UNIVERSITY OF CAMBRIDGE
COMPUTER LABORATORY
RAINBOW GRAPHICS GROUP

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

Luminance

$$\frac{\max\ L}{\min L}$$

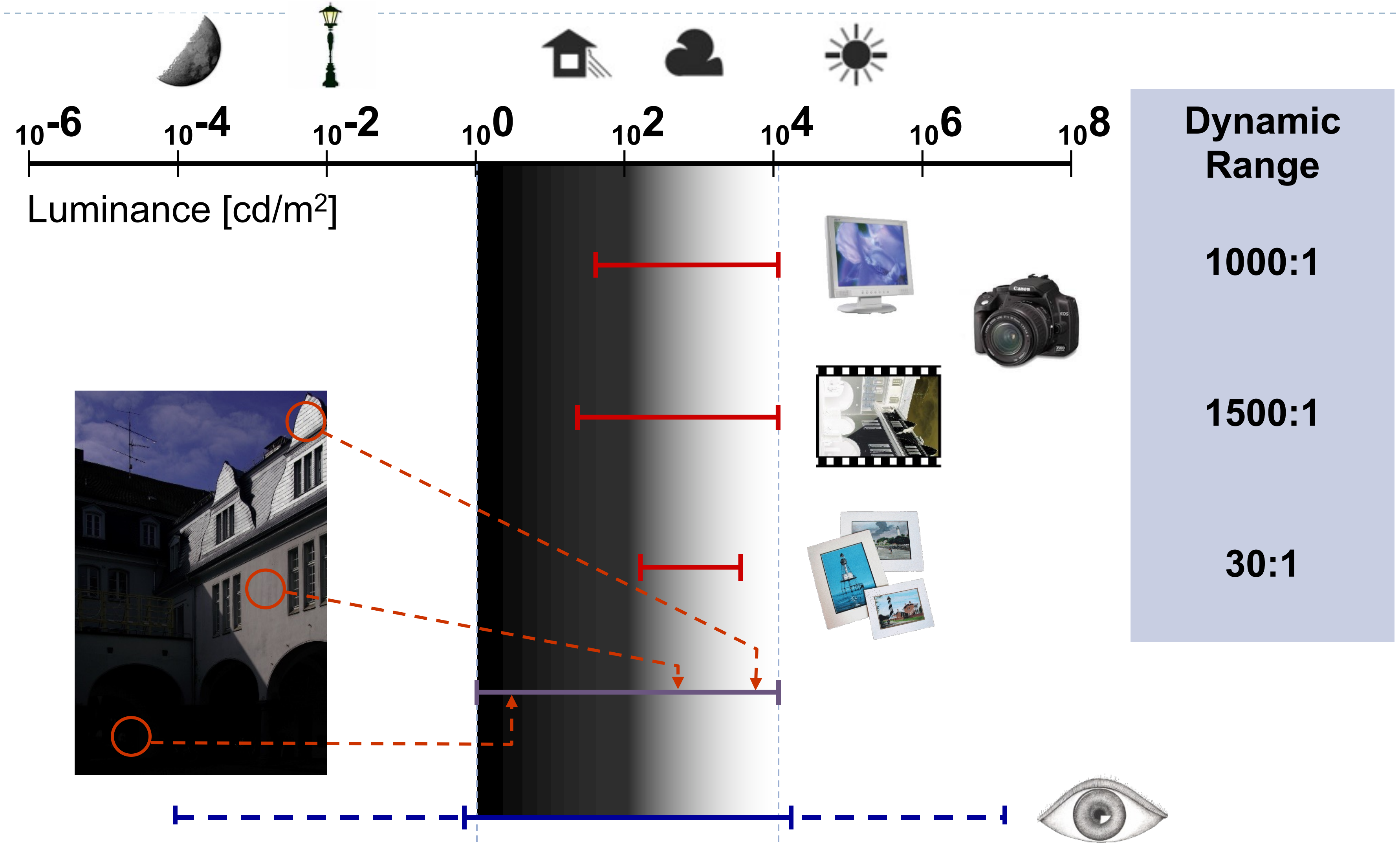
(for SNR>3)

Dynamic range (contrast)

- As ratio: $$C = \frac{L_{\max}}{L_{\min}}$$
  - Usually written as C:1, for example 1000:1.
- As "orders of magnitude" or log10 units: $$C_{10} = \log_{10} \frac{L_{\max}}{L_{\min}}$$
- As stops: $$C_2 = \log_2 \frac{L_{\max}}{L_{\min}}$$

One stop is doubling
of halving the amount of light

High dynamic range (HDR)



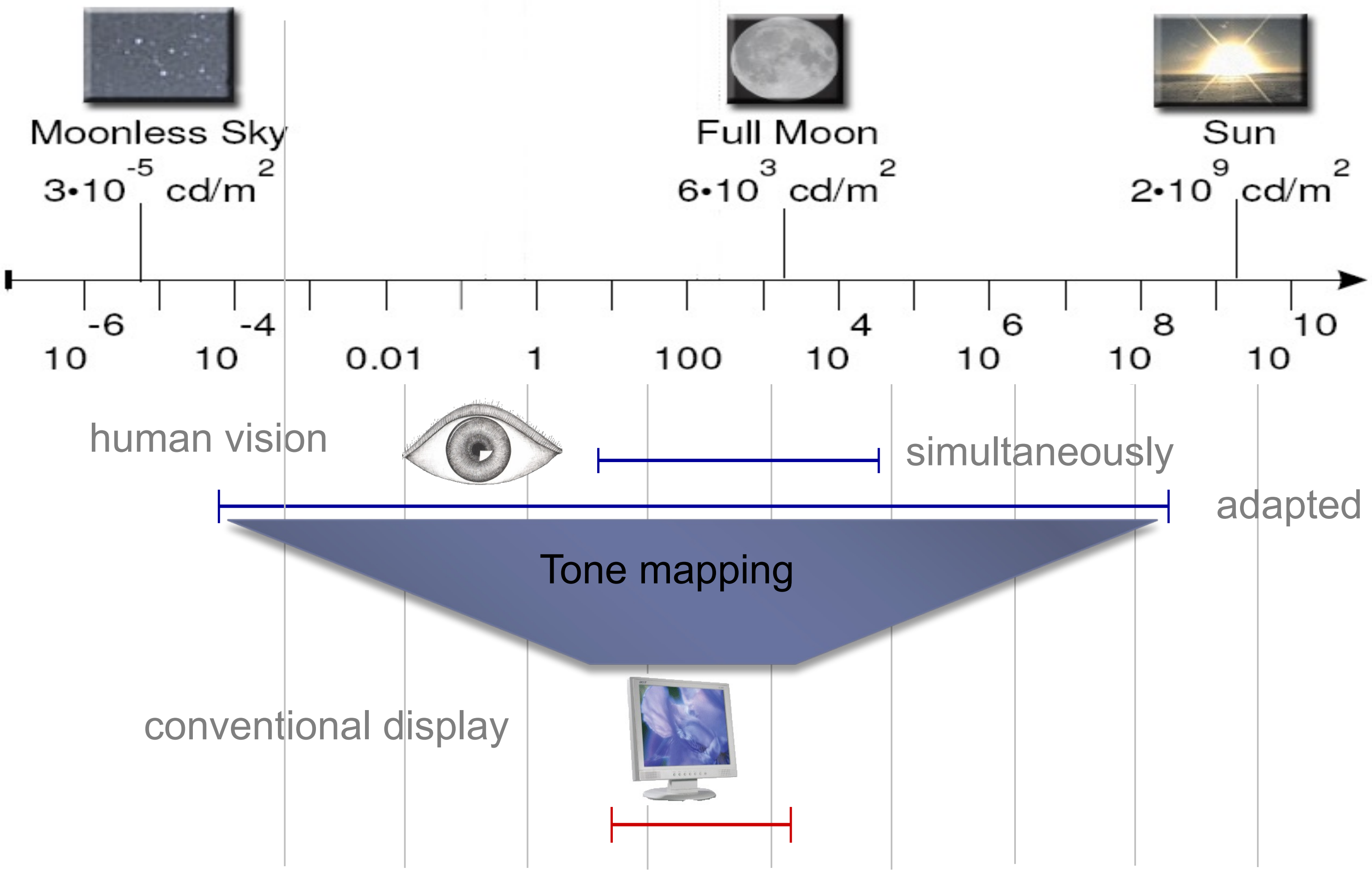
Dynamic Range

1000:1

1500:1

30:1

Tone-mapping problem



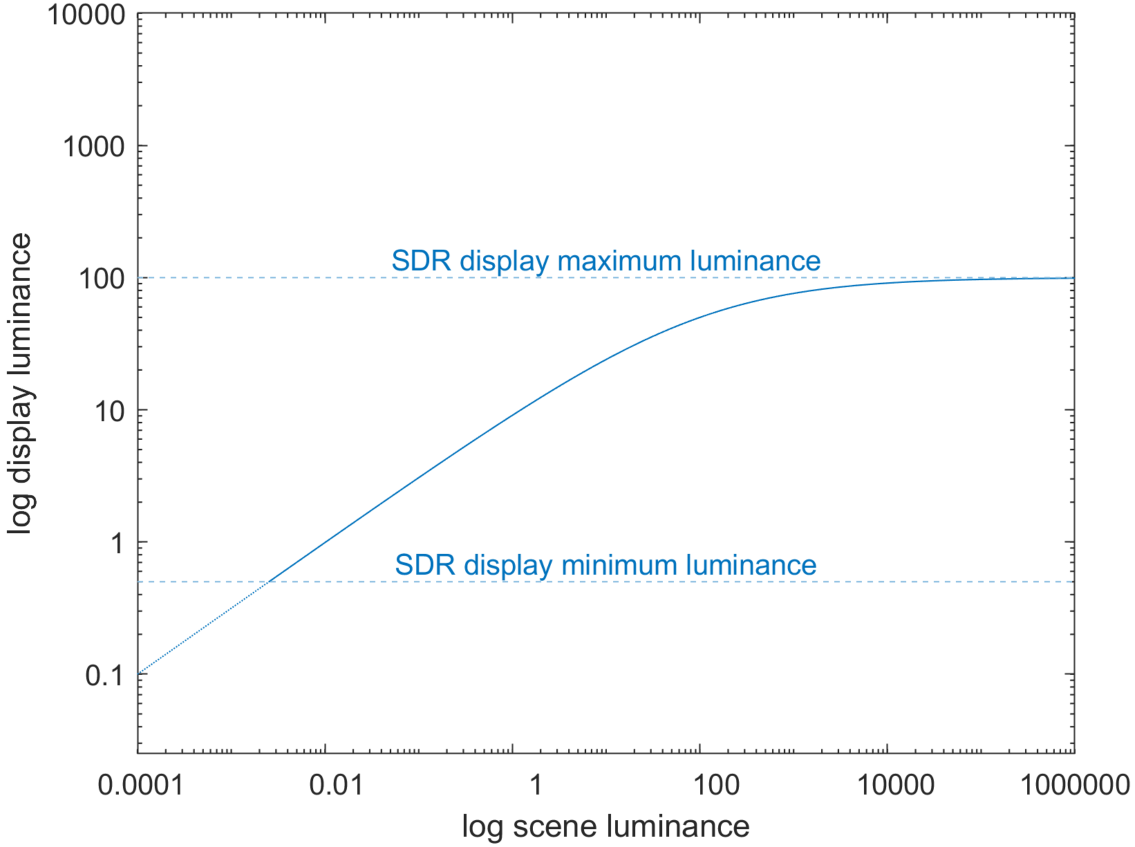
Why do we need tone mapping?

- 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



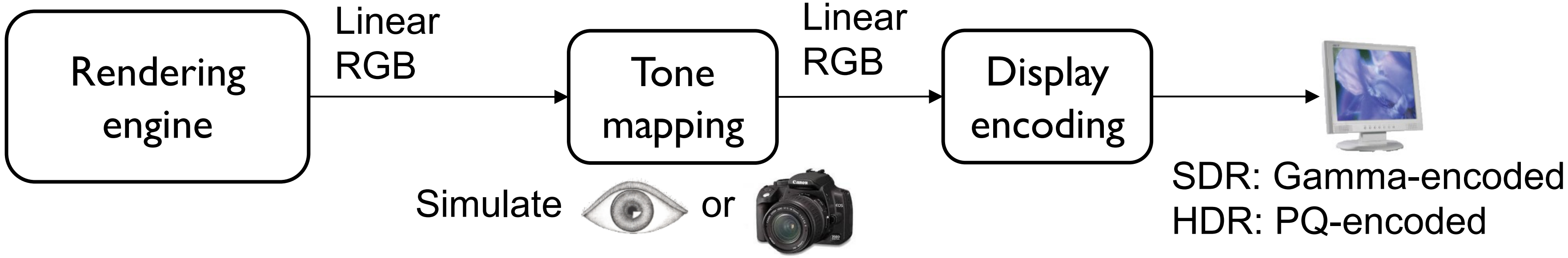
Tone-mapping in rendering

- 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

LDR illumination
No tone-mapping

HDR illumination
Tone-mapping

Half-Life 2: Lost coast



Rendering engine

Linear RGB

Tone mapping

Linear RGB

Display encoding

Simulate or

SDR: Gamma-encoded
HDR: PQ-encoded

Basic tone-mapping and display coding

- The simplest form of tone-mapping is the exposure/brightness adjustment:

Display-referred red value

$$R_d = \frac{R_s}{L_{white}}$$

Scene-referred

Scene-referred luminance of 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"

Prime (') denotes a gamma-corrected value

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

Typically γ=2.2

  - For SDR displays only

Advanced Graphics and Image Processing

High dynamic range and tone mapping

Part 2/2 – tone mapping techniques

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Computer Laboratory, University of Cambridge

Techniques

- Arithmetic of HDR images
- Display model
- Tone-curve
- Colour 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

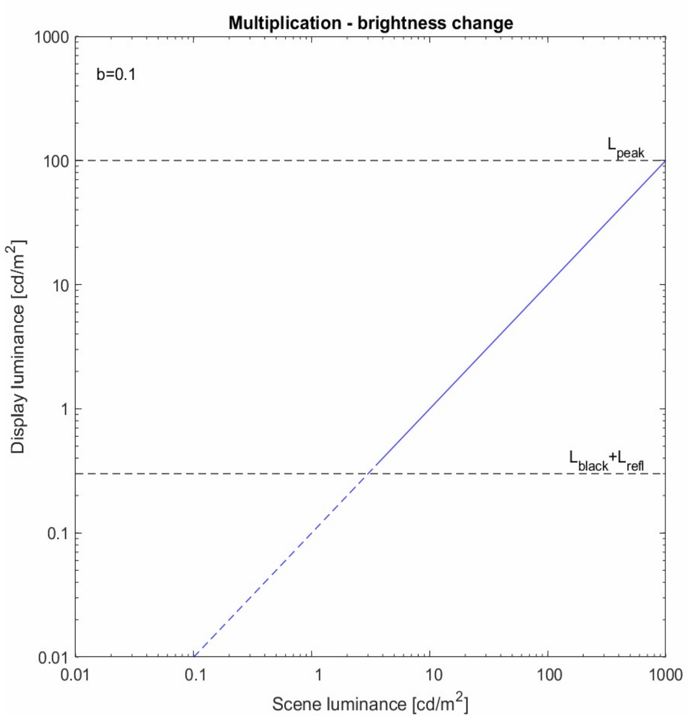
Multiplication – brightness change

Resulting luminance

Input luminance

$$T(L_p) = b \cdot L_p$$

Brightness change parameter



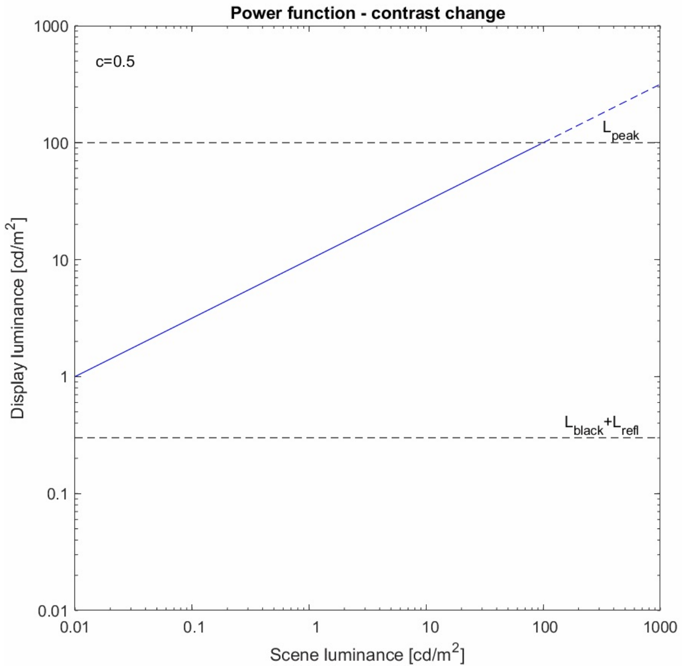
- Multiplication makes the image brighter or darker
- It does not change the dynamic range!

Power function – contrast change

$$T(L_p) = L_{peak}\left(\frac{L_p}{L_{white}}\right)^c$$

Contrast change (gamma)

Luminance to be mapped to white



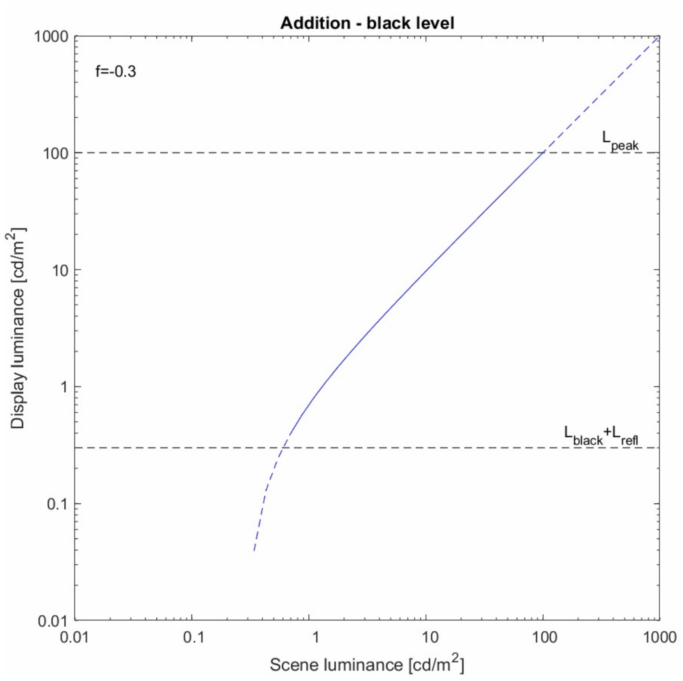
- Power function stretches or shrinks the dynamic range of an image
- It is usually performed relative to a reference white colour (and luminance)
- Side effect: brightness of the dark image part will change
- Slope on a log-log plot explains contrast change

Addition – black level

$$T(L_p) = L_p + f$$

Black level
(flare, fog)

- Addition elevates black level, adds „fog" to an image
- It affects mostly darker tones
- It reduces image dynamic range
- Subtraction can compensate for ambient light



Techniques

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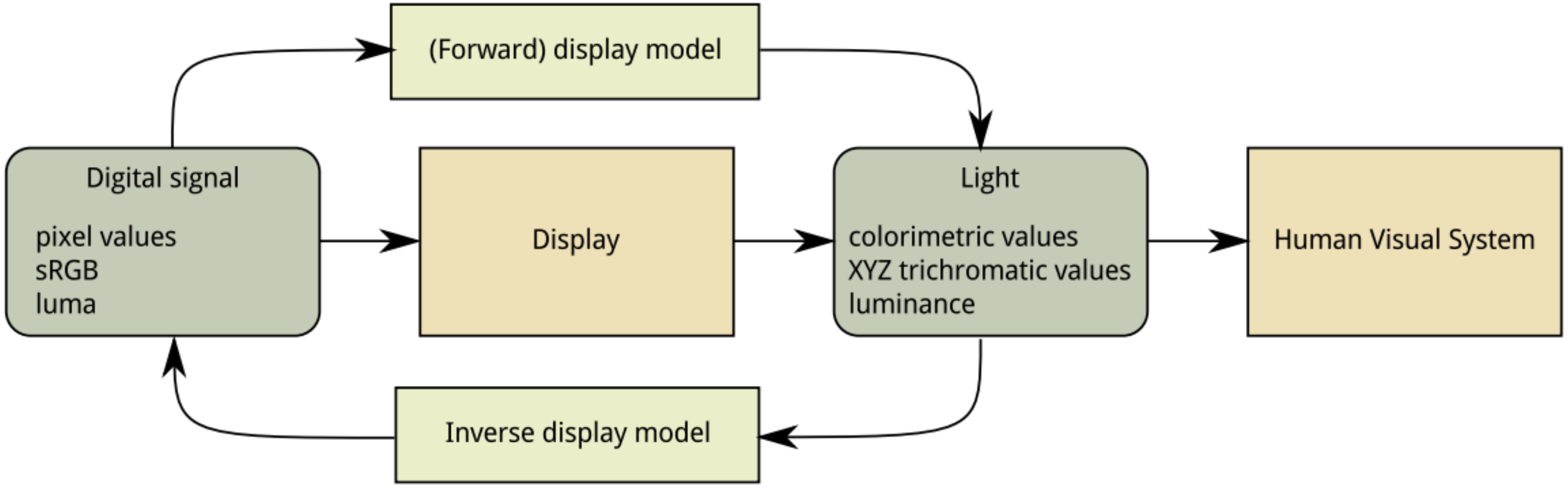
Display-adaptive tone mapping

- 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



(Forward) display model

Digital signal

pixel values
sRGB
luma

Display

Light

colorimetric values
XYZ trichromatic values
luminance

Human Visual System

Inverse display model

Has a similar role as display encoding, but can account for viewing conditions

(Forward) Display model (SDR)

- GOG: Gain-Offset-Gamma

Luminance

Display peak luminance

Gamma

Display black level

Screen reflections

$$L = \underbrace{(L_{peak} - L_{black})}_{\text{Gain}} V^{\gamma} + \underbrace{L_{black} + L_{refl}}_{\text{Offset}}$$

Pixel value 0-1

Reflectance factor (0.01)

$$L_{refl} = \frac{k}{\pi} E_{amb}$$

Ambient illumination (in lux)

(*) assuming a matt screen

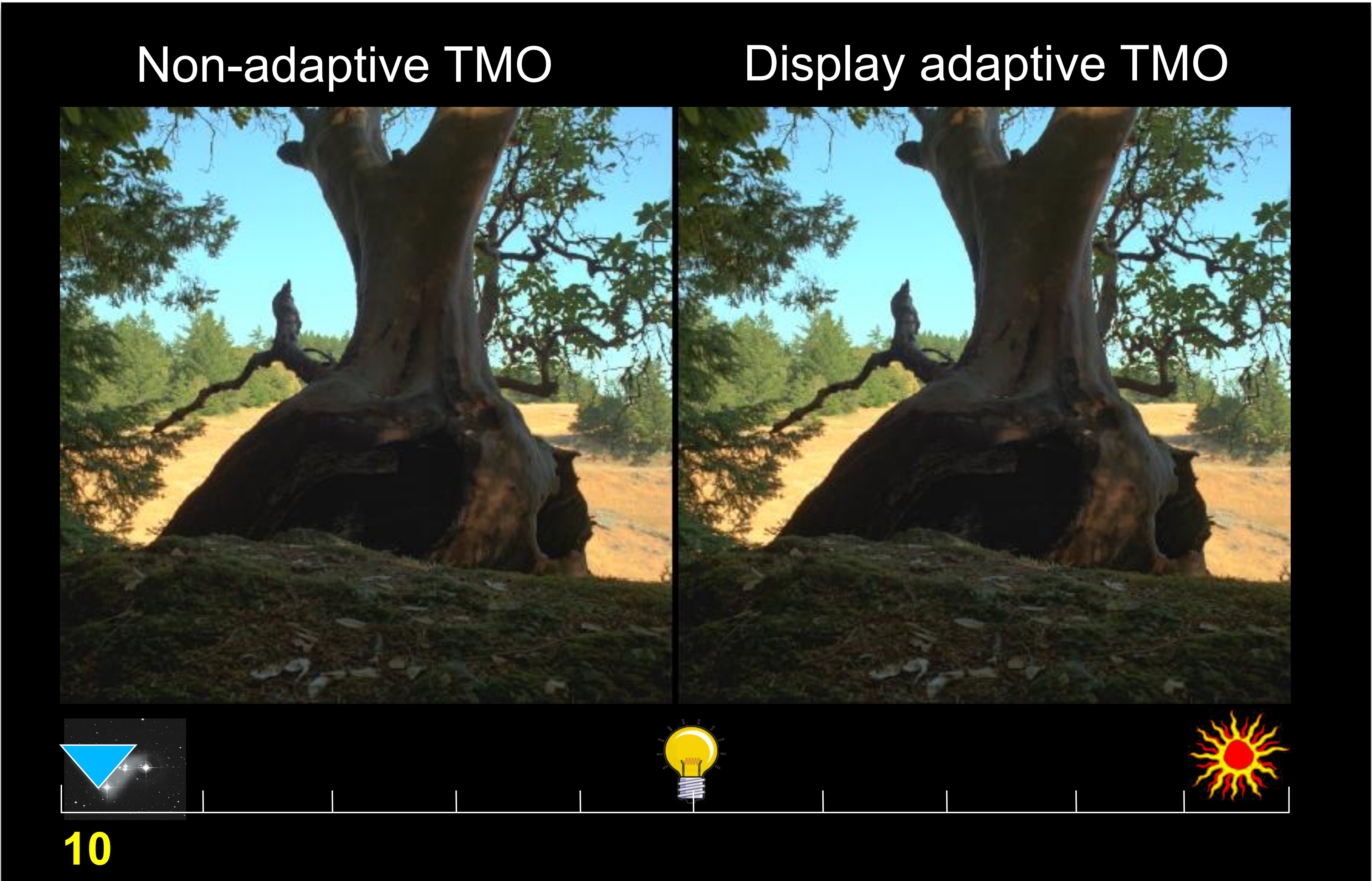
Inverse display model

Symbols are the same as for the forward display model

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

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

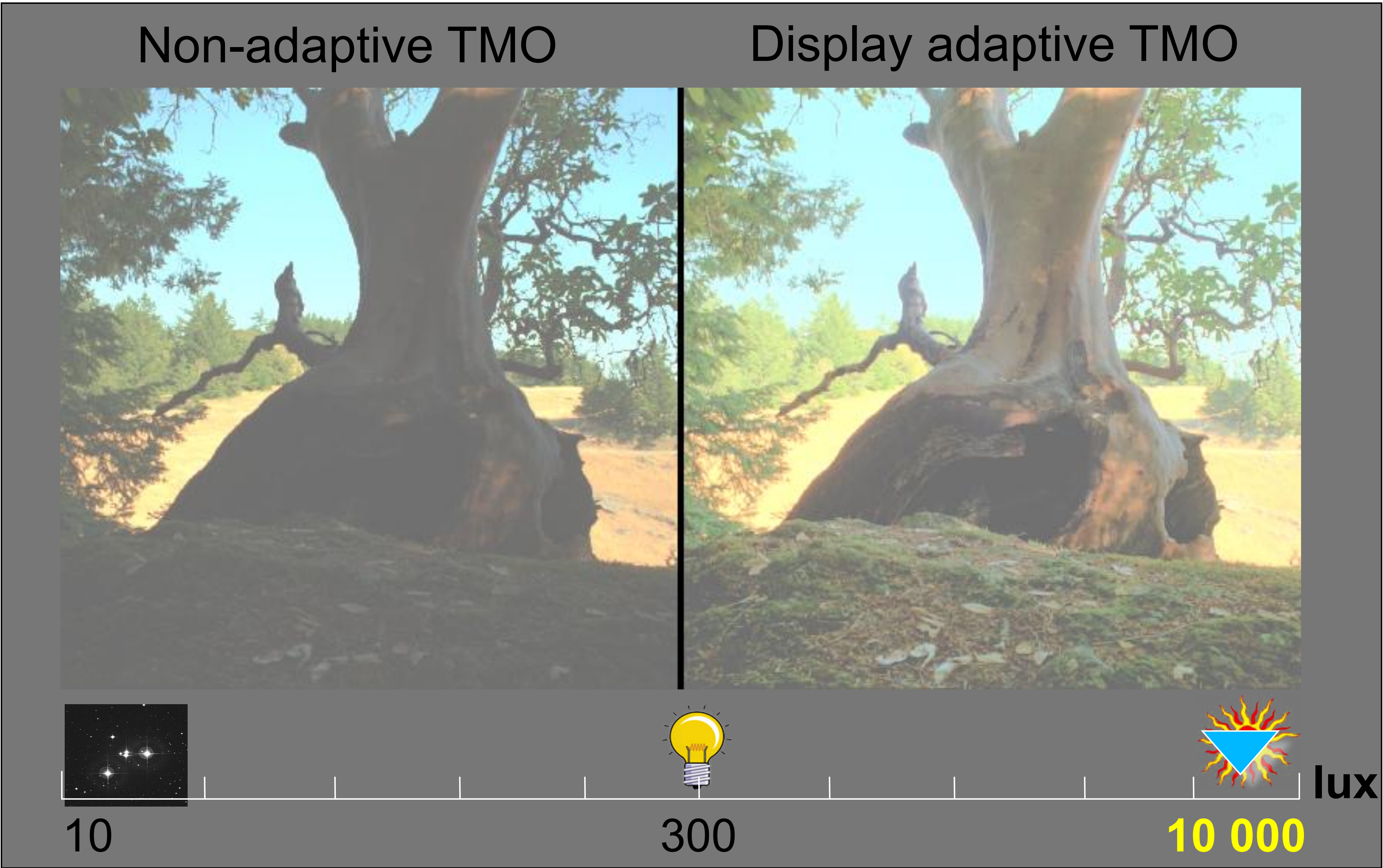
Ambient illumination compensation



Non-adaptive TMO

Display adaptive TMO

Ambient illumination compensation



Example: Ambient light compensation

- We are looking at the screen in bright light

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

Modern screens have reflectivity of around 0.5%

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

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

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

$$r_{in} = 2.6 \qquad r_{out} = \log_{10} \frac{L_{peak}}{L_{black} + L_{refl}} = 1.77$$

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

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

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
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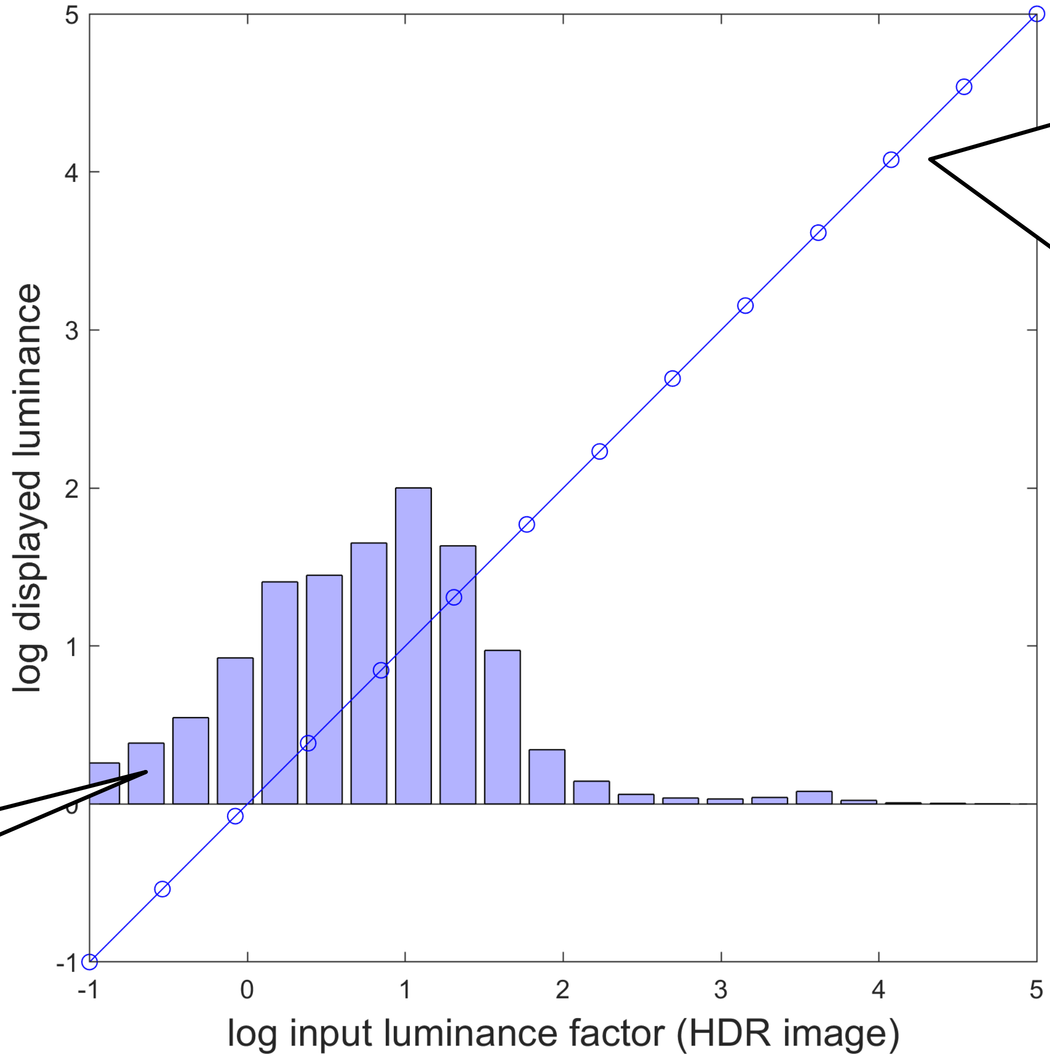
- Glare

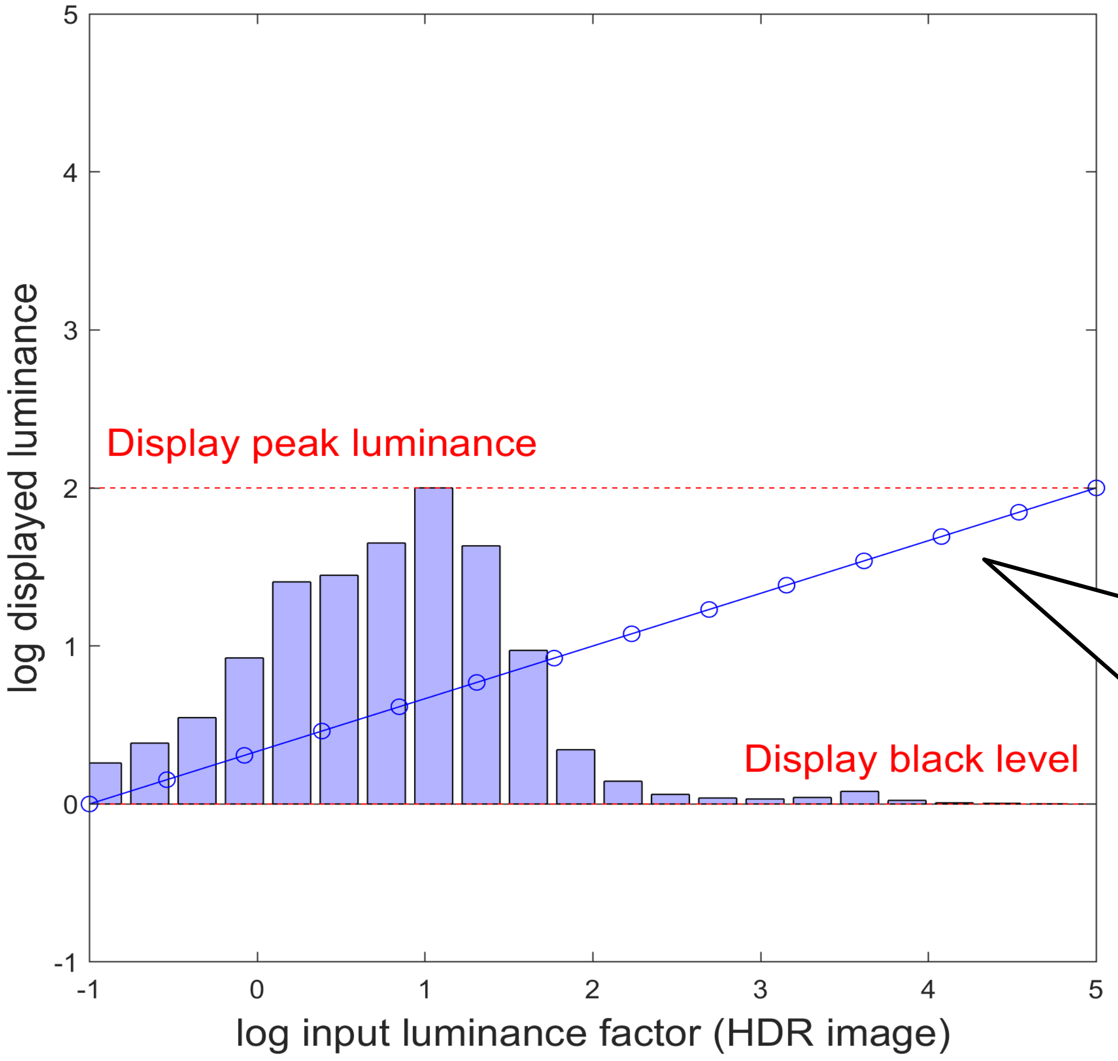
Tone-curve



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

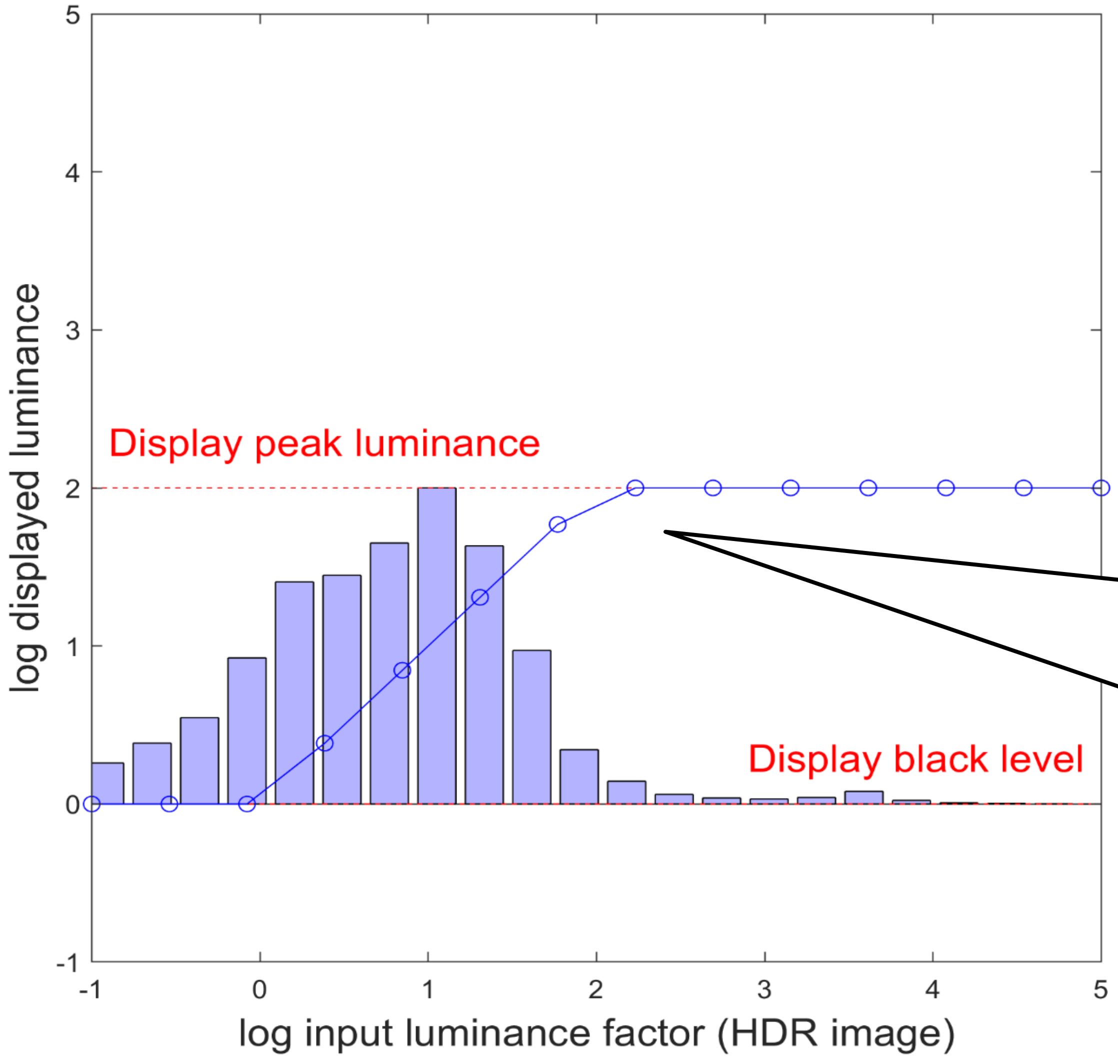
Image histogram

Tone-curve



But in practice contrast (slope) must be limited due to display limitations.

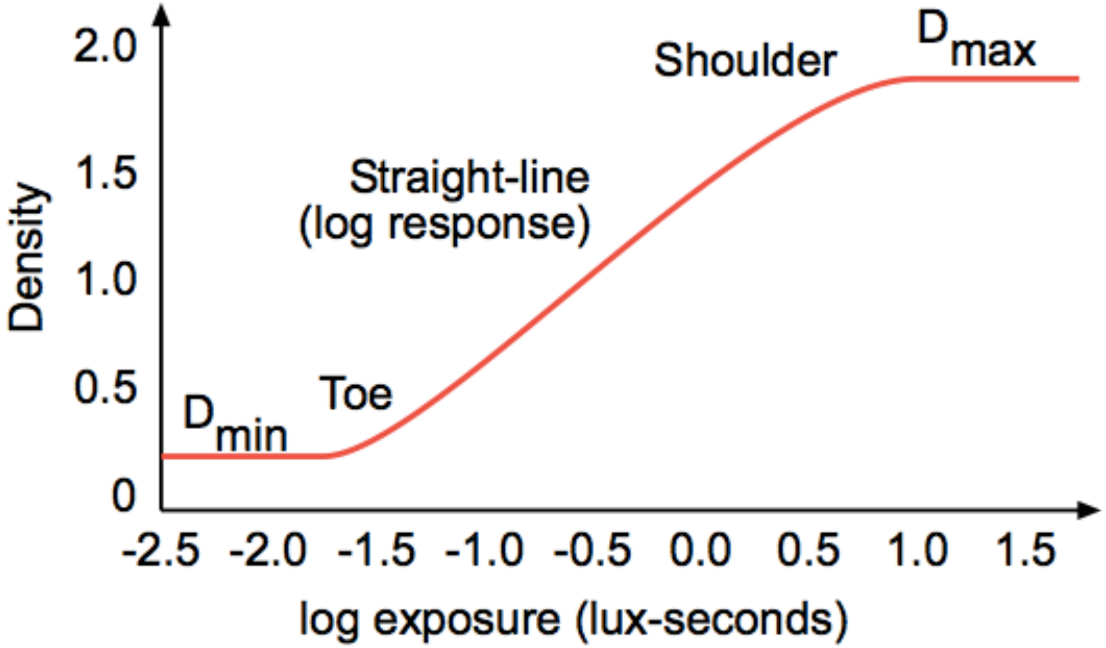
Tone-curve



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
  - An analog film has been engineered over many years to produce good tone reproduction
- Fast to compute



Sigmoidal tone mapping
(a.k.a. Photographic/Reinhard tone mapping)

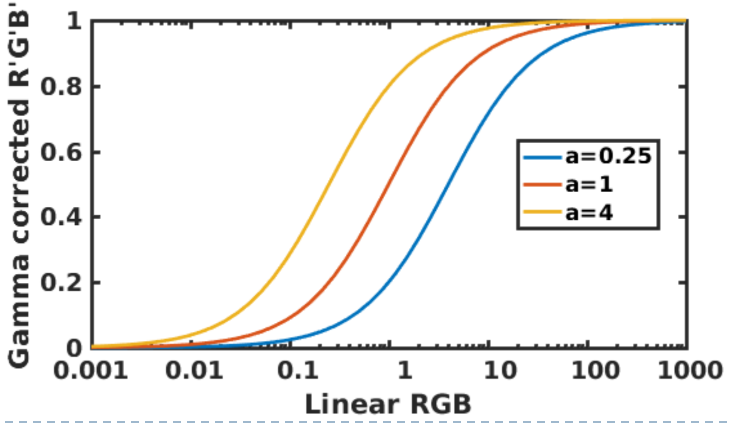
- Simple formula for a sigmoidal tone-curve:

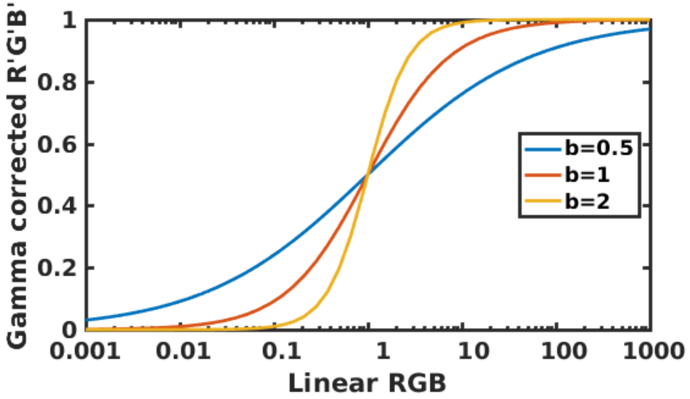
$$R'(x,y) = \frac{R^b(x,y)}{\left(\frac{L_m}{a}\right)^b + R^b(x,y)}$$

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

Histogram equalization

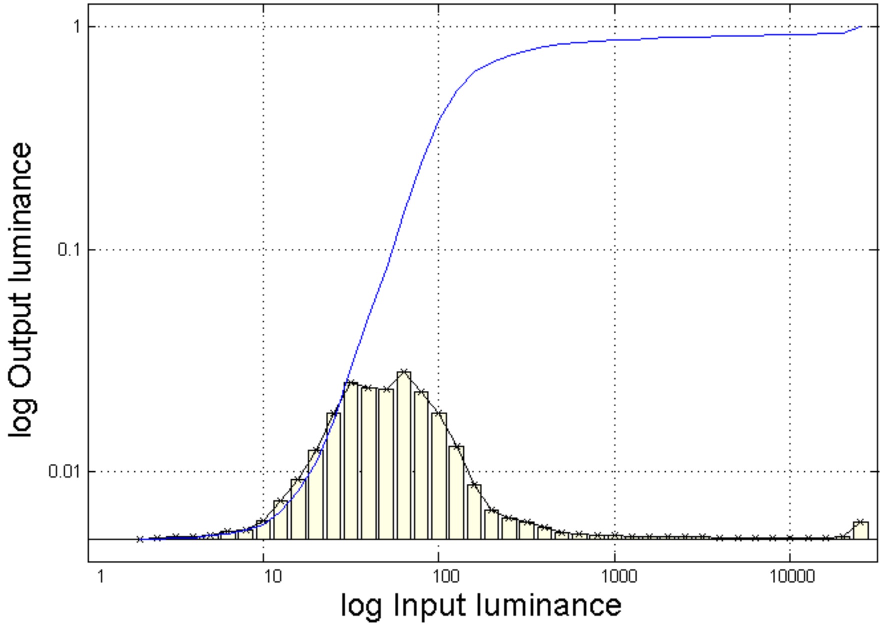
- 1. Compute normalised cummulative image histogram

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

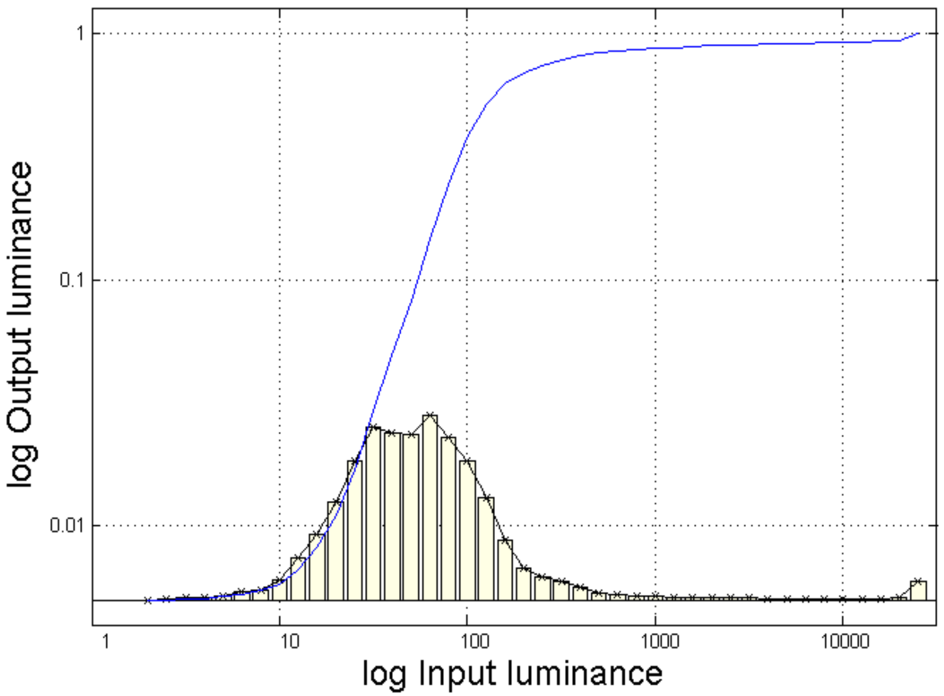
  - For HDR, operate in the log domain
- 2. Use the cummulative histogram as a tone-mapping function

$$Y_{out} = c(Y_{in})$$

  - 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

CLAHE: Contrast-Limited Adaptive Histogram Equalization

- [Pizer et al. Adaptive histogram equalization and its variations. Comput Vision, Graph Image Process 1987], [Larson et al. 1997, IEEE TVCG]

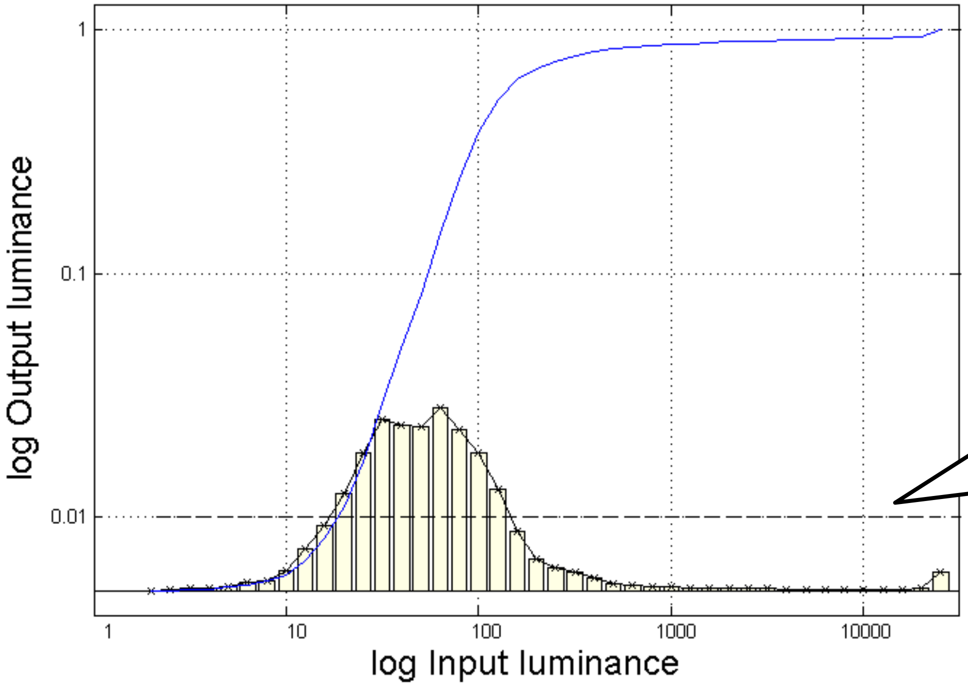

Linear mapping


Histogram equalization


CLAHE

CLAHE: Contrast-Limited Adaptive Histogram Equalization

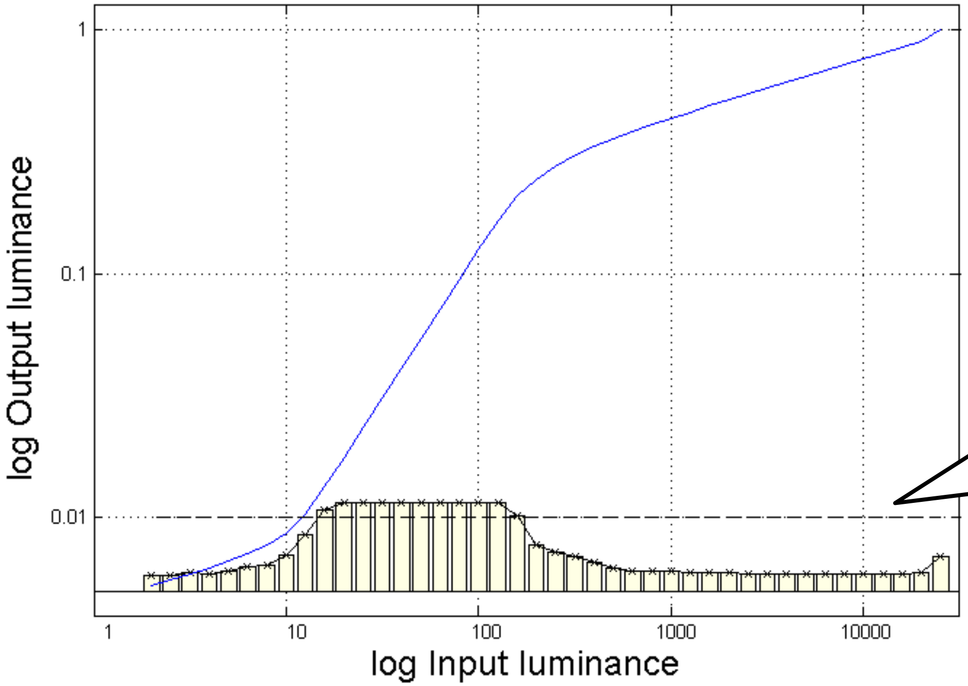
- Truncate the bins that exceed the ceiling;
- Distribute the removed counts to all bins;
- Repeat until converges



Ceiling, based on the maxiumum permissibble contrast

CLAHE: Contrast-Limited Adaptive Histogram Equalization

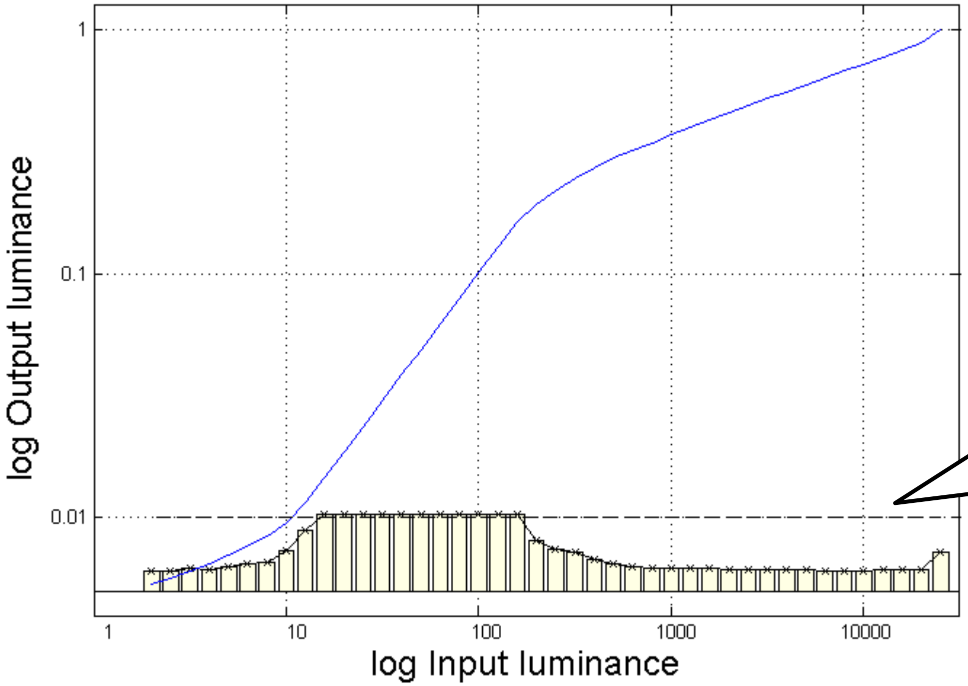
- Truncate the bins that exceed the ceiling;
- Distribute the removed counts to all bins;
- Repeat until converges



Ceiling, based on the maxiumum permissibble contrast

CLAHE: Contrast-Limited Adaptive Histogram Equalization

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



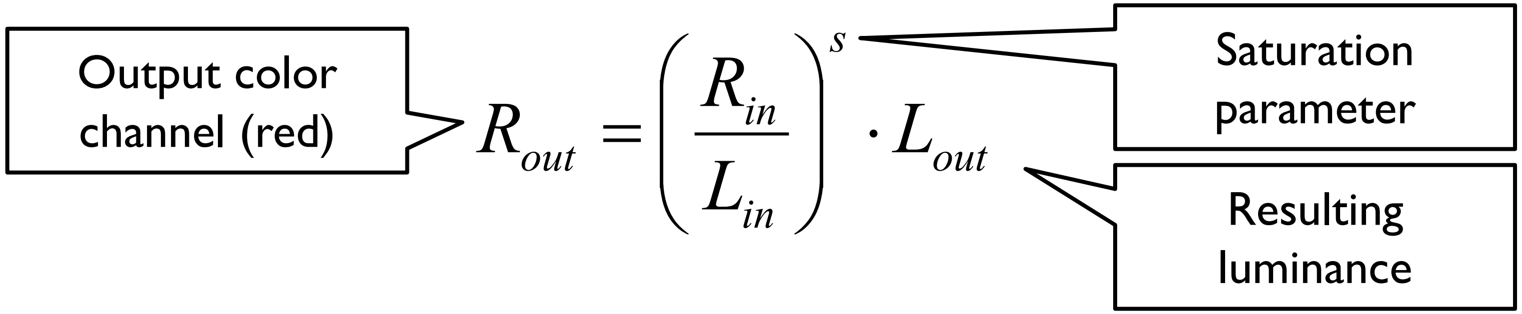
Ceiling, based on the maxiumum permissibble contrast

Techniques

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

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 form 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

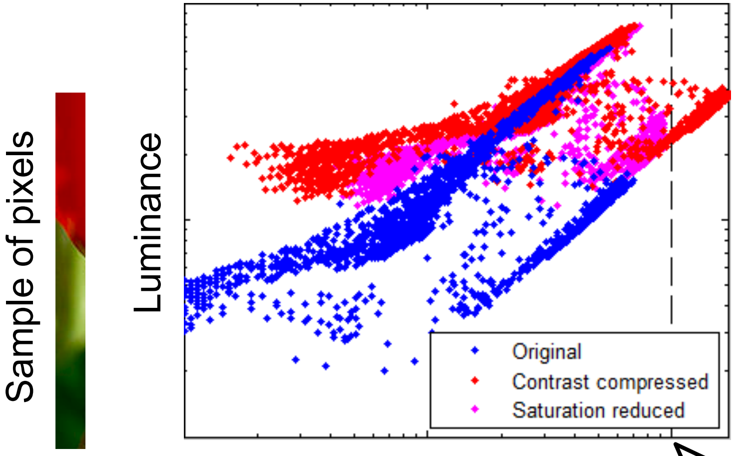
- Colours often fall outside the colour gamut when contrast is compressed


Original image

→


↓ Contrast reduced (s=1)

Colours before/after processing



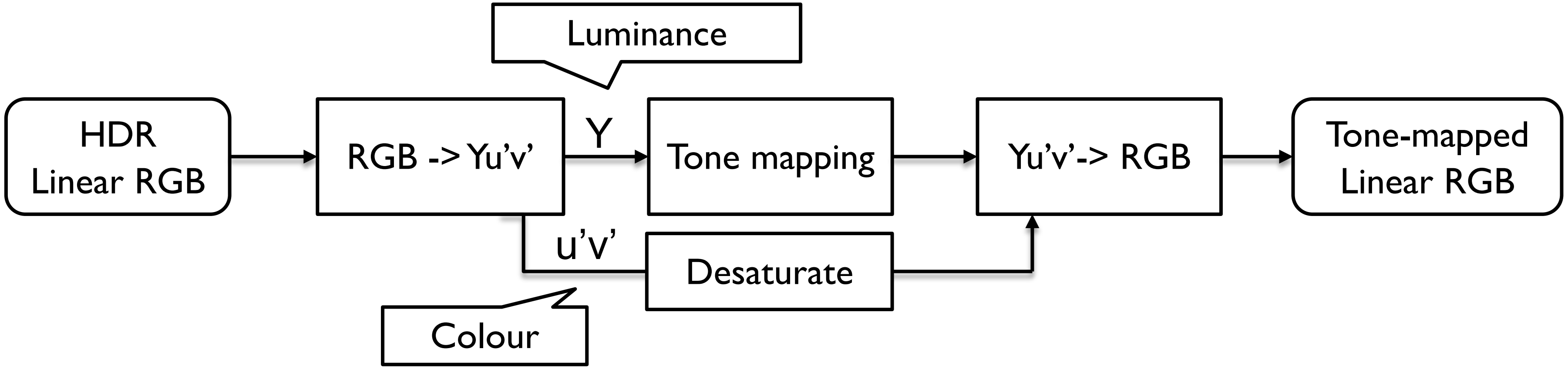
Gamut boundary

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


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:

Chroma of the white

$$u'_{out} = (u'_{in} - u'_{w}) \cdot s + u'_{w} \qquad u'_{w} = 0.1978$$

$$v'_{out} = (v'_{in} - v'_{w}) \cdot s + v'_{w} \qquad v'_{w} = 0.4683$$

Techniques

- Arithmetic of HDR images
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- Tone-curve
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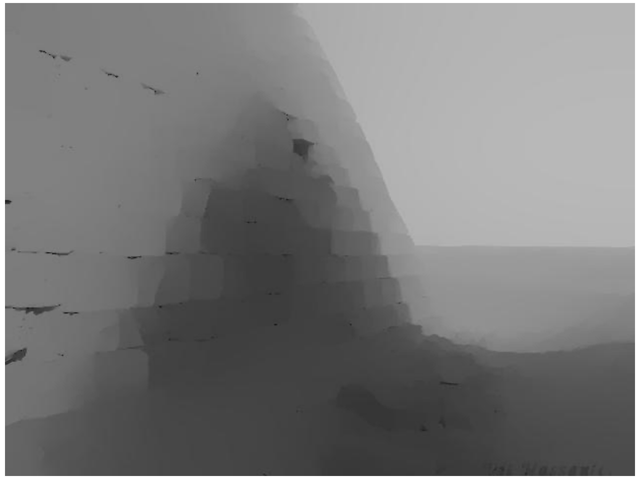
Illumination & reflectance separation

Input



Illumination

Reflectance

$$X_p = I_p R_p$$

Image
linear RGB

Illumination

Reflectance

Illumination and reflectance

Reflectance

- White ≈ 90%
- Black ≈ 3%

- Dynamic range < 100:1

- Reflectance critical for object & shape detection

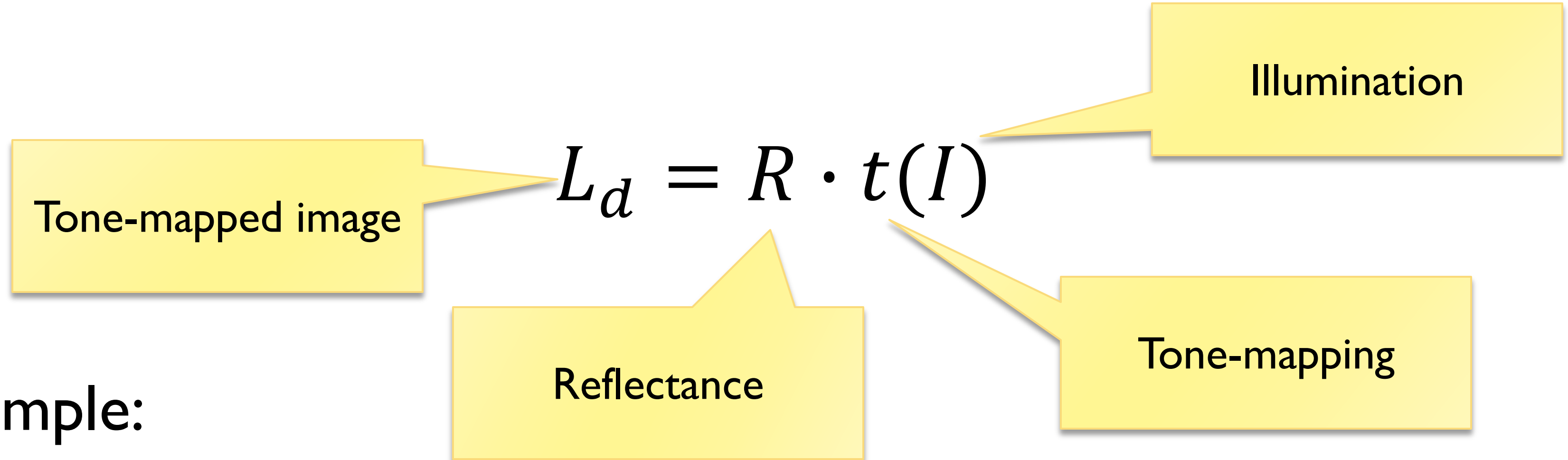
Illumination

- 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

[Tumblin et al. 1999]

Reflectance & Illumination TMO

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



$$L_d = R \cdot t(I)$$

Tone-mapped image

Illumination

Reflectance

Tone-mapping

- for example:

$$L_d = R \cdot (I / L_{white})^c \cdot L_{white}$$

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

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

- First order approximation

- Blurs sharp boundaries
- Causes halos

Tone mapping result

Bilateral filter

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

- Better preserves sharp edges

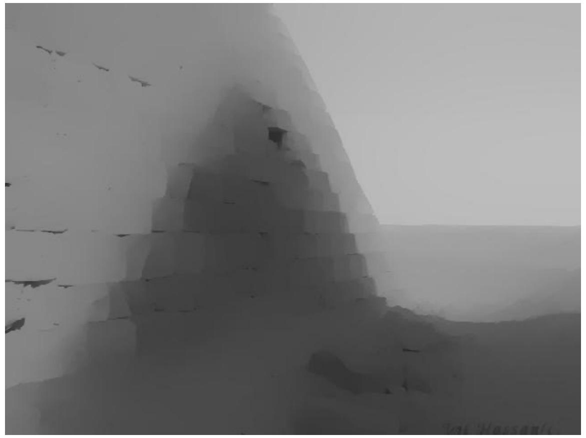
Tone mapping result

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

[Durand & Dorsey, SIGGRAPH 2002]

Weighted-least-squares (WLS) filter

- Stronger smoothing and still distinct edges



Tone mapping result

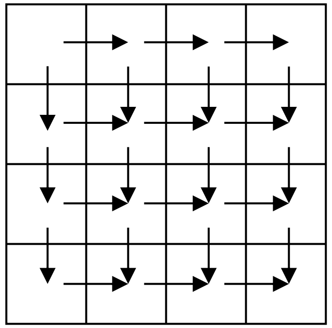
- Can produce stronger effects with fewer artifacts
- See „Advanced image processing" lecture

[Farbman et al., SIGGRAPH 2008]

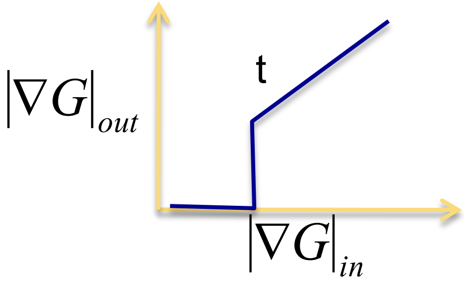
Retinex

- 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 small gradients from an image. Small gradients are attributed to the illumination

1 step: compute gradients in log domain



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



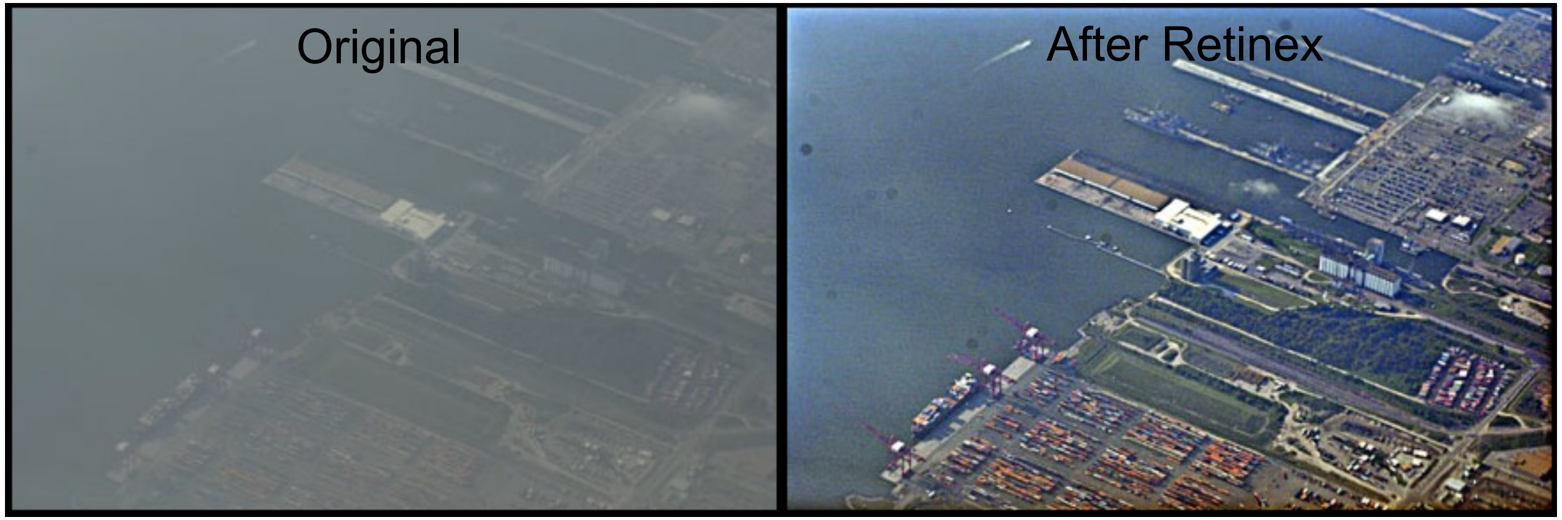
3^{rd} step: reconstruct an image from the vector field

$$\nabla^2 I = \operatorname{div} G$$

For example by solving the Poisson equation

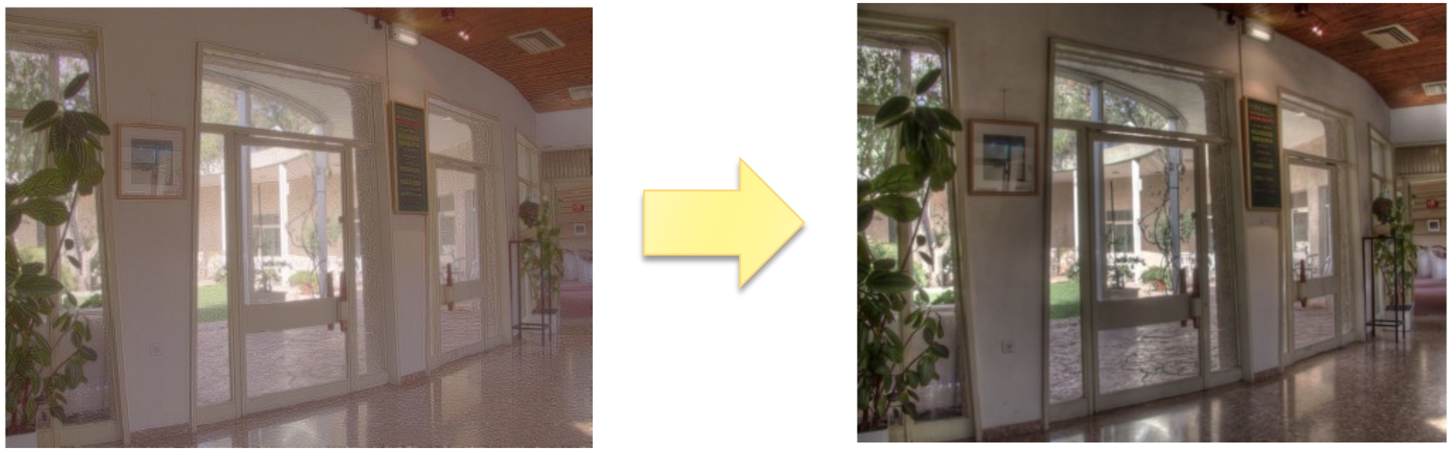
Retinex examples

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



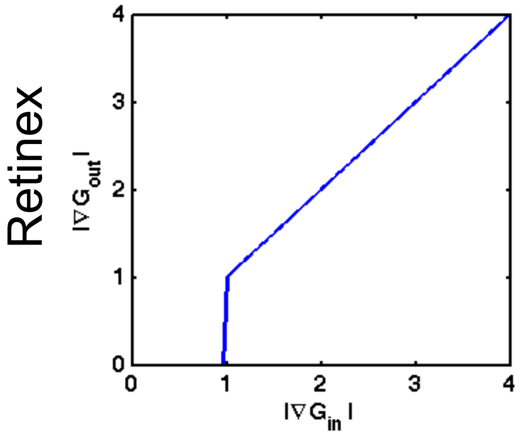
From:http://www.ipol.im/pub/algo/lmps_retinex_poisson_equation/#ref_1

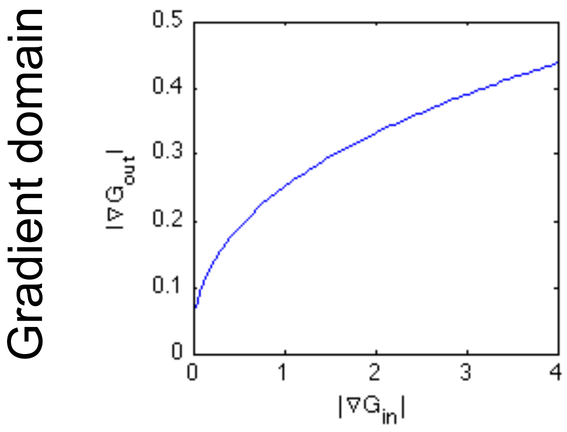
Gradient domain HDR compression



[Fattal et al., SIGGRAPH 2002]

- 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

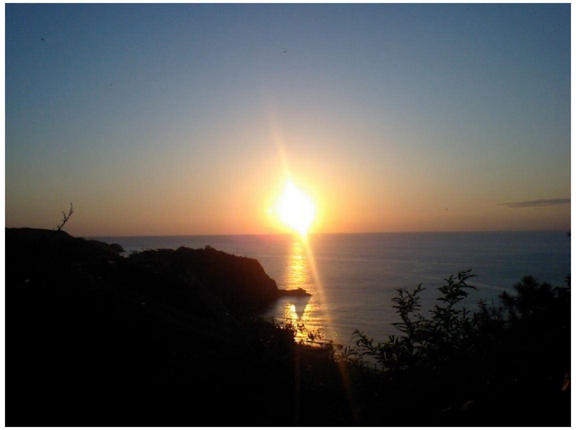
Techniques

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

Glare

“Alan Wake” © Remedy Entertainment

Glare Illusion

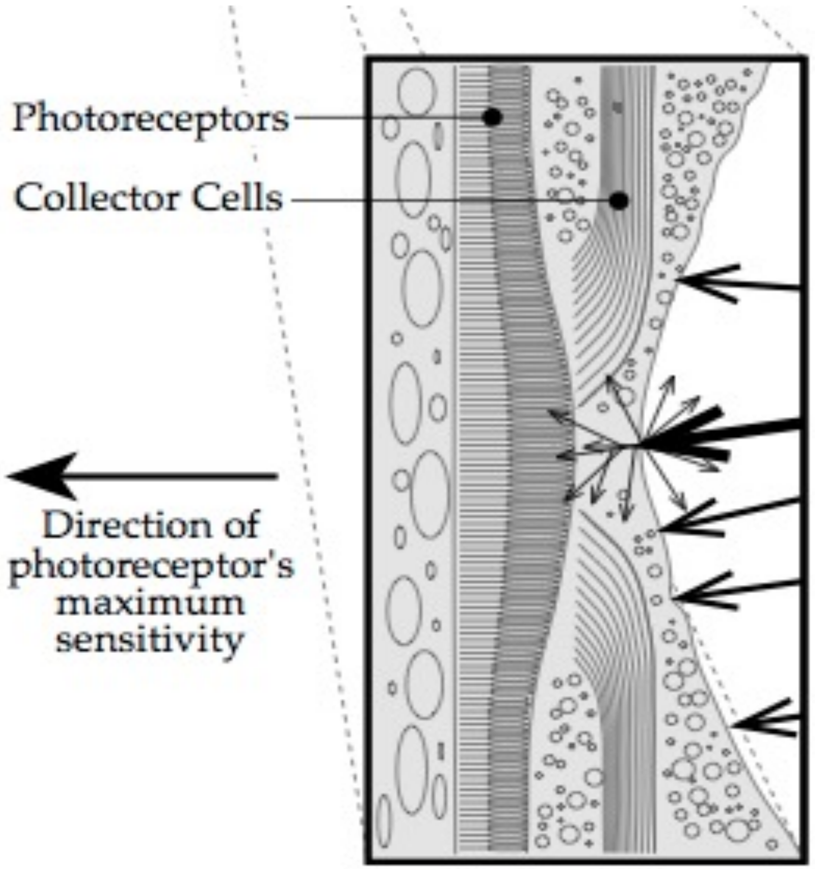


Photography

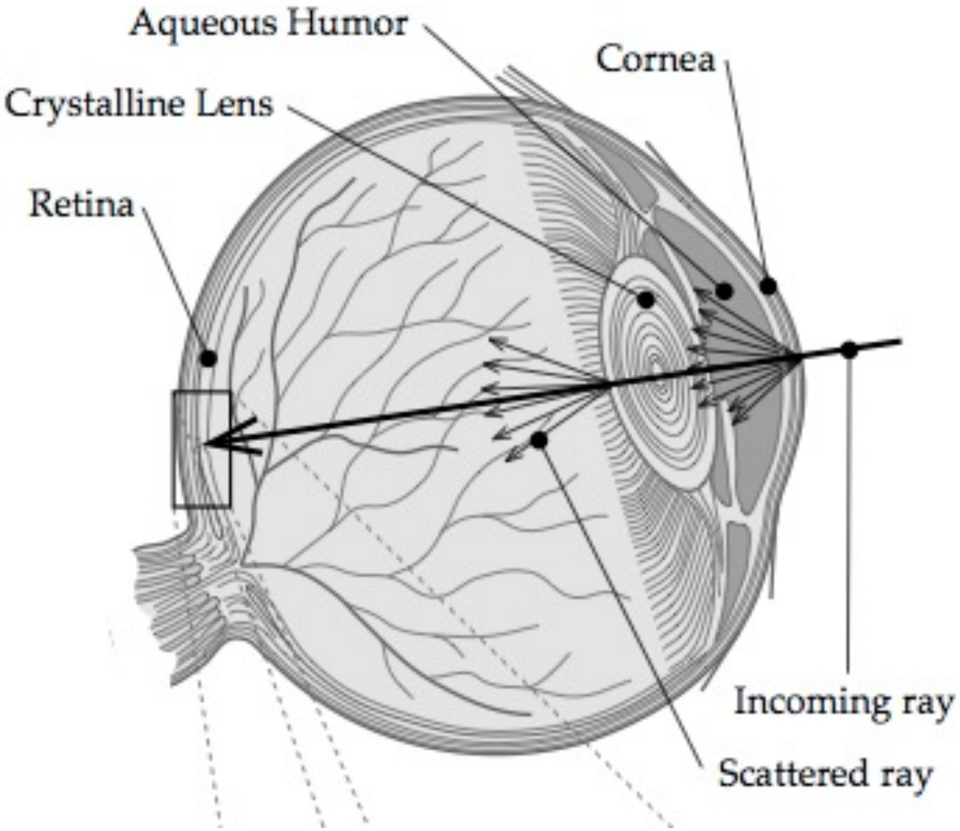
Painting

Computer Graphics
HDR rendering in games

Scattering of the light in the eye

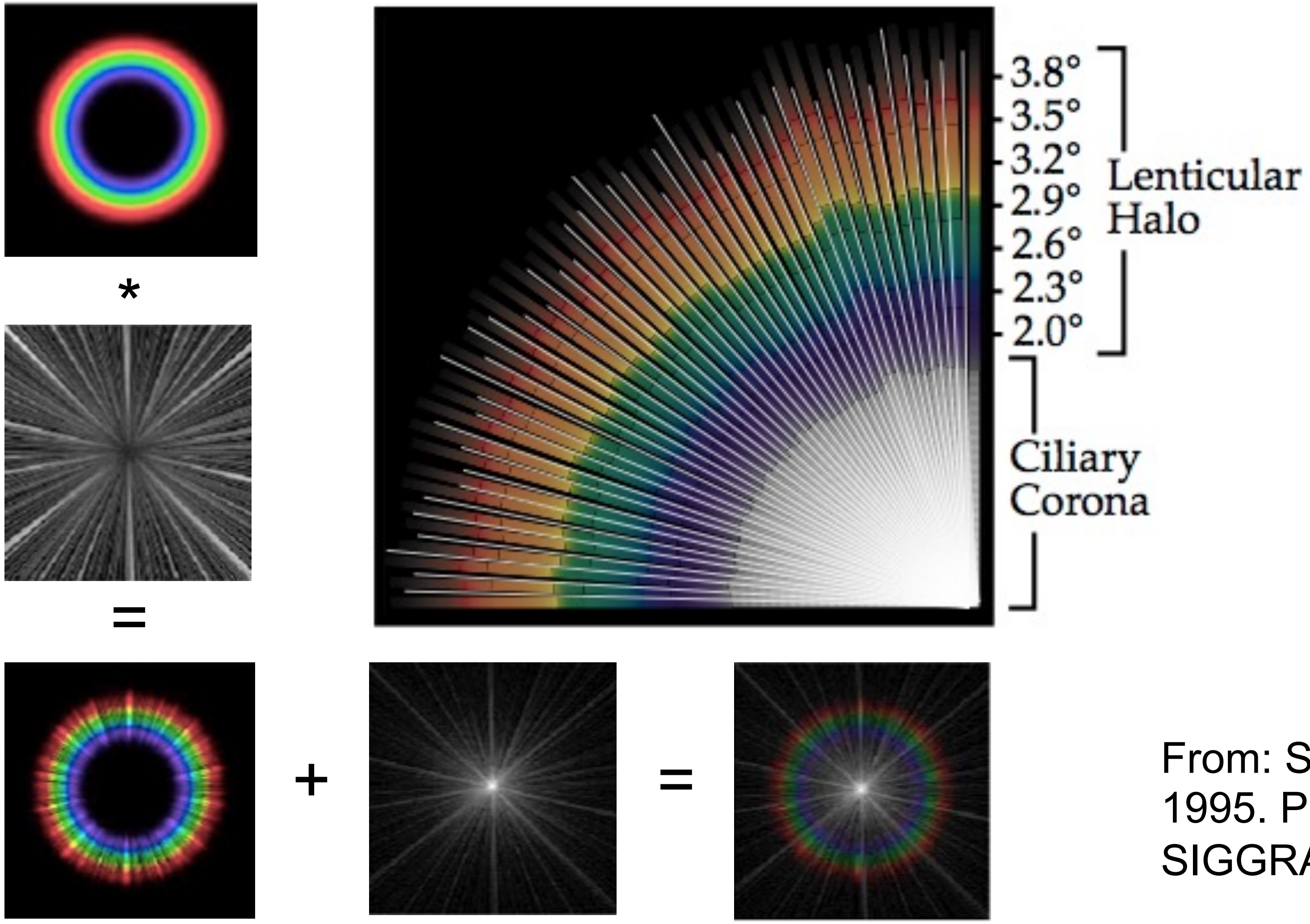


Magnification of Retina



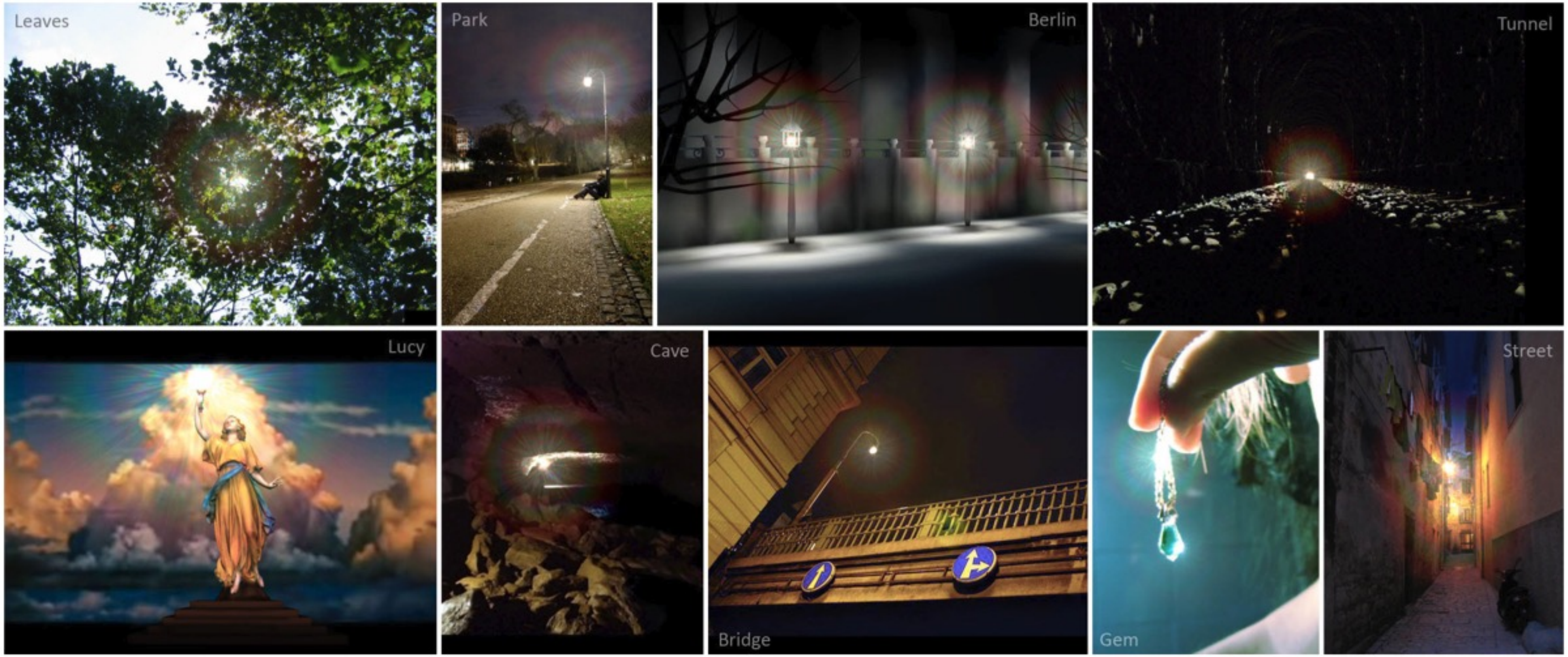
From: Sekuler, R., and Blake, R. Perception, second ed. McGraw- Hill, New York, 1990

Ciliary corona and lenticular halo



From: Spencer, G. et al. 1995. Proc. of SIGGRAPH. (1995)

Examples of simulated glare

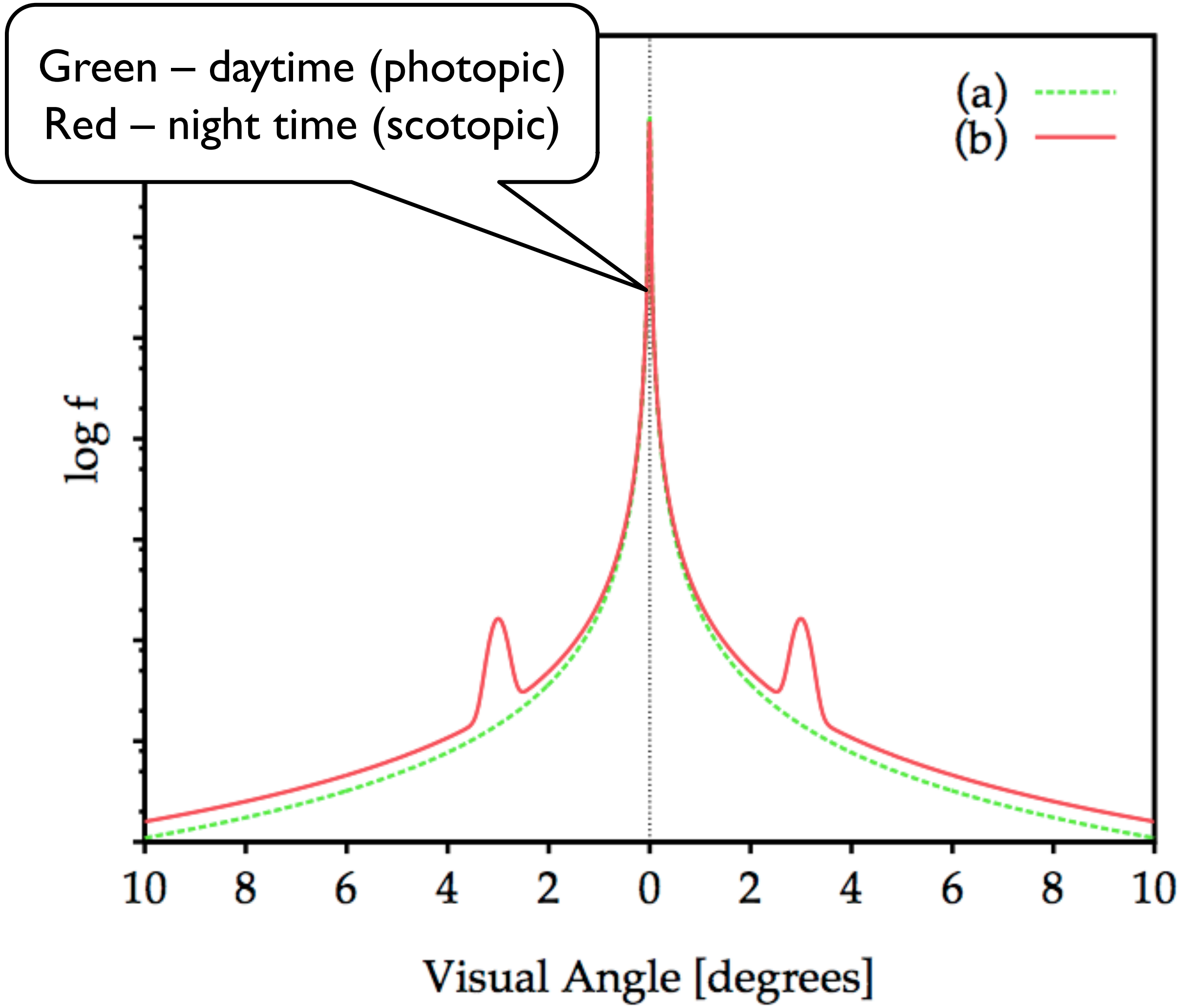


[From Ritschel et al, Eurographics 2009]

Temporal glare

[From Ritschel et al, Eurographics 2009]

Point Spread Function of the eye

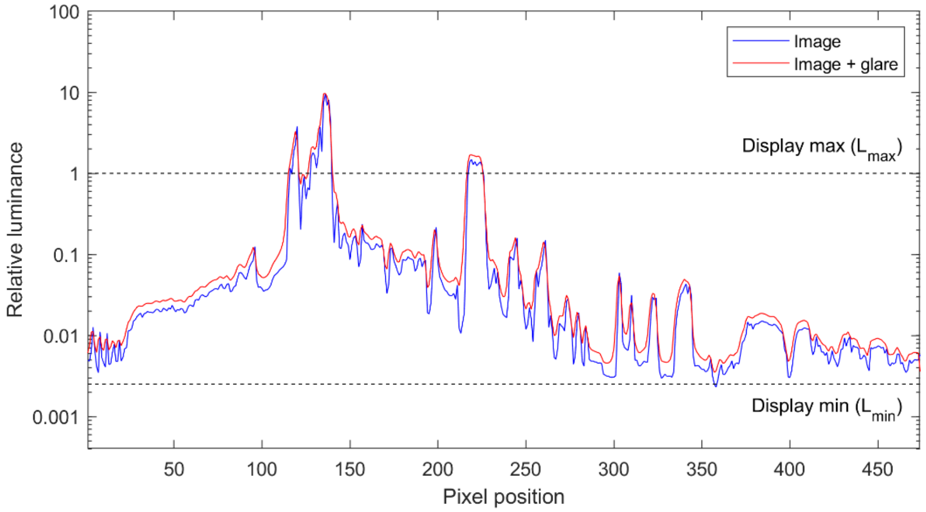


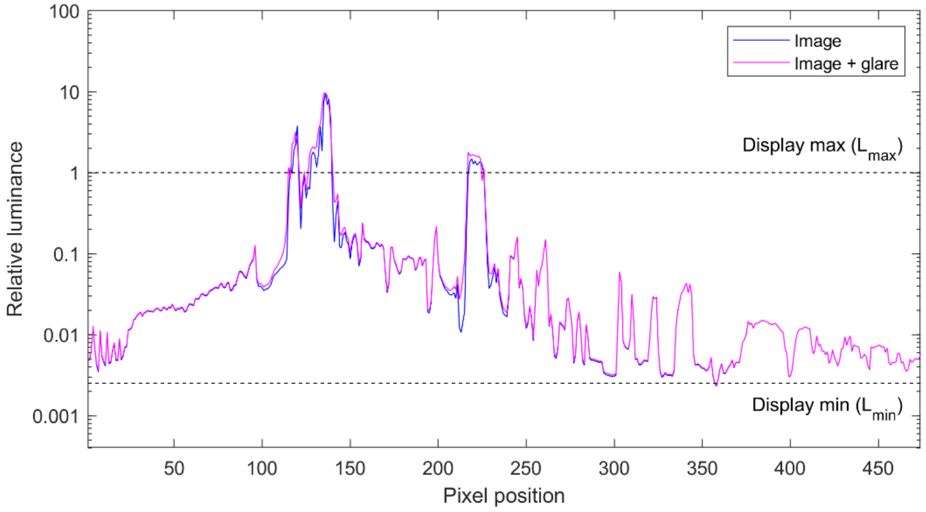
Green – daytime (photopic)
Red – night time (scotopic)

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

From: Spencer, G. et al. 1995. Proc. of SIGGRAPH. (1995)

Selective application of glare





A) Glare applied to the entire image

$$I_g = I * G$$

Glare kernel (PSF)

- Reduces image contrast and sharpness

B) Glare applied only to the clipped pixels

$$I_g = I + I_{cliped} * G - I_{cliped}$$

where $I_{cliped} = \begin{cases} I & for\, I > 1 \\ 0 & otherwise \end{cases}$

Better image quality

Selective application of glare

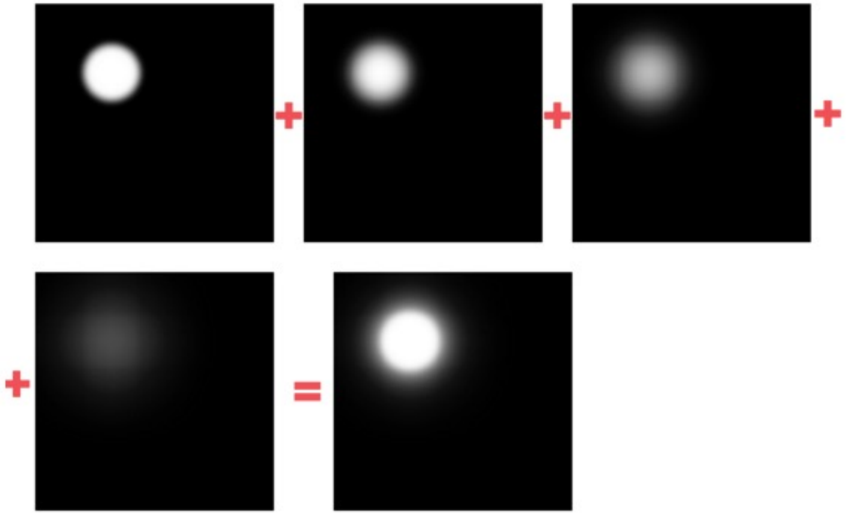
Original image

A) Glare applied to the entire image

B) Glare applied to clipped pixels only

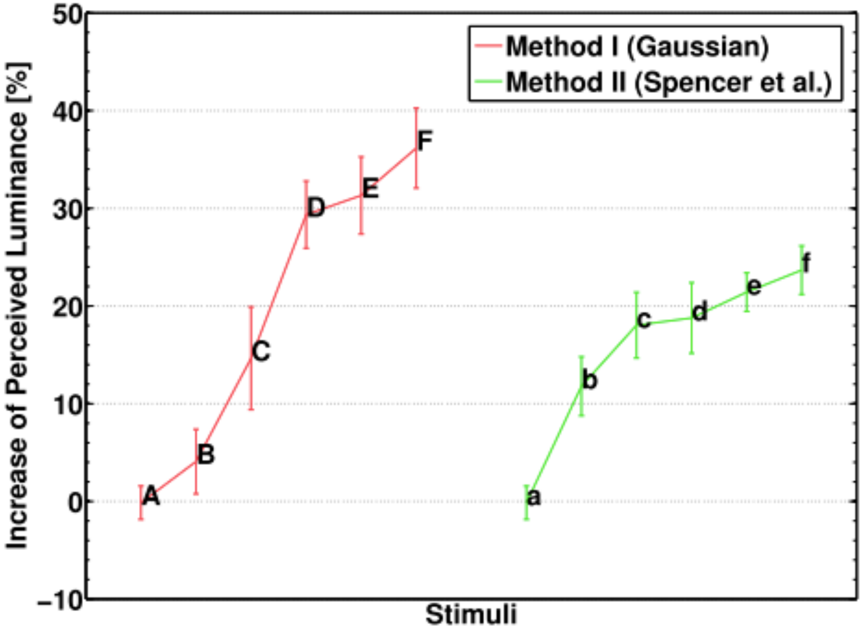
Glare (or bloom) in games

- 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



red - Gaussian

green - accurate

[Yoshida et al., APGV 2008]

HDR rendering – motion blur

From LDR pixels

From HDR pixels

References

- Comprehensive book on HDR Imaging
  - E. Reinhard, W. Heidrich, P. Debevec, S. Pattanaik, G. Ward, and K. Myszkowski, High Dynamic Range Imaging: Acquisition, Display, and Image-Based Lighting, 2nd editio. Morgan Kaufmann, 2010.
- Overview of HDR imaging & tone-mapping
  - http://www.cl.cam.ac.uk/~rkm38/hdri_book.html
- Review of recent video tone-mapping
  - A comparative review of tone-mapping algorithms for high dynamic range video *Gabriel Eilertsen, Rafal K. Mantiuk, Jonas Unger*, Eurographics State-of-The-Art Report 2017.
- Selected papers on tone-mapping:
  - G.W. Larson, H. Rushmeier, and C. Piatko, "A visibility matching tone reproduction operator for high dynamic range scenes," *IEEE Trans. Vis. Comput. Graph.*, vol. 3, no. 4, pp. 291–306, 1997.
  - R. Wanat and R. K. Mantiuk, "Simulating and compensating changes in appearance between day and night vision," *ACM Trans. Graph. (Proc. SIGGRAPH)*, vol. 33, no. 4, p. 147, 2014.
  - Spencer, G. et al. 1995. Physically-Based Glare Effects for Digital Images. Proceedings of SIGGRAPH. (1995), 325–334
  - Ritschel, T. et al. 2009. Temporal Glare: Real-Time Dynamic Simulation of the Scattering in the Human Eye. Computer Graphics Forum. 28, 2 (Apr. 2009), 183–192
  - ...