminance

Tone-curve

\[ T(l) \]
Example processing

Simulation of night vision

Source

Target
Rod contribution to colour vision

Rods and cones share the same pathway. Rods contribute to all cone responses.

[Cao et al. 2008]
Purkinje shift (effect)

- A shift in spectral sensitivity associated with the transition of cone to rod vision
  - Blue appears brighter and red appears darker in twilight
  - And the reverse is observed in daylight
- The shift to bluish hues is sometimes attributed to the Purkinje effect
  - In practice the blue-shift is very subtle
  - Much more pronounced in movies
Loss of colour saturation with luminance

- Cones become less sensitive at low light
- Colours become less saturated
- Empirical formula [Wanat 2014]
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:
  - ...