Learning outcomes

- What is tone-mapping?
- What problem(s) does it solve?
- Why is the problem so difficult?
- How do we perceive high dynamic range images?
- What are the major approaches to tone-mapping?
- How to choose a tone-mapping for a particular application?
Tone-mapping problem

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

Luminance range [cd/m²] simultaneously adapted

Human vision

Conventional display

Tone mapping
Question to the audience

- Who has never used a tone-mapping operator?

Each camera needs to tone-map a real-world captured light before it can be stored as a JPEG. This is essentially the same process as tone-mapping, although known as ‘color reproduction’ or ‘color processing’.
Color space retargeting problem

Real-world

Display

Goal: map colors to a restricted color space
Perceptual retargeting problem

Goal: match color appearance

Real-world

The eye adapted to the real-world viewing conditions

The eye adapted to the display viewing conditions

Display
Tone Mapping?

- HDR?
- Or something else?
What is tone-mapping?

Although tone-mapping may have different meanings, this course is about:

A) Transformation of an image from an unrestricted color gamut of real world or an abstract scene to the restricted color gamut of a device

B) Retargeting the perceptual appearance from one viewing conditions to another
Input and output

- HDR
- (approximate) physical units
- luminance
- linear RGB
- scene-referred

Tone mapping

- LDR (SDR)
- pixel values
- luma
- gamma corrected R’G’B’
- display referred
Luminance

- Luminance – perceived brightness of light, adjusted for the sensitivity of the visual system to wavelengths

\[ L_v = \int_0^\infty L(\lambda) \cdot V(\lambda) d\lambda \]
Do HDR images contain luminance values?

- Not exactly, because:
  - the combination of camera red, green and blue spectral sensitivity curves will not match the luminous efficiency function

- But they contain a good-enough approximation for most applications
  - For multi-exposure camera capture the error in luminance measurements is 10-15%
Sensitivity to luminance

- Weber-law – the just-noticeable difference is proportional to the magnitude of a stimulus

\[ \frac{\Delta L}{L} = k \]

The smallest detectable luminance difference

Background (adapting) luminance

Typical stimuli:

Ernst Heinrich Weber
[From wikipedia]
Consequence of the Weber-law

- Smallest detectable difference in luminance

\[ \frac{\Delta L}{L} = k \]

<table>
<thead>
<tr>
<th>L</th>
<th>ΔL</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 cd/m²</td>
<td>1 cd/m²</td>
</tr>
<tr>
<td>1 cd/m²</td>
<td>0.01 cd/m²</td>
</tr>
</tbody>
</table>

- Adding or subtracting luminance will have different visual impact depending on the background luminance

- Unlike LDR luma values, HDR luminance values are not perceptually uniform!
How to make luminance (more) perceptually uniform?

- Using Fechnerian integration

\[ dR(L) = \frac{1}{\Delta L(L)} \]

Luminance transducer:

\[ R(L) = \int_{0}^{L} \frac{1}{\Delta L(l)} \, dl \]
Assuming the Weber law

\[ \frac{\Delta L}{L} = k. \]

- and given the luminance transducer

\[ R(L) = \int_0^L \frac{1}{\Delta L(l)} \, dl \]

- the response of the visual system to light is:

\[ R(L) = \int \frac{1}{kL} \, dL = \frac{1}{k} \ln(L) + k_1 \]
Fechner law

\[ R(L) = a \ln(L) \]

- Practical insight from the Fechner law:
  - The easiest way to adopt image processing algorithms to HDR images is to convert luminance (radiance) values to the logarithmic domain.
But…the Fechner law does not hold for the full luminance range
  - Because the Weber law does not hold either
  - Threshold vs. intensity function:

The Weber law region
Weber-law revisited

- If we allow detection threshold to vary with luminance according to the t.v.i. function:

- we can get more accurate estimate of the “response”:

\[
R(L) = \int_{0}^{L} \frac{1}{\Delta L(l)} dl
\]
Fechnerian integration and Steven’s law

\[ R(L) = \int_0^L \frac{1}{\Delta L(l)} \, dl \]
Major approaches to tone-mapping

- Illumination & reflectance separation
- Forward visual model
- Forward & inverse visual models
- Constraint mapping problem

This is not a crisp categorization
  - Some operators combine several approaches
Major approaches to tone-mapping

- Illumination & reflectance separation
- Forward visual model
- Forward & inverse visual model
- Constraint mapping problem
Illumination & reflectance separation

Input

Illumination

Reflectance
Illumination and reflectance

Illumination
- Sun \( \approx 10^9 \text{ cd/m}^2 \)
- Lowest perceivable luminance \( \approx 10^{-6} \text{ cd/m}^2 \)
- Dynamic range 10,000:1 or more
- Visual system partially discounts illumination

Reflectance
- White \( \approx 90\% \)
- Black \( \approx 3\% \)
- Dynamic range < 100:1
- Reflectance critical for object & shape detection
Reflectance & Illumination TMO

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

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

- for example:

\[ I_d = R \cdot L^{1/\gamma} \]
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

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]
WLS filter

- **Weighted-least-squares optimization**

\[
\sum_{p} \left( (u_p - g_p)^2 + \lambda \left( a_{x,p}(g) \left( \frac{\partial u}{\partial x} \right)_p^2 + a_{y,p}(g) \left( \frac{\partial u}{\partial y} \right)_p^2 \right) \right) \rightarrow \text{min}
\]

- [Farbman et al., SIGGRAPH 2008]
WLS filter

- Stronger smoothing and still distinct edges

- Can produce stronger effects with fewer artifacts
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
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

[Fattal et al., SIGGRAPH 2002]
Contrast domain image processing

[Rationale: Human eye is more sensitive to contrast than luminance]
Contrast domain image processing

Wavelets

Image transform: Multi-scale contrast pyramid

Contrast pyramid

Gradients

1st level

2nd level

1st level

2nd level
Contrast transducer function

Goal: Transform contrast to the representation that is possibly perceptually uniform.
Contrast Equalization: Examples

- Log-Linear Scaling
- Contrast Mapping $l=0.4$
- Contrast Histogram Equalization
- Contrast equalization
Contrast Equalization: Examples

Log-Linear Scaling

Contrast mapping

Contrast equalization
Tone mapping in photography

- **Dodging and burning**
  - Darken on brighten image parts by occluding photographic paper during exposure
  - Ansel Adams, *The print*, 1995
  - Photoshop tool

- Essentially – attenuate low-pass frequencies associated to illumination
Automatic dodging and burning

- Reinhard et al., *Photographic tone reproduction for digital images*. SIGGRAPH 2002
- Choose dodging and burning kernel size adaptively
  - depending on the response of the center-surround filter
  - thus avoid halo artifacts
Major approaches to tone-mapping

- Illumination & reflectance separation
- Forward visual model
- Forward & inverse visual model
- Constraint mapping problem
Forward visual model

- Mimic the processing in the human visual system

- Assumption: what is displayed is brightness or abstract response of the visual system
Forward visual model: Retinex

- Remove illumination component from an image
  - Because the visual system also discounts illuminant
- Display ‘reflectance’ image on the screen

Assumption:
- The abstract ‘reflectance’ contains most important visual information
- Illumination is a distraction for object recognition and scene understanding
Photoreceptor response

- Dynamic range reduction inspired by photoreceptor physiology
  - [Reinhard & Devlin ‘05]

\[ V = \frac{I}{I + \sigma(I_a)} V_{\text{max}} \]
\[ \sigma(I_a) = (fI_a)^m. \]

- From gamma to sigmoidal response:
Results: photoreceptor TMO
Photoreceptor models

- **Naka-Rushton equation:**

\[
\frac{R}{R_{max}} = \frac{Y^n}{Y^n + \sigma^n}
\]

- **Response of the photoreceptor to a short flicker of light** - less applicable to viewing static images
Sigmoidal tone-curves

- Very common in digital cameras
  - Mimic the response of analog film
  - Analog film has been engineered for many years to produce optimum tone-reproduction (given that the tone curve must not change)
- Effectively the most commonly used tone-mapping!
Why sigmoidal tone-curves work

- Because they mimic photoreceptor response
  - Unlikely, because photoreceptor response to steady light is not sigmoidal

- Because they preserve contrast in mid-tones, which usually contains skin color
  - We are very sensitive to variation in skin color

- Because an image on average has Gaussian distribution of log-luminance
  - S-shape function is the result of histogram equalization of an image with a Gaussian-shape histogram
Lightness perception

- Lightness perception in tone-reproduction for high dynamic range images [Krawczyk et al. ‘05]
- Based on Gilchrist lightness perception theory

- Perceived lightness is anchored to several frameworks
Gilchrist lightness perception theory

- **Frameworks** – areas of common illumination
- **Anchoring** – the tendency of
  - highest luminance
  - largest area
to appear white
- **Tone-mapping**
  - Rescale luminance in each framework to its anchor
Results – lightness perception TMO

Photographic Tone Reproduction

Bilateral Filtering

Presented Computational Model
Major approaches to tone-mapping

- Illumination & reflectance separation
- Forward visual model
- Forward & inverse visual model
- Constraint mapping problem
Forward and inverse visual model

Original image

Visual model

Inverse visual model

Displayed image

World viewing conditions

Luminance, radiance

abstract response

Display viewing conditions

Editing (optional)
Contrast domain image processing


Rationale: Human eye is more sensitive to contrast than luminance
Multi-scale model

- Multi-scale model of adaptation and spatial vision and color appearance
  - [Pattanaik et al. ‘98]
- Combines
  - psychophysical threshold and superthreshold visual models
  - light & dark adaptation models
  - Hunt’s color appearance model
- One of the most sophisticated visual models
Results – multiscale model …

a) daylight: 1000 cd/m^2

t=0 s., L=0.1 cd/m^2
t=1 s., L=5623 cd/m^2
t=10 s., L=5623 cd/m^2
t=25 s., L=0.1 cd/m^2
t=50 s., L=0.1 cd/m^2
t=25 s., L=5623 cd/m^2
t=1 m 40 s., L=0.1 cd/m^2
t=75 s., L=5623 cd/m^2

t=3 m 20 s., L=0.1 cd/m^2

c) moonlight: 0.04 cd/m^2
Forward and inverse visual model

- Advantages of F&I visual models
  - Can render images for different viewing conditions
    - Different state of chromatic or luminance adaptation
  - Physically plausible
    - Output in the units of luminance or radiance

- Shortcomings F&I visual models
  - Assume that a standard display can reproduce the impression of viewing much brighter or darker scenes
  - Cannot ensure that the resulting image is within the dynamic range of the display
    - Not necessary meant to reduce the dynamic range
  - Visual models are difficult to invert
Major approaches to tone-mapping

- Illumination & reflectance separation
- Forward visual model
- Forward & inverse visual model
- Constraint mapping problem
Constraint mapping problem

- Goal: to restrict the range of values while reducing inflicted damage
Global tone mapping operator

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

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

1. Compute cumulative distribution function:

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

2. Use that function to assign new pixel values

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

- Steepest slope for strongly represented bins
  - Enhance contrast, if many pixels
  - Reduce contrast, if few pixels

- HE 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
- Recompute the ceiling based on the truncated histogram
- Repeat until converges
Display adaptive tone-mapping

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

input scene

tone-mapping

argmin E

Visual metric

Display model

[Mantiuk et al., SIGGRAPH 2008]
Display adaptive tone-mapping

Forward-inverse visual model

argmin E

Visual metric

Display model

[Mantiuk et al., SIGGRAPH 2008]
Results: ambient illumination compensation

Non-adaptive TMO

Display adaptive TMO
Results: ambient illumination compensation

Non-adaptive TMO

Display adaptive TMO

10 lux

300 lux

10 000 lux
Results: ambient illumination compensation

Non-adaptive TMO  Display adaptive TMO

10  300  10,000 lux
Results: display contrast

ePaper

standard LCD

HDR display
Tone-mapping for video compression

- Find the tone-curve that minimizes distortion in a backward-compatible HDR video encoding

Closed-form solution:

\[
s_k = \frac{v_{max} \cdot p_k^{1/3}}{\delta \cdot \sum_{k=1}^{N} p_k^{1/3}}
\]
Which tone-mapping to choose?

- Illumination & reflectance separation
- Forward visual model
- Forward & inverse visual model
- Constraint mapping problem

1. Think what is the target application - and thus the goal of your tone-mapping
2. Consider which tone-mapping approach(es) will deliver that goal
Future of tone-mapping

Tone-mapping of today
- Built into cameras
- Assumes that all displays are the same

Tone-mapping of tomorrow
- Display tone-maps content on demand
- Depending on viewing conditions, viewer, its capabilities
- Content recorded, stored and transmitted in an HDR format

HDR-HDMI
Thank you